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# COMMUNICATION/EXPLORATION/NAVIGATION TECHNOLOGIES - APPLICATIONS, TRADE-OFFS AND POSSIBLE TRANSFERS BETWEEN SPACE AND GROUND AT THE EXAMPLE OF MOA², A NOVEL PULSED PLASMA ACCELERATOR

**DISSERTATION**

zur Erlangung des akademischen Grades

Doktor der technischen Wissenschaften

eingereicht an der

**Technischen Universität Graz**

Betreuer

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Graz, Juli 2014

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# 1. Abstract / Kurzfassung

Technology Transfer has a long tradition in the areas of space commercialisation and high-tech products/materials. Micro-chips, alloys, solar cells and high-temperature materials are a few representative examples for the extensive knowledge transfer in these areas, which has driven a significant number of the recent technology paradigm shifts worldwide. If a company can establish itself in both the space and the commercial high-tech area, it can benefit from significant synergies, thus allowing for an unrivalled competitive advantage, coming along with substantial financial profits.

Given the importance of technological progress and innovation for the functioning of our western industrial society and the growing implications of technological progress being made in space, this dissertation is bound to discuss the potential applications, the underlying trade-offs and the possible technology transfers between space and ground. Owing to the complexity of the topic it will not be possible to draw a full picture; by looking at the subject matter from three different angles however, such as:

- the **domains** in which technology transfer takes place (communication, exploration and navigation);
- the **players** that conduct technology transfer, all engaging a specific set of rules in their repective domain (CERN, ESA and the European Joint Research Centre); and
- the **examples** for successful technology transfers (spin-in vs. spin-off – aerospace and automotive);

it will be possible to identify the most important ‘rules of the game’ that govern the technology transfer process between space and ground. Acknowledging that there is an exception to every rule, this thesis will conclude with a close look at an innovation, which has the potential to exactly change these rules of the game – MOA², the Magnetic field Oscillating Amplified Accelerator, a paradigm buster within the high-tech area, which will, as the final missing technology transfer building block, be able to close the gap in the propulsion area between aerospace and the terrestrial industrial area, thereby finally interlinking the two sectors.

Technologietransfer hat eine lange Tradition in den Bereichen der kommerziellen Raumfahrt und der Hightech Produkte/Materialien. Mikro-Chips, Legierungen, Solarzellen und Hochtemperaturmaterialien sind nur einige der Beispiele für den extensiven Wissenstransfer in diesen Gebieten, welcher in letzter Zeit eine signifikante Anzahl an Technologieparadigmenwechseln auf der ganzen Welt ermöglicht hat. Wenn eine Firma imstande ist, sich sowohl im Weltraum- als auch im kommerziellen Hightech-Sektor zu etablieren, dann kann sie von signifikanten Synergien profitieren und sich damit einen Wettbewerbsvorteil verschaffen, der mit substanziellen finanziellen Gewinnen einhergeht.

In Anbetracht der Wichtigkeit des technischen Fortschritts und der Inovation für das Funktionieren unserer westlichen industriell geprägten Gesellschaft, sowie der steigenden Auswirkungen des im Weltraumsektor generierten technologischen Fortschritts hat diese Dissertation ein klares Ziel; die Diskussion der potenziellen Anwendungen, der zugrundeliegenden Austauschbeziehungen und der möglichen Technologietransfers zwischen dem Weltraum und dem Boden. Aufgrund der Komplexität des Themas wird es keinesfalls möglich sein, das vollständige Bild zu erfassen. Durch die Betrachtung der Thematik aus drei verschiedenen Blickwinkeln, wie:

- den **Domänen**, in welchen es zum Technologietransfer kommt (Kommunikation, Exploration und Navigation);
- den **Spielern**, welche Technologietransfer mit einer spezifischen Reihe von Regeln in ihrer jeweiligen spezifischen Domäne betreiben (CERN, ESA und die Gemeinsame Forschungsstelle der Europäischen Union); und
- den **Beispielen** für erfolgreiche Technologietransfers (Spin-in und Spin-off – im Raumfahrt- und Automobilsektor);

ist es möglich, die wichtigsten “Spielregeln” zu identifizieren, welche den Technologietransferprozess zwischen dem Weltraum und dem Boden steuern. Bekanntermaßen hat jede Regel ihre Ausnahme und der Technologietransfer ist keine Ausnahme – deswegen wird diese Dissertation zum Abschluss auch eine Innovation genauer unter die Lupe nehmen, die das Potential besitzt, genau diese Spielregeln von Grund auf zu ändern. Die Rede ist von MOA², dem Magnetic field Oscillating Amplified Accelerator (Magnetfeldoszillationsbeschleuniger), einem „Paradigm Buster[1]“ im Hightech-Sektor, welche in der Lage ist, als letzter noch fehlender Technologietransferbaustein die Lücke im Antriebsbereich zwischen der Luft- und Raumfahrt und der terrestrischen Industrie zu schließen, um damit endgültig die beiden Sektoren miteinander zu verbinden.

[1] Frei übersetzbar als “Paradigmenwechsler”

# 2. Table of Contents

# 3. Introduction

**Technology Transfer has a long tradition in the areas of space commercialisation and high-tech products/materials**. Micro-chips, alloys, solar cells and high-temperature materials resemble only but a few examples of the extensive knowledge transfer in these areas, which has driven a significant number of the recent technology paradigm shifts worldwide. If a company can establish itself in both the space and the commercial high-tech area, it can benefit from significant synergies, thus allowing for an unrivalled competitive advantage. Building upon R&D funding as readily available in the strategic aerospace area, it is possible to adapt and transfer the acquired knowledge/expertise for the commercial market(s), thereby ensuring substantial financial profits.

Given the importance of technological progress and innovation for the functioning of our western industrial society and the growing implications of technological progress being made in space, this dissertation is bound to discuss the potential applications, the underlying trade-offs and the possible technology transfers between space and ground. In acknowledging that technology transfer covers a very wide field, we limit the focus in a first step to **three specific technology transfer domains, namely space exploration, satellite communication and satellite navigation, as these are the areas where technology transfer has played, continues to play for the time being and is expected to play a significant role in the near future.** The analysis of the technology transfer flows within these domains is based on three respective articles, which I have contributed to the book "Outer Space in Society, Politics and Law" published in 2011.

**After this initial look onto the different technology transfer domains, we will continue by assessing different players and their programmes and projects to identify both requirements and constraints that govern this process**. Given the complexity of the framework, a generic assessment approach will not be easily possible. Technology transfer is not a "clear cut", as it does often span over several domains, such as communication, propulsion, navigation, energy, etc., governed by requirements and constraints like highest safety, best performance, lowest cost, etc., which cannot be easily rated in terms of importance – not even for a specific application. Therefore, instead of trying to make a direct match between requirements and constraints, which are quite often not as obvious as one would expect, I will invite you to have a look at specific players, which are confronted with technology transfer – all with a different flavour to it. The players selected are:

- **CERN, the European Organisation for Nuclear Research**, an international entity and a world-renown particle research laboratory, which perfoms basic research in particle physics. I have worked at CERN from 1994-1998, supporting the development of a high-end particle detector making use of VLSI technology. CERN, performing frontier science, is very active in technology transfer, spinning in and off the latest technologies. Achieving the highest scientific performance is the key driver behind these activities.
- **ESA, the European Space Agency, an internatonal space agency**, conducting a broad set of spaceflight programmes in an international context. I have worked at ESA from 1998-2006, supporting the development of the avionics system of the ATV (Automated Transfer Vehicle), a project with a strong focus on communication technologies, governed by manned spaceflight requirements and constraints, which rates the safety of the astronauts as the top priority that every other design aspect has to adhere to.
- **JRC-IET, the Joint Research Center, Institute for Energy and Transport**, a European research center, devoted to set-up international codes and standards in the area of energy and transport research. I have worked at the JRC-IET from 2009-2011, supporting the development of hydrogen fuel cells and tanks in support of the Hydrogen Economy.

> Simplicity of use and highest safety at low cost are the main drivers for the activities at the JRC-IET.

CERN, ESA, the JRC-IET and others, all these entities perform technology transfer - all at different levels. Given the specific constraints that these different players are confronted with, both the technologies transferred as well as the encompassing strategies will vary, as will the partners, which participate to this transfer. Consequently **every technology transfer example is unique, very much dependent on the involved technology, the partners and the specific constraints of the encompassed sectors**. Therefore the technology flow, hence the decision whether the technology transfer will be a spin-off or a spin-in depends very much on the involved R&D strategies and the possible applications. Naturally terms like spin-in and spin-off are of relative nature; one entity's spin-in is the other one's spin-off. **Given the importance of spin-ins and spin-offs, I have included a chapter into this dissertation, in which I assess the drivers that govern spin-in processes. I continue further by showing that the tide is turning from spin-off to spin-in; one can likely expect that space will more and more spin-in technologies from the aviation, automotive and the Information and Communication Technology (ICT) sector**. Finally I provide an example for a spin-in process that is likely to occur in the satellite communication domain, when fuel cells, which are being developed for the automotive sector will be adapted and utilised in the next generation of telecommunication satellites. This example is based on my activities at ESA and the JRC-IET and hence combines economic, regulatory and technological considerations.

Naturally not everything can be planned and spin-ins, spin-offs and technology transfers are surely no exception to that. It is always possible that certain new innovations might open the door for further technology transfers in other domains – these innovations will then manifest themselves as 'paradigm shift', as they will change the rules of the game in specific technology areas, just as the telephony sytem replaced the telegramme, the car replaced the horse and the jet engine replaced the propeller. Typically this process is rather rapid and not evolutionary; therefore **the underlying technology that enables the paradigm shift is also often called 'disruptive technology'.**

While it is not possible to forecast such a disruption it is nonetheless worthwhile to have a look at specific examples. **The final chapter of this thesis is dedicated to these class of innovations in general and to an outstanding new innovation - MOA², the Magnetic field Oscillating Amplified Accelerator - specifically**. MOA² is a pulsed plasma accelerator with numerous applications in the space, coating, metallurgy area, semiconductor manufacturing and medical sector. With this broad portfolio, MOA² serves a a great role model for a technology opening up a – or several - new area(s) of technology transfer, which has/have not yet been materialised but might become available in the medium to long term. I have therefore included MOA² as an example for a disruptive technology and devoted the last chapter to examine it. MOA² is the intellectual property of $Q_2$, a start-up company in Vienna, Austria, which I support since 2006 in the development of this pulsed plasma thruster and its numerous applications. Backed up by expert opinions of world-leading specialists and recent successful tests of its MOA Accelerator, $Q_2$ provides for an excellent example of a company intending to thrive on a technology transfer concept between space and ground, enabled by the unique MOA² innovation that is being best described as an 'Space R&D Paradigm Buster' as it will enable for the fist time the development of a space propulsion system, which is utterly being spinned in from a commercial application, offering the same performance-to-price ratio level as seen with computers, solar-cells, light-weight materials, etc. eventually helping to make space systems truly commercial for once and for all.

# 4. Technology Transfer Domains: From Exploration to Space Application

Technology Transfer has a long tradition in certain areas of space. Possibly the first examples stem from the Apollo Programme of NASA, conducted in the 1960s, eventually leading to the highest level of miniaturisation of computer technology – the integrated circuit (IC)-based computer using microchips based on silicon technology. These technology transfers are therefore to be classified as spin-offs from a human **space exploration programme**.

While the micro-chip is a legacy of Apollo, the solar cells that energise our pocket calculators are likely based on satellite technology, notably telecommunication satellite technology, which uses nowadays solar arrays of 13 m and beyond, providing 20 kW of electric power to run several transponders on-board. The first civilian telecom satellite to use solar arrays was Telstar, launched on the $10^{th}$ of July 1962 in Cape Canaveral, USA.

Space communication is, together with satellite navigation and Earth observation, grouped under the umbrella of **space applications**. These three areas are today the only branches of the space sector, which are governed by commercial rules, or which are at least developing rapidly into that direction. As of today, **satellite telecommunication** is a fully commercialised sector; **satellite navigation** is allowing for significant commercial profits for companies working in that field and **Earth observation**, is moving into that corner very fast as well, albeit the biggest customers for its services are still the governments and its entities. Given that set-up, the commercial pressure is likely to trigger the spin-in of terrestrial technologies into these areas; hence technology transfer is an integral part of the game.

## 4.1 *“Space Exploration” ([A] Frischauf, 2011)*

Published in Frischauf, N.: Space Exploration, in C. Brünner, & A. Soucek, *Outer Space in Society, Politics and Law* (2011), pp. 97-109 [A]

*"It’s human nature to stretch, to go, to see, to understand. Exploration is not a choice, really; it’s an imperative." Michael Collins, U.S. Astronaut*[2]

Exploration has been a buzzword over centuries, ranging from the early naval endeavours in the 15th century to the space missions of our days. Throughout the centuries, exploration could be best described as the act of searching or travelling around a terrain for the purpose of discovery of resources or information[3]. It were the early exploration missions that led to the discovery of America, Australia, etc.; it were the inland expeditions that brought back innovations and new products; and it was the act itself that brought with it new knowledge, which transformed human culture to an enlightened one - both in Europe and eventually worldwide. Space exploration is the logical continuation of that very process in a world that leaves no major “white” spots to explore further. It is therefore defined "... as the use of astronomy and space technology to explore outer space."[4], a sentence that involves three words, which have to be understood completely to appreciate the gravity of the definition.

[2] Flew into space with Gemini 10 and Apollo 11
[3] http://en.wikipedia.org/wiki/Exploration, accessed April 2011
[4] http://en.wikipedia.org/wiki/Space_exploration, accessed April 2011

### 4.1.1 Astronomy and Space Technology are Key Essentials in exploring outer Space

If exploration is the act of searching or travelling around a(n) (unknown) terrain for the purpose of discovery of resources or information, then one had better assembled an expedition tour guide well in advance. Such a tour guide will have to contain all critical information that is required to turn the expedition into a success. This involves time slots to know when best to start, navigation options how best to get there and forecasts about what might happen along the way and at the destination - all necessary to plan the final route as carefully as possible to reach the place of interest with the highest probability of success.

The essentials for our space tour guide are likely to be provided by astronomy - possibly the world's oldest science. As the natural science that deals with the study of celestial objects, astronomy can provide us with key information in the space context, such as:

- a rough description of the target area/celestial object (mass, atmosphere, rotation period)
- key information about the risks en-route (solar weather, cosmic radiation, specific orbits)
- potential routes, given a defined amount of energy to be spent (launch windows, delta-V)

Given its focus area, which is the celestial objects and phenomena that originate outside the Earth's atmosphere, astronomy is not a science that has a direct impact on our daily lives - not in our modern world, where the night sky in our cities is illuminated by thousands of street lamps blocking the lights of all but the most luminous stars. It is only when dramatic celestial events take place, like a solar or a lunar eclipse or a great comet, such as Hale-Bopp, that we take time to gaze into the sky. But for a scientist or engineer concerned with the planning, design and execution of a space mission, astronomy is THE essential science, providing the knowledge essential to making the mission a success.


*Figure 4-1: Comet C/1995 O1 Hale-Bopp over the Austrian Alps (Source: N. Frischauf)*

If astronomy provides the knowledge, space technology is the means to get to the target, which in space exploration is typically a planet or any other celestial object. According to the book "Space Technology"[5], space technology is technology that is related to entering and retrieving objects or life forms from space.

Typical space technologies deal with missiles and rocket engines of all sorts, attitude control systems, navigation systems, power generation, control and distribution systems onboard spacecraft, on-board computers and avionics. While originally these systems were developed exclusively for space applications and only later transferred to the terrestrial sector (a so-called 'spin-off'), the tide has changed recently and a significant part if not the majority of all these systems is now predominantly developed in the terrestrial field, while the space sector focuses on adapting and integrating these technologies to its missions ('spin-in').

Typical examples of this paradigm shift are Li-Ion batteries, MEMS[6], carbon-fibre reinforced plastics (CFRP) and computer chips. Most of these systems are nowadays developed in a terrestrial context for mass-market applications such as mobile phones, laptops and later on transferred into the space sector.

It is interesting to note that it was NASA's Apollo programme, which helped to create the computer as we know it today. Due to the mission design of Apollo, an on-board computer more powerful than ever was needed to control guidance and navigation on-board the spaceship when it was on its way to the Moon and back to Earth. Designed by MIT and Raytheon, the Apollo Guidance Computer (AGC) provided onboard computation and control for guidance, navigation, and control of the Command Module (CM) and Lunar Module (LM) spacecraft. To make this happen in the confined volume of the CM and LM, electronic miniaturisation had to be brought to a new level - the AGC is therefore one of the first integrated circuit (IC)-based computers - such as the ones we use today. How much did it cost? Estimates range between U.S. $ 90-100 million which today would be between U.S. $ 350 – 400 million.

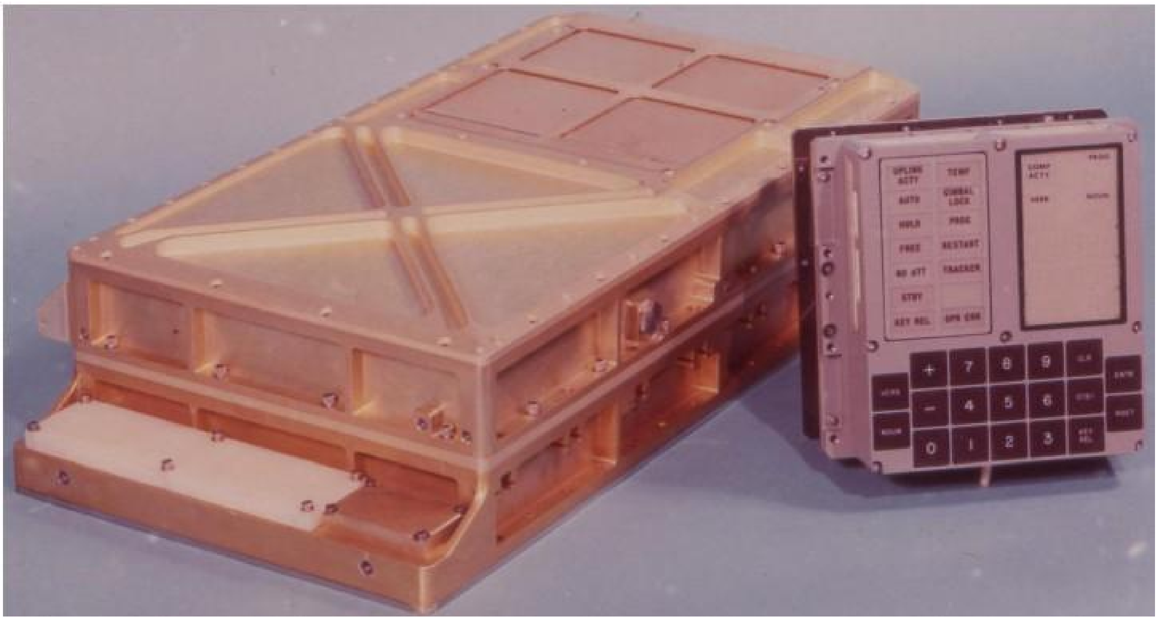

*Figure 4-2: The Apollo Guidance Computer (Source: NASA)*

[5] By Bruce, Linda, John Hilvert, and Jack Bruce. Space Technology. City: Black Rabbit Books. 2006. 32.
[6] Micro-Electro-Mechanical Systems.


Having clarified two major items in the definition of space exploration, the meaning of "outer space" in a space exploration context still needs to be defined. Obviously, outer space is the void that exists beyond the Earth and any other celestial body. “Void” is to be seen as a relative term here and does not constitute a perfect vacuum, as interplanetary and even intergalactic space is populated with particles and radiation. Compared to the atmosphere of the Earth, interplanetary space is like a vacuum however, and although there is no sharp boundary between the Earth's atmosphere and interplanetary space one tries nonetheless to define a borderline from which on outer space starts.

Physics can help here, as was discovered by Theodore von Kármán (1881-1963) a Hungarian engineer/physicist, who deduced the borderline through aerodynamic studies.

Acknowledging that air density drops as one ascends leads to the logical consequence that a plane will have to travel faster and faster to allow for sufficient lift generation to keep it aloft. Modern turbojet aircraft travel at altitudes of 10-12 km, military aircraft may ascend to 30 km, but beyond this altitude, rocket engines will be required to provide sufficient velocity to generate the lift required. However, at 100 km altitude, the point is reached where the plane will have to travel 27000 km/h or 7.5 km/s to stay aloft, but at that speed the orbital velocity is reached as well, which means that the plane will not depend on aerodynamic lift anymore to fly around the Earth - this is where outer space begins.

In honour of his work, the altitude where the required flying speed matches the orbital velocity is called the Kármán line and it is nowadays used as the boundary between the Earth's atmosphere and outer space. Conveniently it is close to the altitude of 100 km, so this value has been set as international standard by the Fédération Aéronautique Internationale (FAI), which is an international standard setting and record-keeping body for aeronautics and astronautics.

If you want to be recognised as astronaut, you will have to travel beyond this 'magic' altitude of 100 km - and this is exactly where SpaceShipTwo and Rocketplane XP intend to take you up to and where space exploration starts…

*Figure 4-3: Layers of the Earth’s Atmosphere and the Kármán Line (Source: NOAA)*

### 4.1.2 Space Exploration: From Humans...

Space exploration has a strong human component. Apollo was a clear human focused space exploration programme culminating in six Moon landings in the late 60s and early 70s. Driven by a context of political competition, Apollo failed to transform itself into a lasting endeavour, such as by establishing a permanently inhabited Moon Base. It did however show that humans can land on another celestial body and will therefore form the basis for future human exploration activities to the Moon, Mars and asteroids, such as envisaged by ESA's Aurora programme.

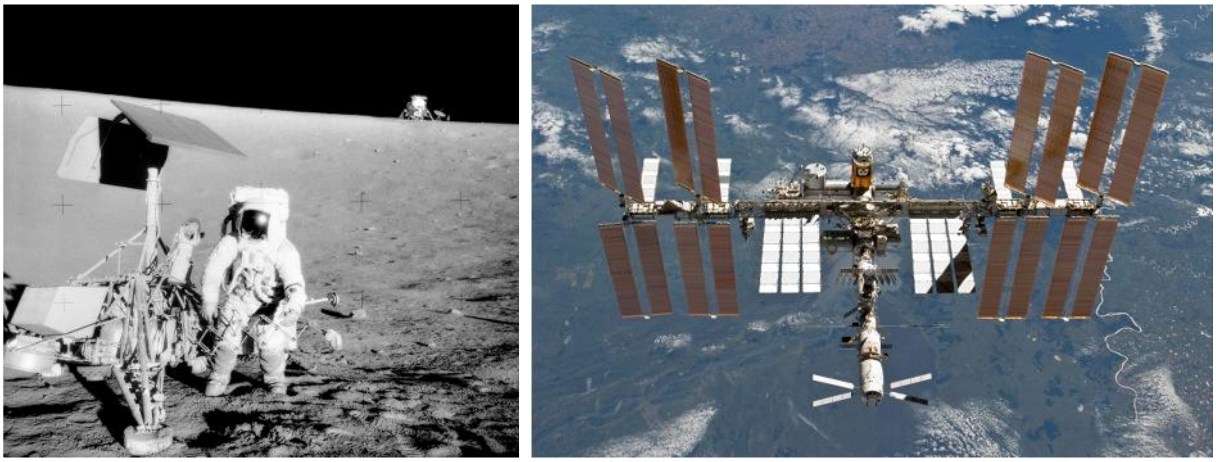

*Figure 4-4: left image: Astronaut Charles Conrad of Apollo 12 examines Surveyor 3; right image: the ISS, photographed by the STS-133 crew on 07/03/2011 (Source: NASA)*

Another major achievement from these early days of spaceflight - and one that was kick-started by the USSR/Russia - are manned Earth orbiting space stations, such as the Russian Saljut stations 1 to 7, and MIR - accompanied by its U.S. counterpart Skylab. All of these are history by now - MIR plunged into the Pacific Ocean on 23 March 2011 - and are superseded by the largest and most massive structure ever installed in space - the International Space Station ISS, with dimensions of 110 x 100 x 30 m and a mass of 303 tons.

As far as human space exploration is concerned that is all there is. At least so far, as numerous space agencies are planning to send humans in the future back to the Moon and possibly further on to Mars and the asteroids. The most ambitious space exploration programme, building upon robotic and human elements, is Aurora, the exploration programme of the European Space Agency. Established in 2001, Aurora envisages manned landings on Moon and Mars, with stepping-stones before and in between, carefully staggered by robotic elements. With the current budget issues of its Member States however, ESA has re-focussed Aurora to a somewhat smaller scale. Focussing on the robotic elements, ESA is currently aiming at maintaining a critical subset of the envisaged missions in a cooperative endeavour with NASA, JAXA and other space agencies.

### 4.1.3 ... to Robots and back to human Explorers

Space exploration also has a strong robotic component. All space missions beyond the Earth's sphere of influence - that is the Earth orbit and the Moon - have been performed by robotic spacecraft. Currently all space fairing nations have neither the technology nor the resources to send humans to a place in space that is further away from the Earth's surface than 450 km - the maximum altitude of the ISS. As long as this paradigm does not change, space exploration of our solar system (and beyond) will be left to our robotic messengers.

Compared to what we know from Science Fiction films, books and novels, it might sound odd that space exploration is currently left to robotic spacecraft only. Where is the human dimension? Are we superseded by our own creations? The answer is a clear no - a robot cannot replace a human, neither on Mars nor on the Earth. What it can do, however, is to reach places that are currently too dangerous or too far away to be explored by humans, it can perform scientific experiments, carefully designed beforehand and properly executed step-by-step during the mission, and it can be left behind to save on mission costs. All this makes a robot the perfect substitute for the scientist/explorer at site. With continued technological progress our robotic sphere of exploration will progress outwards into the cosmos, as will the sphere where humans can follow - now replacing their own substitutes. At the very end it is the human explorer that again will follow in the footsteps of its robotic envoys, if only for the reason that it is his desire to explore - and this desire forms the root cause of the whole process.

Beside this somewhat emotional reasoning, it can also be argued that science/exploration at the highest level will demand human explorers, as the process of relying exclusively on robotic exploration will eventually become too time consuming. The following thought scenario might shed some light on this argumentation:

*Imagine that it is the year 1996 and assume that we want to send a robotic spacecraft to Mars to look for permafrost and possible signs of extinct or extant life. Now let us conceive the idea, design, manufacture and test the spacecraft. If we are doing it in Formula 1 style then we end up with 7 years - this is the record that Mars Express, ESA's € 150 million Mars orbiter, has set recently. 2003, the best Mars opposition to come in 60.000 years lies ahead of us - we barely make it to launch in time and send our spacecraft on its 6-months journey. In 2004 we are finished with commissioning and data collection begins. Our Principal Investigators (PIs) finish their first data scans in 2005 and in 2006 the first papers are published in peer-reviewed journals. Scientists and experts all over the world discuss the papers. Slowly, proposals for the next Mars exploration spacecraft start to emerge...*

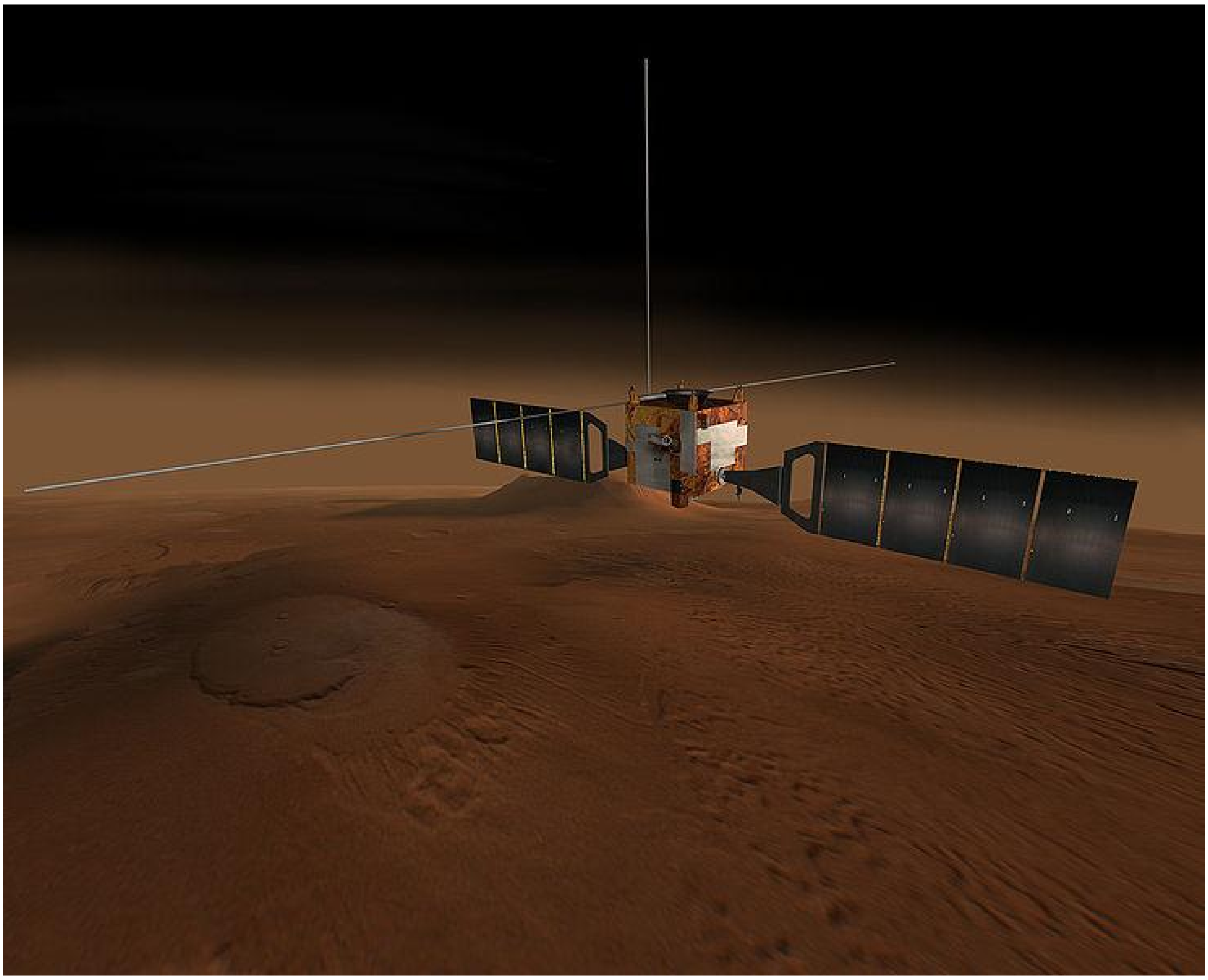

*Figure 4-5: NASA might have coined the slogan "faster, cheaper, better", but ESA can claim that its spacecraft Mars Express has put that slogan into reality (Source: NASA)*

Ten years did pass between the conception and the first published results, and possibly another two years will be required to condense the proposals into a first design. From here the whole process to conceive a Mars exploration mission starts again - now with the second generation spacecraft, building upon the results of its progenitor.

Now let us assume that we do not want or that we cannot afford to wait 10-12 years, but that we have to move fast. Or that we know already that our experiments on-site will trigger answers that we want to check out immediately. Then it really makes no sense to send a robotic spacecraft to Mars and have the scientist waiting back on Earth for the results - in this case it is much better to send the scientist directly to Mars. Of course a manned mission will cost us much more money but it will also save us a lot of time, as he/she will be able to observe, measure and move ahead in real-time on-site. This, however, requires a permanently manned outpost with the necessary resources and laboratory facilities. Robotic exploration missions can be seen as precursors to human science/exploration missions. So what shall our robots do in their role as precursors to human exploration? Captain James T. Kirk has the answer, *"... to boldly go where no man has gone before..."*

### 4.1.4 Highlights and Insights of robotic Space Exploration: From Voyager...

15 August 2006 marks the date that a spacecraft has for the first time reached a distance of 100 AU (100 times the distance Sun-Earth) - this spacecraft was Voyager 1, a NASA spacecraft launched on September 5, 1977. Voyager 1 is now leaving the solar system with a velocity of

66666.6 kilometres per hour, its twin Voyager 2 reached a distance of 91.898 AU from the Sun on April 13, 2010 and continues to travel outward at roughly 3.264 AU per year. By now, Voyager 2 is twice as far away from the Sun as Pluto is, but not yet beyond the outer limits of the dwarf planet Eris.

That both Voyager and the two Pioneer spacecrafts (Pioneer 10 and 11) are travelling at the edge of our solar system is probably one of the major achievements of humanity. The other one - and often neglected - is the fact that the Voyager missions were already conceived in the 1960s, when it became clear that there would be a unique chance to put a spacecraft on a "Grand Tour" through the outer solar system, utilising the fact that Jupiter, Saturn, Uranus and Neptune would align in such a way that a spacecraft could fly from one to the next by making use of gravity assists. Work started in the early 1970s to be ready for launch of the two missions in 1977. Voyager 2 was the first to be launched. It ascended into space on 20 August 1977, while Voyager 1 followed two weeks later. Both spacecraft were sent out to fly past Jupiter and Saturn, however at that planet, their follow-on routes would differ. Voyager 1 was sent in a fly-by at Saturn that would bring it to Titan, Saturn's biggest moon with it dense methane atmosphere, while Voyager 2 would continue with its tour passing by Uranus and Neptune.

The intention to pass all gas giants of the solar system was already contained in the mission design of Voyager 2. To allow for this route, Voyager 2 was launched 2 weeks earlier than Voyager 1, sending it on a longer, more circular trajectory. In contrast, Voyager 1 was to only pass by Jupiter and Saturn, hence it took a swifter route on which it overtook its twin, passing Jupiter and Saturn somewhat earlier. Only when Voyager 1 had passed Titan successfully, did Voyager 2 get the go-ahead for the Grand Tour to Uranus and Neptune, and so Voyager 2 was the first - and so far only - spacecraft to visit all four gas giants in our solar system: Jupiter in 1979, Saturn in 1981, Uranus in 1986 and Neptune in 1989, where it took license of Voyager 1's example in taking a close swing by the planet that would send it close to its moon Triton. From here, Voyager continued to hurl into interstellar space, just as Voyager 1 did after its encounter with Titan.

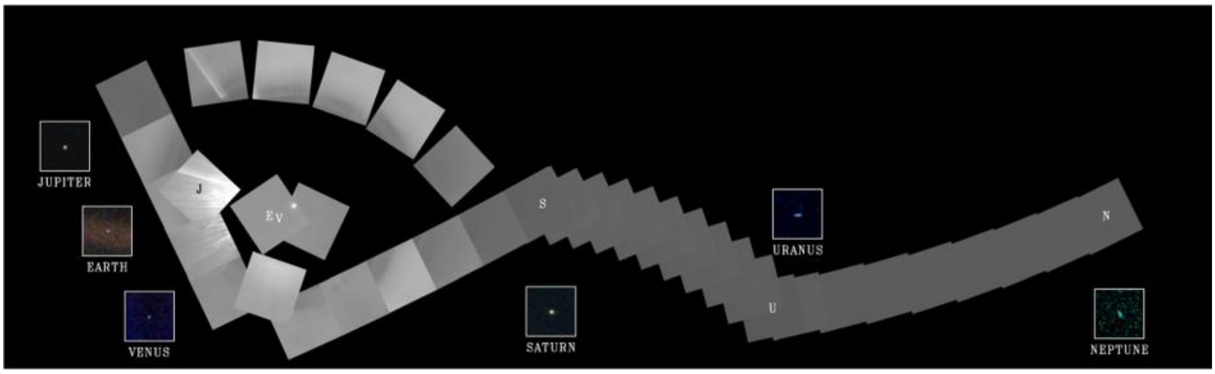


*Figure 4-6: The "Family Portrait" of the solar system, assembled by Voyager 1 on February 14, 1990 at a distance of 40.5 AU from Earth (Source: NASA)*

What have we learned from these four remarkable missions?

- Jupiter - features a few rings, the Great Red Spot is a complex storm twice as large as Earth.
- Jovian moons - Io features active volcanism, Europa is internally active due to tidal heating at a level about one-tenth that of Io. Europa is thought to have a thin crust (less than 30 km) of water ice, possibly floating on a 50-km-deep ocean, which might harbour life.
- Saturn - spokes in the rings, polar lights, new moons were discovered, first detailed observation of Titan

- Uranus - detailed observation of Uranus' rings, discovery of several moons, unique geology of Miranda
- Neptune - discovery of Great Dark Spot on Neptune, close observation of Triton, final explanation of the "Planet X mystery", by an exact measurement of Neptune's mass. When taking into account the more exact mass measurements of Uranus and Neptune, it was found that the imprecise mass assumption for Neptune - and not the gravity of an unseen planet ("Planet X") - had caused the orbital discrepancies that had long perplexed planetary astronomers.
- The two Voyager spacecraft are continuing to explore the outer areas of our solar system. Voyager 2 is expected to keep transmitting weak radio messages until the year 2025, over 48 years since it was launched. To do so, the spacecraft relies on a clever transmission and error-correction scheme - that same system is nowadays implemented in set-top boxes for satellite TV reception. Your satellite TV is therefore powered by true space technology - you might want to remember that the next time you switch it on...

#### 4.1.5 ... to Viking, MEX and MER

Before Mariner 4, Mars was thought to be a planet that could harbour life. Seasonal changes of its surface features, dust storms, ice caps and the famous "Mars channels" were seen as signs that Mars was a planet full of surprises.

The fly-by of Mariner 4 on 15 July 1965 proved that Mars is indeed full of surprises but in a different sense as it showed a cold, devastated world with Moon-like craters, bone dry - the channels were nothing else but optical illusions - there was no ancient civilisation that used a clever channel system to transport water from the poles to its settlements at the equator.

Although these results were disappointing, Mars did not move out of the focus of interest and so two lander missions were sent to Earth's red neighbour, the two Viking spacecraft, which followed in 1976. Both missions were extremely ambitious, as were the required resources, calling for a total expenditure of U.S. $ 1 billion. The Viking spacecraft consisted of both an orbiter and a lander and were deliberately equipped to perform soil sampling and search for life experiments. Out of the four experiments searching for life on Mars, three gave a clear negative and one a positive result. This positive result is strongly debated and is disputed by the life adverse conditions on the Martian surface. A major item that has to be considered in that respect, is that Mars has almost no ozone layer and so the Sun's UV light will be able to hit and sterilise the surface. In addition, the Phoenix Lander discovered in 2008 the chemical perchlorate in the Martian Soil. Perchlorate is a strong oxidant so it may have destroyed any organic matter on the surface. If it is widespread on Mars, carbon-based life would be difficult at the soil surface. The other fraction - those who believe in a life bearing Mars - bring in the observation that the dry areas of Antarctica do not have detectable organic compounds either, but they have organisms living in the rocks. Today, 35 years later, we still have no clear answer what the real cause for the positive life experiment of Viking was/is and so we are bound to hope for clear results from future missions to solve this issue.

A very positive aspect of space exploration is the fact that several players are active in this area - not only the U.S., but also Russia, Europe, Japan and today also India and China. Mars is alluring to all scientists and so quite often collaborations are formed to study the red planet mutually. One such collaborative effort was MARS-96, launched in 1996 by Russia and at that time the largest space probe built so far. It consisted of an orbiter, two landers and two penetrators (small probes which should have penetrated deeply into the surface of Mars on impact). Europe participated with a multisite of experiments onboard. Unfortunately, due to a failure of the Proton launcher the mission was lost right at the start. ESA didn't want to write off its experiments and so it decided to go for a second attempt, by putting most of its experiments on an own mission, the highly successful MARS Express mission (MEX) which was launched in 2003 and will be operational until 2014. The scientific payload of Mars Express comprises surface and subsurface instruments as well as atmospheric/ionospheric measurement devices. The High Resolution Stereo Camera is continuously delivering impressive three-dimensional colour images of the surface of our neighbour planet with a resolution of 10 metres.

Already in 1976 did Viking show that Mars, as dry as it is at the moment, must have seen very wet periods. Consequently, NASA and ESA embarked on a "Search for the (lost) water" strategy and MEX was no exception. An important goal of this mission has been to find out whether there was or still is water on Mars. In 2005 the OMEGA spectrometer of MEX provided evidence that large amounts of water must have existed on the surface. The sounding radar MARSIS detected water ice at various sites on Mars suggesting that a 1 kilometre thick ice layer exists near the North pole. When assessing the amount of water trapped in frozen layers over Mars' south polar region, MEX found that the amount of trapped water is equivalent to a liquid layer about 11 metres deep covering the whole planet[7].

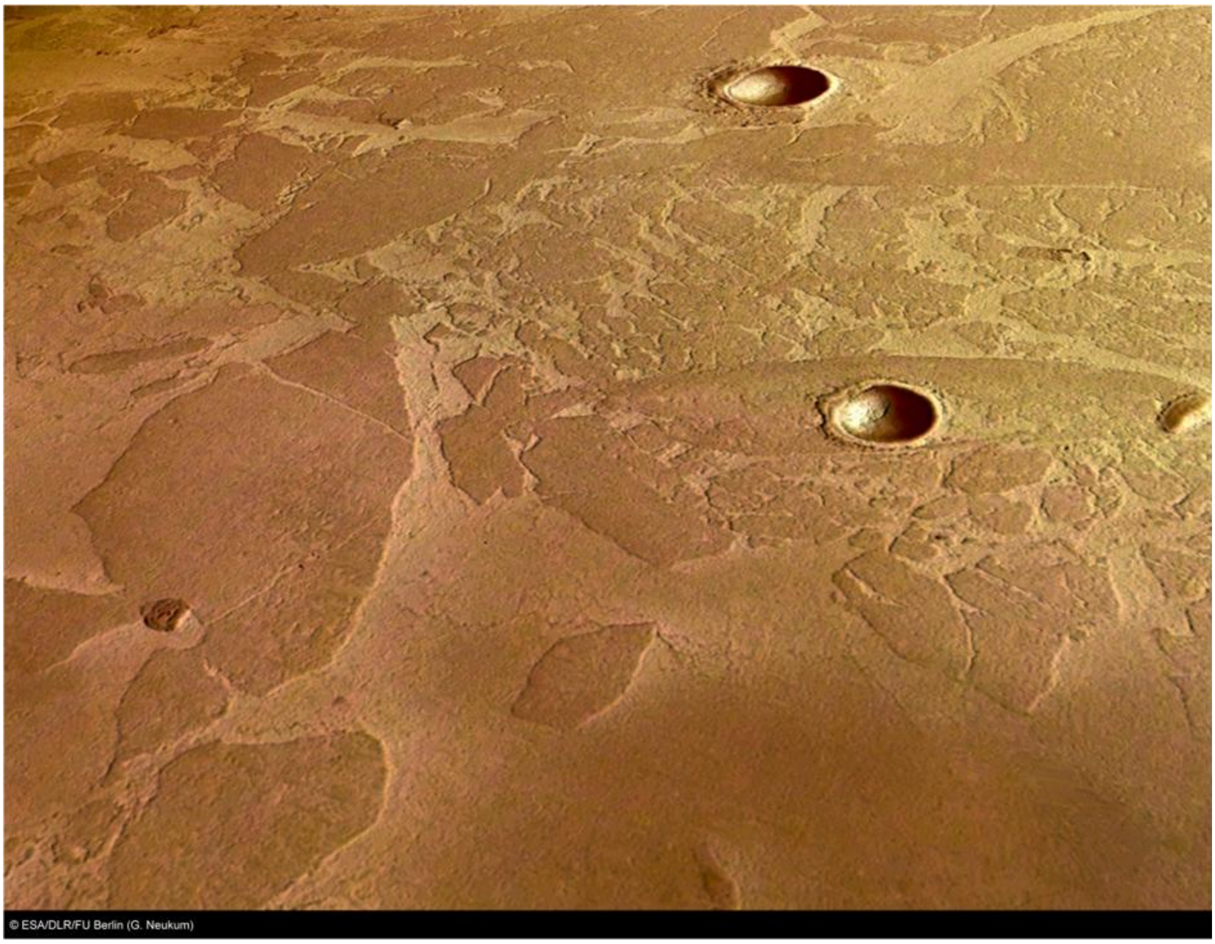


*Figure 4-7: A MEX photo of what is presumably a dust covered frozen sea near the Martian equator (Source: ESA)*

Similar to ESA, NASA's recent Mars exploration mission followed the "Search for the (lost) water" strategy. Building on the successes of Viking in 1976 and Pathfinder in 1997, NASA got an additional new boost with the launch of the Mars Exploration Rover mission (MER) in 2003. The

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[7] ESA News of 15/03/2007, http://www.esa.int/esaCP/SEMSWJQ08ZE_index_0.html, accessed May 2011

Mars rovers “Spirit” and “Opportunity” have the task to investigate the geological conditions and search for hints for the existence of water. Opportunity is still operational, whereas “Spirit” went into hibernation in late 2010. NASA is still trying to revive Spirit, but even if all attempts fail, both rovers have performed far beyond their design parameters. Originally built to last for 90 Martian days (so-called "sols"), Opportunity has continued to function for more than 25 times this planned life span. Both rovers hold the record for travelling the longest distances on Mars, with Spirit having achieved 10 km and Opportunity logging 28 km (on 19/04/2010, sol 2572).

Both rovers have analysed a wide range of rocks along their paths and found clues to a wet history of Mars. In addition, Spirit and Opportunity have also performed astronomical observations and obtained atmospheric data. One of the most remarkable photos sent back to Earth is the one of the sunrise on Mars, where Earth is visible as a morning star on Mars.


*Figure 4-8: A MER photo showing Earth in the rays of the rising Sun on Mars (Source: NASA)*

It was Konstantin Tsiolkovsky, a Russian scientist and one of the founding fathers of modern rocket science who stated, *"Earth is the cradle of humanity, but one cannot live in the cradle forever."* - undoubtedly a statement that cannot be truer than for Spirit's photo of planet Earth seen from Mars.

Space Exploration is the logic continuation of a process that started when Homo Sapiens decided to leave Africa several thousand years ago. Exploring and eventually reaching every corner of the world, humanity is now confronted with a planet that leaves no major [white] spots to explore further. In a sad essay this would be the end, here however it is the beginning - the beginning of humanity's efforts to explore space by robotic and human missions, in trying to obtain a better understanding of our planet, the solar system and the universe as a whole.

## 4.2 “Satellite Telecommunication” ([B] Frischauf, 2011)

Published in Frischauf, N.: Satellite Telecommunication, in C. Brünner, & A. Soucek, *Outer Space in Society, Politics and Law* (2011), pp. 134-136 [B]

Friday, the 3rd of July 2009, saw Wiki news stating the following[8]: "ESA launches the largest commercial telecom satellite" and further "The TerreStar-1, an American communications satellite operated by TerreStar Corporation was launched Wednesday by an Ariane 5ECA rocket at 17:52 GMT by the European Space Agency (ESA) from the ELA-3 at the Guiana Space Centre. The 6,910-kilogram (15,200 lb) TerreStar-1 satellite cost US$300 million. It was launched from Kourou, French Guiana, a department of France in South America. This satellite weighs in as the heaviest and the largest telecommunications satellite ever launched."

While this is a rather technical text, there is jus two information that really count in here anyway: The enormous cost of US$300 million and the circumstance that this is a commercial telecom satellite.

### 4.2.1 Satellite Telecommunications: Costly, risky...

300 million Dollars for a telecom satellite - that is a whole lot of money, at least for someone who does not follow the occupational career as Chief Financial Officer (CFO) of a multi-national enterprise or the one of finance minister. Especially the latter would probably laugh at such "minuscule" amounts, being confronted with multi-billion budget deficits and financial crisis left-overs. But even a finance minister would moan, if he was requested to transport this amount of money in the form of banknotes to a potential recipient. If we assume that he would want to pay the satellite prime contractor with an all-at-once payment in the form of 200 Swiss Franc bills (the Swiss Franc nearly matches the US Dollar at the moment), then he might want to split the amount into some handier format, such as 300 times one million Swiss Francs. The best way to transport this million is via a suitcase of 2 kg. The 5000 200 Swiss Franc banknotes will be around 6 kg of mass, so at the end every SFR1 million suitcase will weigh EIGHT kilograms - and you need 300 of those[9]!

Luckily we have electronic banking systems - also because of GPS & Co.[10] - otherwise projects like these might as well falter in their very early stages altogether. Joking aside, besides the financial logistics, I have always been - and still am - flabbergasted that it is possible to raise this money for a space commercial project of this magnitude. Please bear in mind: The fact that someone invests US$300 million in a nearly 7 ton massive spacecraft, means that this someone believes that there is value for money in this business and that he/she is courageous enough to accept a non-negligible level of risk that the business might falter right at its start - literally speaking, as the launch of a satellite is still the riskiest endeavour in the project's life[11].

[8] http://en.wikinews.org/wiki/ESA_launches_largest_commercial_telecom_satellite, accessed October 2010

[9] And to carry these 300 suitcases, one will need at least a truck, with 3-5 tons. So at the end we will have to move 6-8 tons of "financial" mass to launch a spacecraft of 7 tons!

[10] As discussed in the sub chapter on "Satellite Navigation"

[11] Dependent on the launch vehicle one might have to assume a risk of 1% for the total loss of mission at launch

Nonetheless insurances for most risks exist - and this is also true for the space sector. In the case of a telecommunications satellite, to be launched and operated for 15 years in the geostationary orbit, the insurance premiums against failure of the launch vehicle and the satellite in the first year of its operation will be around 7-10% of the insured sum[12]. So for a 300 million Dollar satellite, we might assume US$30 million as insurance premium.

Albeit these are costly premiums, there is an insurance market out there. According to an article in SPACE.COM, insurance underwriters booked between US$800 million and US$825 million in premiums and paid out slightly more than US$400 million in claims for full or partial satellite losses in 2009. So far in 2010, premiums have totalled around US$400 million, with no claims paid.

This seems like a rather large market and yes it is. In 2007, the top 10 fixed satellite operators ran 164 satellites, had 31 new ones ordered and achieved revenues of approximately US$7.7 billion. SES, the market leader out of Luxembourg, which operates the ASTRA satellites, achieved revenues of nearly US$2.4 billion in 2007. To come back on the Ample example before; SES achieved revenues of nearly 50% of the worldwide market for cosmetic medical products. If I were an investor, I would bet my stakes in the satellite sector, although I admit that the latter one is certainly more attractive.

### 4.2.2 ... but highly profitable and resilient as well

| Rank | Satellite Operator | Revenues [million $] | | Country | Satellites in Orbit | Satellites on Order |
|---|---|---|---|---|---|---|
| | | 2007 | 2006 | | | |
| 1 | SES | 2370.0 | 1900.0 | Luxembourg | 37 | 9 |
| 2 | Intelsat | 2200.0 | 2100.0 | Bermuda, US | 54 | 4 |
| 3 | Eutelsat | 1240.0 | 1050.0 | France | 24 | 6 |
| 4 | Telesat Canada | 684.7 | 575.0 | Canada | 12 | 3 |
| 5 | JSAT Corp. | 347.4 | 326.0 | Japan | 8 | 3 |
| 6 | Star One SA | 207.4 | 195.8 | Brazil | 7 | 0 |
| 7 | Hispasat | 188.6 | 159.1 | Spain | 3 | 1 |
| 8 | SingTel Optus | 172.2 | 158.4 | Australia | 4 | 1 |
| 9 | Russian Satellite Communications Co. | 161.0 | 152.0 | Russia | 11 | 3 |
| 10 | Space Communications Corp. | 151.4 | 151.2 | Japan | 4 | 1 |

*Table 4-1: The top 10 fixed satellite operators in 2007 (Source: Space.com)*

Space is a lucrative place, as depicted in the table above. None of the top 10 fixed satellite providers saw a decrease in its revenue stream between 2006 and 2007. Interestingly enough there was also no major impact of the biggest financial crisis that had hit the world for many decades - and this was not a given, bearing in mind that the aerospace industry had developed strong ties with the automotive, commercial, and high-tech industry during recent years. So, how could that be? What makes the satellite telecom sector so special?

Originally the worldwide financial crisis started off as a crisis of the US real estate market. However, it crossed the US borders quickly and spread, due to the global nature of the banking sector. At the beginning of 2009, the financial crisis had become a global phenomenon sending economic shock waves throughout automotive, tourism and other industries, some of which are currently strongly cross-connected to the aerospace sector. Although it may sound counterintuitive at the beginning, a recent study of the European Space Agency ESA[13] showed that the aerospace

[12] http://www.spacenews.com/satellite_telecom/100903-satellite-insurers-profitable.html, accessed October 2010

[13] "Survey of the Chinese and Indian Telecom Space Industry and Market", http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=29500, accessed October 2010

sector appeared to be resilient in the financial and economic crisis. Of course within certain limits, as the increased technology transfer between the aerospace and terrestrial sectors would eventually become a pathway for impacting the aerospace market in the medium and/or long term. However for short term effects, two specialities of the satellite telecom sector could be identified that proved to repel any immediate effects: The long-term time scales of aerospace projects and the transformation of SatCom services into a utility, like electrical power, gas or water.

The long-term nature of aerospace projects, on the one hand, is well documented - just think on the International Space Station, which was first conceived in the 70s and is to be finished within these weeks. The number one driver for this long time scales of aerospace projects is complexity. Try to imagine the sheer number of subsystems in an Airbus A340 or an Ariane 5 that need to work together in a perfect manner to ensure safety and mission success. Safety is probably not the prime requirement for a telecom satellite, but still, the investors want the satellite to work flawlessly for 15 years without maintenance - imagine this for your car! Consequently, satellite manufacturers think in long term scales. Although the construction of a large telecom satellite resembles one of the fastest projects in the aerospace world, it still takes typically three years, which means that short term events have only limited consequences.

On the other hand, there is the rapid transformation of space telecommunication services into a utility in the recent years. As such, telecom satellites provide for TV, telephone and fax services as well as Internet access to areas, which are too remote to be connected via land lines. I assume I am not the only one who checks his emails every day, reads news articles in online newspapers, uses online dictionaries and conducts researches in online libraries like Wikipedia. Most of us use the Internet in one way or the other and for all of us, the underlying transport medium is unknown. Your internet service provider might use a glass fibre backbone, coax lines, and/or a satellite link to send the data stream to the server and back again. Mobile phone operators do the same and let satellite communications come deliberately into play when a base station is too remote to be connected via a landline - just think of a mobile phone tower somewhere adjacent to a highway in the middle of nowhere that allows you to talk with your loved ones while you drive through the wilderness. The point is that telecom satellites have a role in all these utilities and just like electrical power, these communication services are so essential by now that one will not cut them off entirely in case of economic/financial troubles. You will likely save on your meals and cinema visits, but not on your telephone calls and internet accesses. So the commercial success of satellite telecommunications is not a one day event, but bound to continue in the years to come.

### 4.2.3 SatCom is a story of Mergers and Acquisitions and huge global Players

When looking at the table of the top-10 fixed satellite operators above there are two things that strike the eyes immediately - besides the impressive monetary figures. Obviously there are a few leaders of the pack - such as SES, Intelsat, chased by Eutelsat and Telesat Canada - who themselves are followed by a large group of smaller player, while there are no Chinese and Indian players in the list - although these two countries are the two largest ones in terms of citizens and potential customers for satellite telecommunication services. Is there a specific reason for this?

The answer reflects a mixture of effects. Just like the global satellite communication market, SatCom growth is expected to continue in all of Asia at 6–8% per annum, mainly fuelled by more and more TV programmes. Therefore – much like its global counterpart – the Asian SatCom market was found to be resilient in the financial crisis. It is, however, distinctive from its western counterparts in specific points, mostly related to the fact that regional Asian markets are not yet liberalized. Because of this protected nature, the Asian SatCom market is the least penetrated by the “Big 4” Satellite operators, SES, Intelsat, Eutelsat, and Telesat.

A strong growing market with a certain amount of protection is attractive and thus, for the moment, Asia features the highest number of satellite operators. This is not expected to change for some time, as the financial crisis has slowed the wave of operators' mergers and acquisitions activity and industry consolidation. However, looking back at the history of the satellite telecom sector, mergers and acquisitions have been a dominant rule of the game throughout the sector's history. Therefore one can expect that as the credit market becomes more stable, transactions beyond share-swap will become feasible again and consequently, in the long run, provider consolidation will hit Asia, especially when markets become liberalised. In the end, fixed satellite services still thrive on economy of scale; therefore the "Big 4" are expected to maintain or expand their market share and remain the drivers for consolidation – also, and especially, in Asia.

### 4.2.4 "2001: The Year We Make Communication"

I admit that this subtitle is a slight word game on two of the best - at least in my mind - science fiction movies; "2001: A Space Odyssey" and "2010: The Year We Make Contact". But since both movies are based on the novels of Arthur C. Clarke, who has been very instrumental in bringing forward modern satellite telecommunication and based on the observation that 2001 was the first year that the commercial space sector outran the institutional one in terms of expenditure (thanks to the commercial success of the telecom satellite sector), I deem this word game as highly appropriate.

In fact the idea of using a satellite for communication was not coined by Arthur C. Clarke but builds upon the idea of another gentleman named Herman Potočnik, often using the pseudonym Herman Noordung, an Austro-Hungarian rocket engineer. Already in 1928, he was the first to calculate the geostationary orbit, the 36000 km high trajectory over the Earth's equator in which a satellite will need 24 hours to circle the Earth underneath its position. As the Earth will need exactly the same time to revolve around itself, an object placed in the geostationary orbit will therefore remain in a fixed position in the sky, as seen from the Earth. So while the stars rise and fall during the course of a night, a satellite in the geostationary orbit remains steady, resembling therefore a perfect target to aim at with a fixed satellite dish. In a next step, Herman Potočnik discussed the communication between the satellite and the ground using radio, but eventually fell short of the idea of using satellites for mass broadcasting and as telecommunications relays. This idea was later on developed by Arthur C. Clarke in his "Wireless World" article of 1945. What Herman Potočnik did describe in great detail however, was the concept of a wheel-shaped space station, placed in the geostationary orbit, and the special conditions of space, which would be useful for scientific experiments. Interestingly enough, Herman Potočnik visions and the ones of Arthur C. Clarke were bound to cross once more, but this time in an indirect manner via Wernher von Braun. In 1952, the wheel-shaped space station, originally conceived by Herman Potočnik, served as an inspiration for further development by Wernher von Braun, who saw orbiting space stations as a stepping stone for the travel to other planets. And when Stanley Kubrick's directed the ground-breaking film "2001: A Space Odyssey" in 1968, which is based on the novel of Arthur C. Clarke, he finally implemented this advocated wheel-shaped space station into the movie as "Space Station V". Herman Potočnik, who had died already in 1926 at the age of 36, would have certainly been delighted to see how his concepts were further developed and visualised.

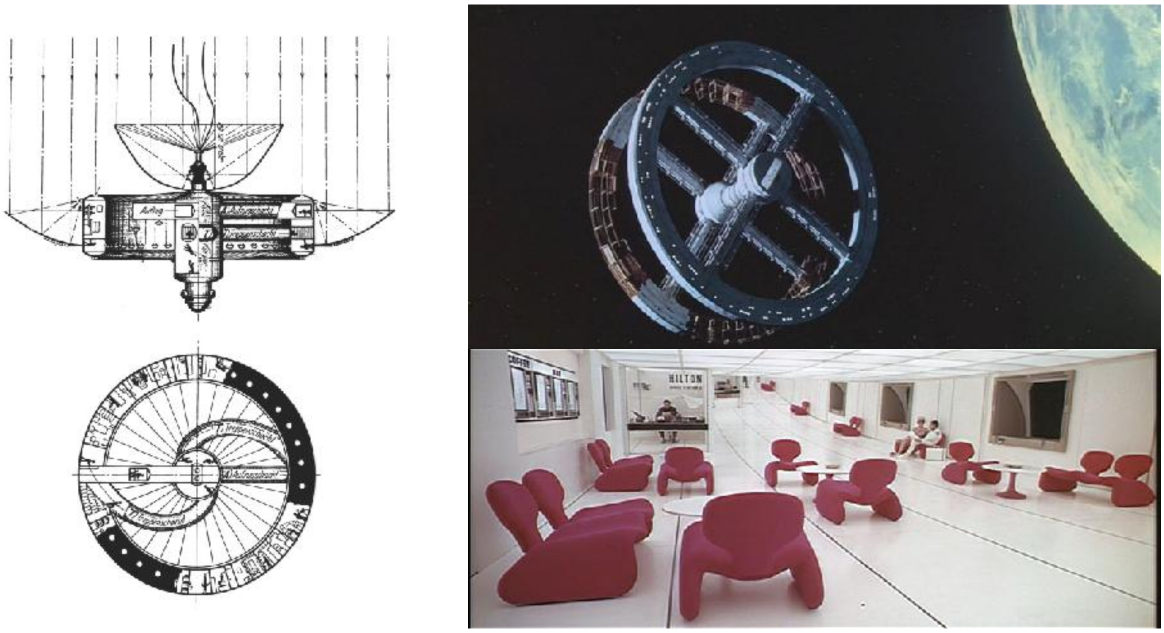

*Figure 4-9: Herman Potočnik's wheel-shaped space station published in 1929 and the derivative of it in the movie 2001: A Space Odyssey (outside and inside view)*

Back to the year 2001, not the movie. This year marks the breakthrough of the space commercial market, as it is the first time that the commercial sector outran the institutional one in terms of expenditure. As such the world space market, including commercial revenue generated by space applications (telecommunication, navigation, Earth observation), was estimated to have reached €167 billion. While the 2001 budgets for institutional space programs worldwide totaled €42 billion (civil activities: €26 billion; defense activities: €16 billion), the world commercial market (satellites, launch services, and operations) was estimated at €49 billion[14] - a clear surplus of €7 billion.

#### 4.2.5 Satellite Telecommunications: The Reasons for Success...

ASTRA, GPS and Galileo, as well as GMES, these four names are synonyms for the three space application areas – telecom, navigation, and Earth observation. Of these three, the telecom sector is by far the most developed, demonstrated by the fact that private investors are willing to raise US$300 million for a telecom satellite. This is in stark contrast to the other application areas, where projects with this magnitude will clearly demand public financing - at least for the time being.

Telecom has reached its leading position especially because of the continuing worldwide growth of satellite TV platforms - and this growth is forecasted to continue in the years to come with double-digit growth rates; a truly remarkable success. There is a saying that, "Success has many parents but failure is always an orphan"; applying this to SatCom means that there must be many members in the family tree and naturally such a large family tree can always provide for a certain amount of surprises.

Satellites are hi-tech devices - no doubt about that. Technology is an integral part of any telecommunication system and for a satellite; rocket science comes into play as well, which is sometimes complicated and difficult to understand. Just think on some of the communication

[14] As stated in the Green Paper on European Space Policy COM/2003/0017 final, http://eur-lex.europa.eu/smartapi/cgi/sga_doc?smartapi!celexplus!prod!DocNumber&lg=en&type_doc=COMfinal&an_doc=2003&nu_doc=17, accessed October 2010

means that are nowadays used (e.g. spread spectrum signals), as well as the particular orbital dynamics and the complexity of the involved space hardware (rockets and satellites). However, technologies are not the prime reason for success. I would rather rank the small acronym "KISS", which stands for "Keep It Simple and Stupid", as the prime guarantor for the success of the telecom satellite industry[15]. In the following, we will have a closer look at two KISS principles, which have proven themselves as very important success factors: The geostationary position of the satellite and the bent pipe approach.

We have already seen before, that placing a satellite in the geostationary orbit allows for the ground antenna to always point in a fix position in the sky. This might not sound too dramatic at the first glance, but from a commercial point of view it allows the antenna – in case of a Very Small Aperture Terminal (VSAT) - to be rather simple - and cheap. Nowadays you can by a VSAT or satellite dish for €100, which is low enough to allow for a mass market. Imagine what the cost might be if the telecom satellite was not in the geostationary orbit but whizzes over your spot in a mere period of 7 minutes. Then you would need a VSAT with motors to track the satellite AND a computer to control the motors AND a software algorithm to pre-calculate the orbit AND a database, which contains the data. In short you would have to perform a complicate procedure, just as it was done in October 1957, when everybody tried to get a sight on Sputnik 1. I suppose you can imagine that such a system will not be very cheap and therefore detrimental to a mass market application.

Beside of its fixed position in the sky, the geostationary orbit offers also another advantage to satellites and that is a splendid view on planet Earth. At an altitude of 36000 km the Earth is only but 17°[16] in diameter and so one can easily see a huge proportion of its surface, as depicted in the image below.

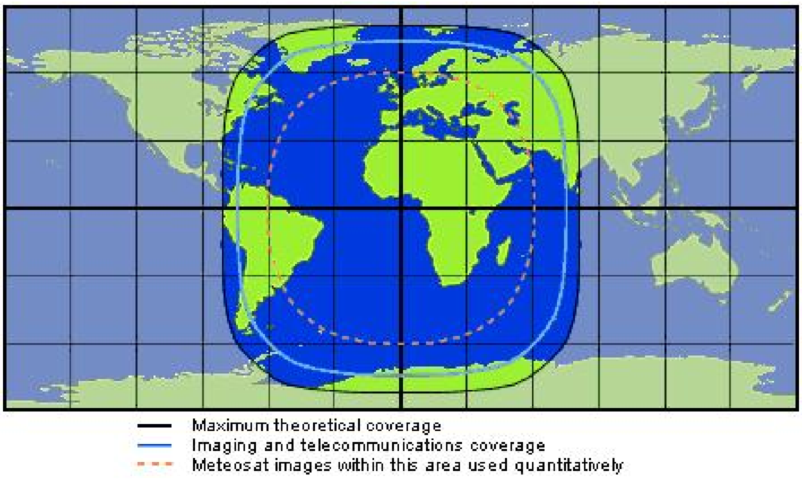


*Figure 4-10: Coverage area of the Earth's surface from the geostationary orbit. Not only telecom satellites use the geostationary orbit, meteorological satellites like Meteosat do so as well (Source: Eumetsat)*

Taking into account that each meridian and parallel is separated by 30° from its neighbour, one can calculate that the field of view of a satellite in the geostationary orbit covers 120-150°. Is there any better location for a radio mast you can think of? In principle, three satellites would be sufficient to cover the whole Earth, and this is exactly what Arthur C. Clarke described in his

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[15] and would also propose to give it the title of "the loveliest acronym in the space world"
[16] This is approximately the length of the big dipper's arched handle

"Wireless World" article of 1945, building upon the works of Herman Potočnik, published back in 1929.

What have we established by now? A very simple and hence mass market friendly satellite terminal on the ground and a satellite network transmitting signals on global scale made up of only three satellites. Still there is one ingredient missing - the satellite technology itself, whose peculiarity is best described by the buzz word "bent pipe". Now, what's that about?

If you want to use a satellite to transmit telecom signals, you will have to make sure that the signals being sent up to the satellite (uplink) will not interfere with the signals that the satellite will broadcast back to the Earth (downlink). The easiest way to do this is by changing the frequency of the signal. This is done onboard of the satellite by specific micro-wave systems, called transponders. Their role is to receive the uplink signal, to amplify and change its frequency and finally downlink it back to the Earth.

As stated before, the bent pipe is the preferred approach - for a simple reason: A telecom satellite is a costly system and so one wants to operate it as long as possible. Nowadays telecom satellites last for 15 years in geostationary orbit and of course in this time numerous communication algorithms are developed and introduced to supersede its precursors. Don't forget: Computer technologies follow Moore's law, which leads to a doubling of computer power every two years! If our telecom satellite was to regenerate the signals, it would be confronted with the advancement of 5 complete computer generations. Therefore it makes sense to apply the bent pipe approach, which is absolutely agnostic to transmission formats (modulation/coding/access schemes).

### 4.2.6 ... and the Way ahead

Another thing that the bent pipe does is to allow for economies of scale, already mentioned before. Applied to a telecom satellite this means nothing else but that the costs per service become less the more services one offers. The services of a telecom satellite are provided by its transponders, as these are the devices, which broadcast TV channels, transmit data streams and so on. The more transponders a satellite has, the more revenues this satellite will make. Of course more transponders mean also more power, provided by solar arrays, more mass, to be launched into orbit, more fuel to be spent when the satellite is sent to its final orbit. But all over all, it pays off to have a bigger satellite with more transponders, as economies of scale are at work. In short one could say that a satellite with twice the transponders, achieving twice the revenues, will not be twice as big, hence the costs are not doubled and therefore the profit is bigger. If we want to compare it with a terrestrial example then we can think on a car and a bus, which will transport persons from a to b. While both have an engine - and the bus has a usually a bigger one, which costs a bit more - both use only ONE motor to transport 4-5 or 30 persons respectively. Other subsystems scale similarly (think of the transmission, the lights, the electric system, etc.), which ultimately makes it cheaper for the passenger to take the bus instead of the taxi. While it may sound odd at first, the mass transportation market model holds also true for the satellite telecom sector, with the exception that the payload differs; it is transponders and not passengers.

Another similarity between transportation and SatCom is the fill factor. If you were a bus driver, you would always aim to fill your bus to the maximum to use economies of scale, cutting down on your cost and maximising your profits (by the way certain airlines do the same, especially the low cost airlines thrive on this model). Consequently you will not use your biggest bus (or plane or ship) to serve a route where there are just 5 passengers - and satellite telecommunication managers think the same way. They will therefore place the biggest satellites with the largest transponder number only in a position in the geostationary orbit - also called "orbital slot" - where there is enough demand. And where is this the case? Over well developed regions, where people use phone, fax, TV and internet services on a daily basis - such as in the USA, Japan and Europe. The following graphic provides an overview of the orbital slots where most of the telecom satellites are stationed.

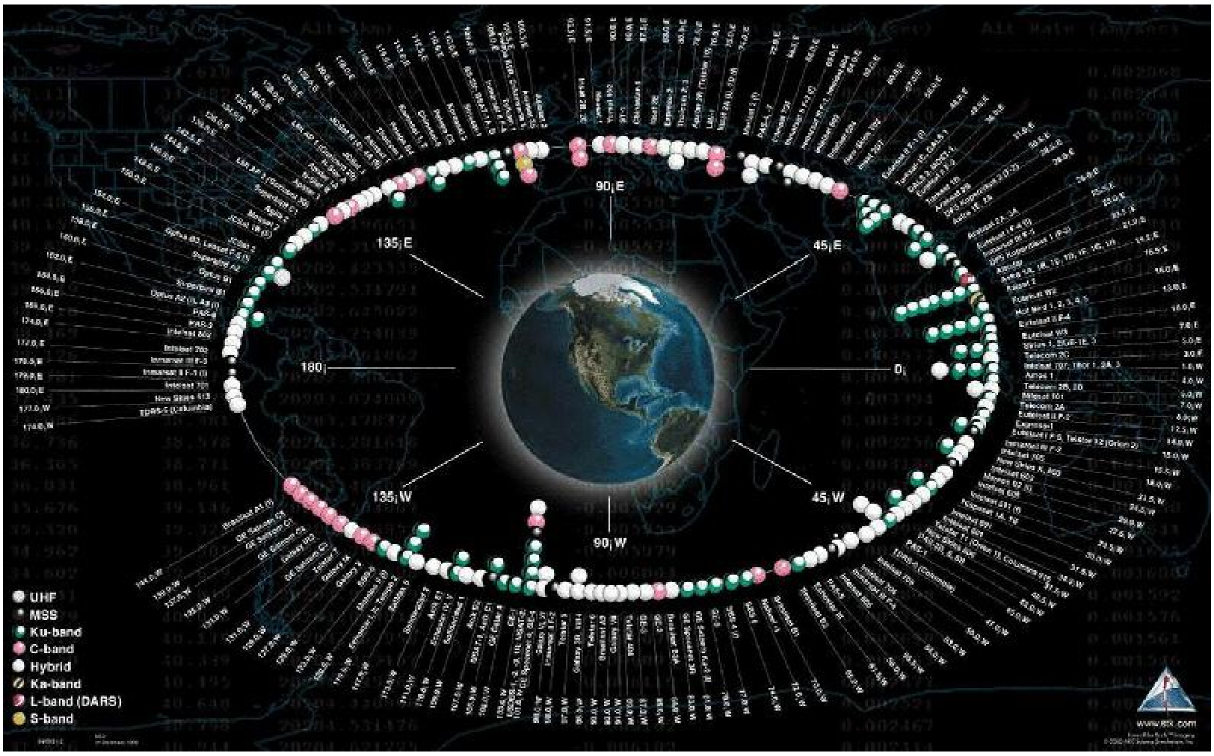


*Figure 4-11: Telecommunications satellites in the geostationary orbit (Source: CNES)*

As can be easily seen, there are certain orbital slots, where several telecom satellites agglomerate - the so-called "hot spots". If you are looking for the one where the ASTRA satellites broadcast your daily TV programme - you will find it at 19.2°E.

What one can also see from the image above, is that the geostationary orbit (some call it also belt, although it resembles more a ring, like a very small version of the one of Saturn), is the prime location in space. I know that this sounds a bit like an advertisement for a real estate market in space, but, "Stop!" It might be tempting to start considering making a career as an estate agent, but I am afraid that I will have to disappoint you: there is no such real estate business and there won't be any - international treaties clearly prohibit this. Neither you, nor a country, can own property in space - full stop!

Still, that does not mean that everyone can send his spacecraft into a position he deems beneficial, not carrying about the intentions of the others. Someone needs to take care that all these satellites can be placed in a position where there is no risk of collision with another satellite and that the transmitted signals will not interfere with the ones of a neighbouring satellite - and yes, someone does. The entity that coordinates this effort is well known to all of us. It is the United Nations, or, being more precise, the International Telecommunication Union (ITU), an agency of the UN. If you want to launch a satellite into space, the ITU is the orchestrating agency to make sure that you can receive and send its signals back to Earth without interference.

As stated before, the continuing worldwide growth of satellite TV platforms - and this growth is forecasted to continue in the years to come with double-digit growth rates - will remain fuelling the satellite telecommunications sector. Other applications, such as direct video streaming to your mobile phone, directly broadcasted from the satellite above, as well as integrated applications combining both the telecom, the navigation and the Earth observation sector and several others are right at that moment coming over the horizon as well. So the ITU is likely to be kept busy in the years to come, thereby acknowledging that telecommunication satellites have become an indispensible part of our society, providing and extending communication services to areas, which else would be out of reach. Based on the mentioned observations, there is a clear need to launch 20-25 geostationary telecom satellites per year and the fact that launcher prices are extremely volatile - as depicted in the figure below - tells us that the world needs a few more launch vehicles to serve this market.

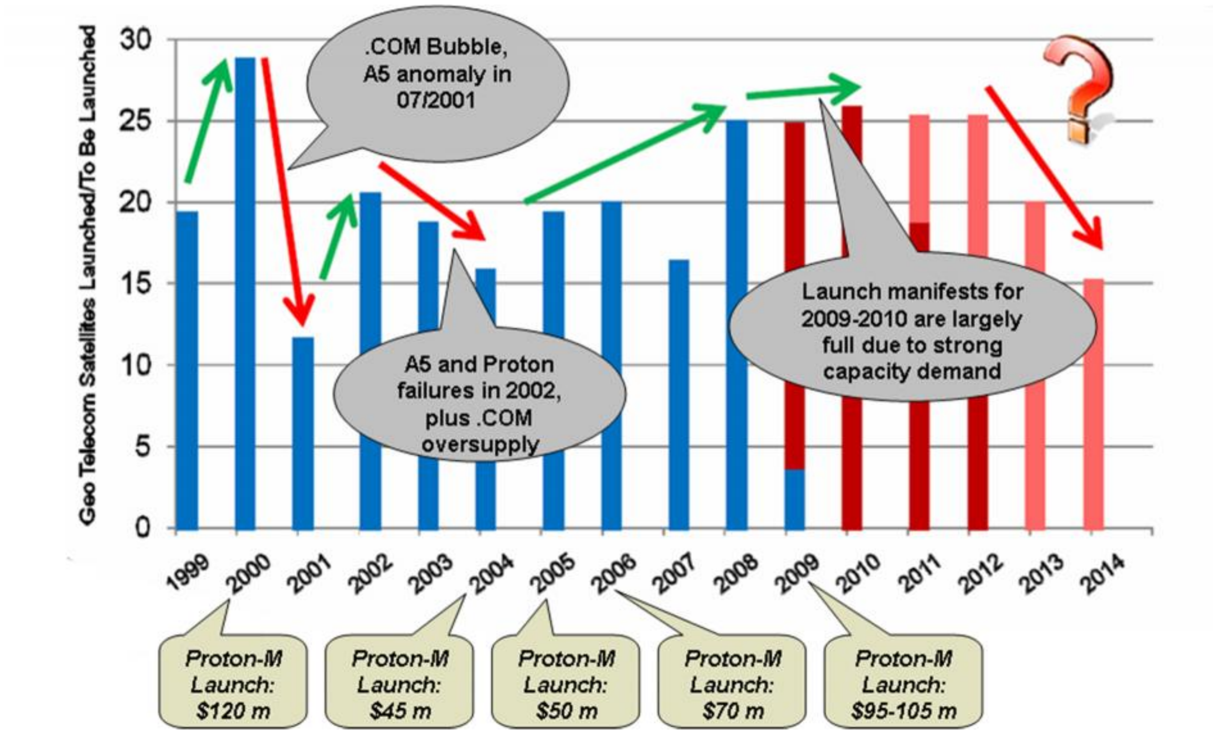


*Figure 4-12: Number of launches of geostationary telecom satellites and associated launch costs (Source: ESA Survey of the Chinese and Indian Telecom Space Industry and Market)*

The figure above presents the price that a SatCom operator will face when launching his geostationary telecom satellite with the Russian Proton-M rocket[17]. Over the years, prices have ranged from $45 million to $120 million for a launch of the geostationary telecom satellite. These large variations are caused by changes on the demand side (e.g. .COM bubble) and on the supply side (e.g. launcher failures). Although new rockets - as being developed currently in China, India, the USA and Europe - will not change the situation on the demand side, we are likely to see an improvement on the supply side, potentially even reducing the prize of sending 1 kg into orbit to values below the current “standard value” of €10,000 -€20,000.

For the time being, launcher costs are still a big entrance hurdle for any space enterprise. So far only telecom can provide for sufficient business that an investor is willing to pay millions of Dollar/Euro for a launch, even accepting the rather high risk associated with it. Insurances do help in mitigating the risks, but what is really needed are lower launch prices to kick-start additional markets. As soon as the threshold can be lowered to €1000/kg or even lower values, business cases for space power platforms, pharmaceutical manufacturing and resource mining might become

[17] The Russian rocket was taken as reference, as its performance remained rather constant throughout the studied period.

feasible. Most of this may sound like science fiction, but don't forget, telecom satellites were once also science fiction, especially in the years 1929 and 1945 when major foreground work was conceived and published.

Now, more than 65 years later, communication is a driving factor of the modern world and telecom satellites are an integral part of it, providing new services to a world that resembles more and more a global village. Technological advances have helped to exceed the expectations of those early pioneers and have enabled satellite telecommunication to establish itself as the only true commercial space market. Building upon the KISS principle and thriving on economies of scale, SatCom has introduced mass market methodologies into the space sector, thereby transforming itself into a utility, which readily provides an open access to information services to everyone, everywhere on the world.

2001 was the year we made communication, in 2007 the world's leading fixed satellite operator achieved revenues of US$2.4 billion and 2009 saw the launch of a telecom satellite, worth US$300 million, lifting off with an Ariane 5 of ESA. This satellite has a mass of nearly 7 tons and is the largest and heaviest telecom satellite ever launched - and more heavyweights are likely to follow in the years to come...

## 4.3 “Satellite Navigation” ([C] Frischauf, 2011)

Published in Frischauf, N.: Satellite Navigation, in C. Brünner, & A. Soucek, *Outer Space in Society, Politics and Law* (2011), pp. 124-133 [C]

Satellite Navigation might not provide for glossy pictures as Earth Observation does, nor can it (yet) allow for commercial profits as we see nowadays with satellite telecommunications, but it surely has one thing that the two other applications do not have: a name! GPS, Galileo, GLONASS, Compass - all these names represent Global Navigation Satellite Systems (GNSS) and I cannot imagine anyone’s brain in the western world that will not immediately trigger an association, which circles around the ominous words, “You have reached your destination. The destination is on the left/right side.” - while one is stranded in the middle of nowhere and the anticipated destination is (obviously) miles away. This however is another story and is more connection to Earth observation data, global information systems, address data and the fusion of all these different data sources into a clever search algorithm.

### 4.3.1 GPS, GLONASS and Galileo: “Stealthy” Global Navigation Satellite Systems

Despite the occasional setbacks, when one navigates with a car in a rural area, GNSS has become a commodity that one would not want to miss, once you have started using it. Bearing in mind that GPS serves today more than 800 million users (!), the chances are quite good that you – the reader of this article – uses a GPS based navigation device as well, enjoying the benefits of this technology[18]. And even if you do not call a personal navigation device your own, I can assure that you are bound to use GPS in your daily life. This is because as GPS & Co. are all “stealth utilities”, enabling many more services than most of us are aware of. Beside of its obvious uses for positioning and navigation, GPS, GLONASS and in the future Galileo, provide also precise timing signals. These timing signals have become key enablers of our society as they facilitate electronic banking, the handing over of data streams in telecommunication networks and the switching of power systems – without this time dimension, the world that we know would cease to exist. From

[18] Prof. Bradford Parkinson, Highlight Lecture: Origins, Surprises and Future of GPS, IAC 2010, 28/09/2010

that perspective, GPS et al have become real infrastructure assets and therefore indispensable for all of us.

*Figure 4-13: A GPS satellite of the second generation (Source: US Air Force)*

From today's perspective one might think that the worldwide usage of the navigation and timing function of GPS - as fantastic as it is - is nothing else but a logical consequence of the original design. But the truth is that neither the civilian navigation application nor the "stealth" services were envisaged at the time when GPS was invented in 1973. Conceived as a pure military navigation system, GPS was designed to allow for readily available navigation at all places and at all times; everything else emerged underneath the radar - to stay within the military jargon. However, it seems that life underneath the radar can provide for some interesting stimulus, as 37 years later, the world depends on the navigation signals that are broadcasted by a system of satellites and one wonders, what ingredients were required to start up this unforeseeable success story.

### 4.3.2 Satellite Navigation: Sailing on rough Seas for 2000 Years

Although the strategic value of precise navigational data on every possible place on Earth was clear from the very beginnings of human society and already acknowledged by the Roman Plutarch (46?–120 AD), who delivered us the classical Roman proverb: *"Navigare necesse est, vivere non est necesse!"*[19] it took humanity 2000 years to come up with a real global navigation system – simply because it requires a sophisticated space element.

The start of the first satellite based navigation system was directly influenced by Sputnik 1, the first satellite. Its famous beep, beep transmission, was not only a political signal to the West, but it provided for a great stimulus of some clever brains, to forecast the future orbit of the satellite by measuring the Doppler shift of this transmitted signal. Although this sounds like pure rocket science, it is nothing else but a fairly simple extension of a daily observation that we all make when we move along a street with passing cars. When one listens carefully to the sound of the engine, one realises that the frequency changes; when the car comes towards you, the sound is higher pitched, contrary it is lower pitched, when the car moves away again. The physics behind this phenomenon was already discovered in 1842 by Christian Doppler, an Austrian mathematician and physicist. Given the unpopularity of these two subjects among today's pupils and students, I assume that he would be delighted to see children intonating the sound of a formula 1 car, when it whizzes by.

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[19] "Sailing is necessary, while survival is not!" According to Plutarch, Pompeius exclaimed these words when boarding a sailing ship, whose crew was reluctant to leave the harour because of a strong gale lingering outside on the open sea.

Now obviously a sound shift will not work in space, but the Doppler effect holds true for any kind of waves and therefore for electromagnetic waves like radio waves as well. By measuring the Doppler shift of Sputnik's beacon, the velocity of the spacecraft along its flight path could be measured. In combination with orbital dynamics, it was then possible to forecast the position of the satellite at the next pass so that spectators would know where to find the little moving light in a starry sky, in these days of October 1957. Now turn the whole system upside down and you have established the foundation of GNSS - assuming that the satellite's position is known and predictable, the measurement of the Doppler shift of an electromagnetic wave transmitted by the space craft, can be used to locate a receiver on Earth.

The first ones to use such a kind of system - which was conveniently called TRANSIT - were the USA and in particular the naval forces. Using the very same system as described above, US submarines were able to acquire a lock of their position with an accuracy between 15 and 500 m. This was sufficient to fix the position accurately enough to allow for a launch of a Submarine-Launched Ballistic Missile (SLBM). On the downside the limited number of satellites (at maximum 10) and their low altitude of 1100 km, restrained the availability of the satellite signals, hence allowing for a fix only every few hours. In addition the time to fix was in no way comparable with today's GPS, but required 10-16 minutes for the locking procedure by then. Nonetheless TRANSIT/NavSat proved to be useful - even the Soviets used NavSat receivers on some of their warships (!) - so the interest of the Navy in designing a better design was naturally not the most profound one (to say it in politically correct terms). It seemed that 2000 years after the risky endeavours of the Roman navy, a navigation system was finally in place, but now it was the US counterpart that slowed down the further development to a true global system with meter-scale performance.

### 4.3.3 GPS: Head starter against all (military) Odds

Luckily it was not only the US Navy, which was in need for accurate navigation systems. The US Army and in particular the US Air Force were also interested in such systems. The US Air Force however, had their own ideas how such a Global Navigation Satellite System should look like. While the navigation issue was less of importance for the Intercontinental Ballistic Missiles (ICBM), the strategic bombers demanded an accurate and available navigation service - a fix every few hours, as offered by the Navy's TRANSIT system, was considered far from being satisfactory, simply because the updates were too slow for the high speeds that the Air Force operated at. Consequently, the US Air Force issued an own study on the subject in 1963, which would eventually become "Project 621B", which saw a concept developed that resembled many of the attributes that we see nowadays in GPS.

Still the US Air Force and the Navy followed their own paths and where it not for the infamous "Lonely Halls Meeting"[20], which took place over the Labour weekend in 1973 in the Pentagon, GPS, as we know it, would have never been realised. But over a period of three days, left abandoned in a place that usually bursts with activity, 12 military officers discussed the creation of the Defense Navigation Satellite System (DNSS) thereby conceiving a system that was later known as Navstar or Global Positioning System - GPS.

The working principle of the system is fairly easy as it makes use of only two physical factors: the constant speed of light and the fact that we can measure time differences relatively precisely. The combination of these two things leads to a satellite-based system, where a satellite emits a time-

[20] Prof. Bradford Parkinson, Highlight Lecture: Origins, Surprises and Future of GPS, IAC 2010, 28/09/2010

stamped signal; the personal receiver combines it with its own time reference, and measures its distance to the satellite by calculating the time difference with the signal's speed (the speed of light). If one combines the signals of four satellites, the receiver can calculate latitude, longitude, and elevation as well.

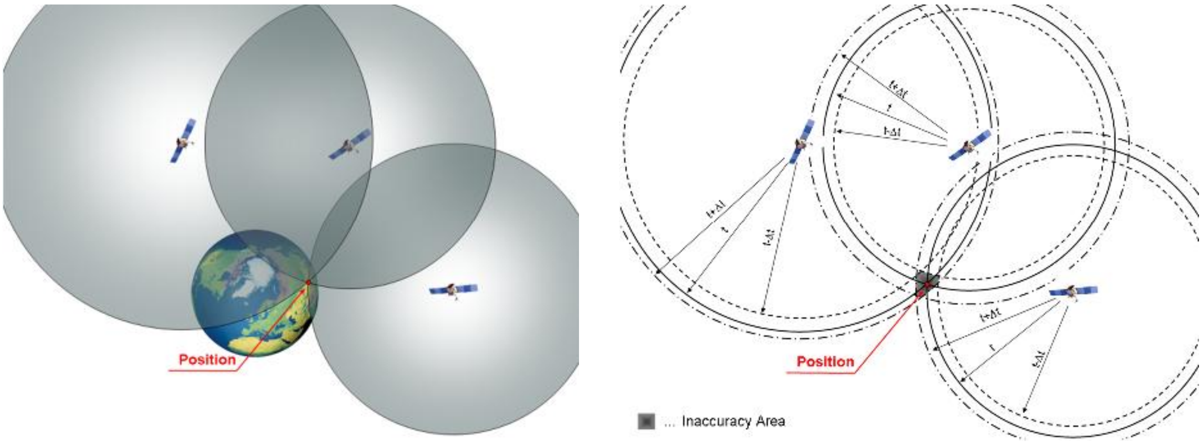


*Figure 4-14: The working principle of systems like GPS and Galileo builds upon measuring the time difference between emission and reception of a signal sent by a satellite (left image). Dependent on the error of this time measurement, the final position is to a certain degree inaccurate (right image).*

Of course, in details things are not that easy. In aiming to achieve a better performance than TRANSIT & Co. could offer, it became clear quickly that GPS would had to rely on a bigger space segment with more satellite and certain revolutionary technologies, such as space qualified atomic clocks, but most of all GPS would had to call for significant amounts of money, not millions but billions of US Dollars. Back then, such amounts of money could only be spent by governmental budgets and the request to spend billions of Dollars to allow for the necessary research, development, deployment and operation of a complex constellation of navigation satellites could be only justified if there was the need to mitigate a risk of such gravity that it would endanger the very existence of the USA - such as the Cold War arms race.

In the end it was the nuclear threat to the USA that convinced the US Congress to invest into GPS. In the period of 1973 to 2002, 6.3 billion US Dollars - excluding military equipment and launch cost - were spent on Navstar-GPS[21]. The operational costs amount to approximately 750 million US Dollars per year. For this amount of money, the USA obtained a system that acted as force multiplier to its nuclear deterrent - and the world got its first and so far only truly operational Global Navigation Satellite System.

### 4.3.4 Dual Use: From the nuclear Triad to the Potato Chip Market

At the peak of the Cold War, "nuclear triad" was the buzz word of the hour. In short it refers to a nuclear arsenal, which consists of three components that are independent from each other. Of all nuclear powers, only the USA and Russia/USSR have maintained a nuclear triad for most of the nuclear age. As such they operate(d) both strategic bombers, land based ICBMs and Submarine-launched Ballistic Missiles. This way, both countries would significantly reduce the risk that all of its nuclear forces could be possibly destroyed in a first strike attack, thereby ensuring a credible threat of being able to launch a counter strike and ultimately increasing their nuclear deterrence.

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[21] As stated on the NavStar Global Positioning System Joint Program Office website

I assume it is apparent that the costs of a full-fledged nuclear triad are extremely high. Although it offers the best level of deterrence from attack, only the US and the USSR wanted and were able to afford such a system initially. China eventually became the third nation and by now Israel might have full nuclear triad capabilities as well. India is assumed to join the "club" in 2012, when its Arihant class submarine is likely to be commissioned.

A major cost driver for the nuclear triad is the quality with which a deterrent is supposed to do harm to the enemy. This is a particularly true for submarine based missiles. Although they allow for a greater chance of survival from a first strike and are therefore the weapon of choice for the second strike, their limited range requires the submarine to move closer to the target, thereby increasing the risk of early detection. In aiming to optimise the flight path of an SLBM and hence extending its range to the maximum possible, it is necessary to obtain an accurate value of the SLBM's launch position - being able to rely on an operational GPS like system is therefore a clear force multiplier. Consequently, GPS is a GNSS with a clear military focus and according to the classical military doctrines it needs therefore to be counterweighted by a country's own system. GLONASS is therefore the Russian pendant, while COMPASS is to be seen as the Chinese answer - in military terms.

To repeat it once more; GPS, GLONASS and COMPASS are all military systems, serving primarily the interests of their country's armed forces. And were it not for the USA then the story would most likely end up here. Instead the civilian society of the USA enabled the development of civilian applications simply because the use of the signal by private entities was not explicitly encouraged but at least it wasn't prohibited. And so clever minds created applications that transformed GPS from a pure military into a dual-use system. This transformation was so successful that the GPS market has become the second largest space market (after satellite communications). GPS serves millions of civil users and to do so more than 1.4 million handheld and vehicle-mounted GPS receivers have been produced each year since 1997. The rapidly growing GPS market, including equipment and applications, reached US$6.2 billion in 2000 and is forecasted to surpass the 50 billion US Dollar threshold this year[22]. To put this in perspective: The GPS market is twice as large as the worldwide potato chip market![23]

### 4.3.5 GPS is great - but the World needs Galileo

Let's face it: GPS is an excellent GNSS that has set THE world-wide standard. But there is one major flaw: It is - and will remain - under military control. Being operated by the US Department of Defense, there is always the risk that in times of crisis, GPS will be degraded and/or switched off over specific regions if deemed necessary. This is, of course, the sole right of the US government, as it has invested billions of Dollars into the design and development and devotes an annual budget of approximately US$750 million to keep the system operational. The money is spent to maintain and control a fleet of 24 satellites, which circle the Earth at an inclination of 55° once every 12 hours at an altitude of 20,200 km. This constellation allows users to estimate their position with an accuracy of 10 m in the horizontal and 35 m in the vertical plane. The "selective availability" – an artificial degradation of the navigation signal, leading to an accuracy limitation of ca. 100 m – had been switched off in May 2000 by a directive of President Bill Clinton.

[22] http://www.astronautix.com/project/navstar.htm, accessed October 2010
[23] http://www.potatopro.com/Pr/E-shot/Savory%20Snacks%20Global%20Industry%20Guide.aspx, accessed October 2010

Still the word "availability" hangs like a sword of Damocles over GPS. Besides the fact that usage of GPS can be temporarily denied (some sort of "political availability"), there is also a physical limit to availability of the GPS signals. Twenty-four GPS satellites sounds like a whole lot, but when one takes into account that the accuracy increases with the number of satellites, that a typical airport runway is "only" 45 m wide, and that this system needs to cover the whole surface of the Earth, one can see that physical availability has its limits as well. What the world needs is a civilian system with 24/7 availability and with performances, which are as good as or preferably better than GPS - all this is Galileo!

*Figure 4-15: The NAVSTAR-GPS and the Galileo Logo. Two sides of a "GNSS coin" - but yet ONE coin (Source: InsideGNSS and Wikipedia/ESA)*

### 4.3.6 Galileo: European Quality has a Price

Bearing in mind that systems like GPS are becoming more and more important for our economy and our daily life, the European decision to build Galileo as an independent, better-performing system under exclusive civilian control was quite logical. In 2003 the final decision was made, when ESA and the European Commission agreed on building Galileo with European industry. Until 2007, €1.5 billion had been invested, while additional 3.4 billions have been secured for finalising the project until 2013. With the recent delays, which see Galileo delivering its first signal in 2014 and reaching the Full Operational Capability (FOC) in 2016, these budget numbers are now under question, as is the assessment of the operational costs in the utilisation phase, which had been originally estimated at €220 million per year. Even if Galileo is to cost €6 billion, which is close to the costs of its US pendant - don't forget, the US$6.3 billion do not include launch costs, while they are included in the costs for Galileo - then this is not a cost number of shocking nature. Although 4.9 or possibly €6 billion seems high at first glance, the costs of Galileo are not that extraordinary when one compares them with an infrastructure project such as building a highway. Here the costs can reach values like €100 million per km[24], so a 150 km long highway between two cities - say Brussels and Rotterdam - can easily amount to €15 billion. If one looks at Germany with its dense Autobahn system, one can estimate how much money has been and is continuously being invested into infrastructure projects in Europe.

Once completed, Galileo will comprise 30 satellites (27 operational and 3 spares), circling the Earth in three distinct orbital planes with 9+1 satellites each, at an inclination of 56° and an altitude of 23616 km. Because of the larger number of satellites and more advanced technology (better atomic clocks, dual frequencies, etc.), Galileo aims to provide a better availability and accuracy than GPS and will even offer 24/7 service under all, but the most extreme circumstances. One search-and-rescue and four navigation services are part of the "Galileo package":

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[24] http://www.skyscrapercity.com/showthread.php?t=495808, accessed October 2010

- **Open Service (OS):** Combines open signals, free of charge, interoperable with GPS. Position and timing performances shall be competitive with other GNSS systems (especially GPS IIII) an accuracy of 1 m is envisaged.
- **Safety of Life Service (SoL):** Improves OS performances by providing timely warnings to the user when system integrity is hampered. A service guarantee is envisaged. This is supposed to become the key service for aviation navigation.
- **Commercial Service (CS):** Provides access to two additional signals, to allow for a higher data rate throughput and to enable users to improve accuracy to centimeter level. Signals will be encrypted and a service guarantee is envisaged.
- **Public Regulated Service (PRS):** Provides position and timing to specific users (government agencies, military, etc.) requiring a high continuity of service (also during times of crisis), with controlled access. Two PRS navigation signals with encrypted ranging codes and data will be available.
- **Search and Rescue Service (SAR):** Will broadcast globally the alert messages received from distress emitting beacons. In case of excerption of an incoming emergency message, it will provide feedback to the sender, confirming that help is on the way. The service will contribute to enhancing the performance of the international COSPAS-SARSAT SAR system.

This bundle of four navigation services and one service to support Search and Rescue operations has been identified to cover the widest range of users' needs, including professional users, scientists, mass-market users, safety of life and public regulated domains. The major question that remains now is when Galileo will be ready.

### 4.3.7 Rom wasn't built in a Day...

... and Galileo won't be either. It is a complex programme, with numerous parties involved and is designed to provide a plethora of signals to serve all sorts of customers. The current planning foresees Galileo to provide the Open Service (OS), the Public Regulated Service (PRS) and the Search and Recue Service (SAR) as of 2014 and the complete set of signals once Full Operational Capability (FOC) will be achieved in 2016. There is however still some uncertainty to these dates, mostly due to political and financial issues, which is nothing new for a programme of these dimensions. Looking on its US pendant, one could argue that Galileo's current state is comparable to where GPS was in the middle of the 70s; the technical concept was finalised but the constellation was not yet in full operation. A few years later, GPS was a reality and is until today and this with unrivalled success[25].

Galileo is there to challenge the success of GPS - to give us a truly global navigation satellite system that we can utterly rely on. A system that we can use to guide airplanes to the runway, a satellite system that will help ships and cars to navigate, a navigation satellite system to better direct the traffic on the roads, organise the transport of goods and to reduce carbon dioxide emissions, a global navigation satellite system that will be used in Europe, the USA, Japan and elsewhere in the world.

[25] It should be noted at this point that GPS was declared fully operation in 04/1995, 18 years after the launch of the first GPS satellite! In a slight ironical tone one can therefore say that Galileo is still on track to beat that schedule.

Galileo will come with a price tag - that's for sure. But this price tag is comparable to the one of other infrastructure projects, only that Galileo is a force multiplier in infrastructure, as it supports numerous applications, ranging from positioning and navigation, to the synchronisation of power, telecom and financial networks. These networks are too indispensable for the world of today to have them rely on the mercy of global navigation satellite systems that serve primarily military interests. The world is not the same as it was in the 70s, when GPS was conceived - and it will not be the same when Galileo will be fully operational in 2016.

But even if it takes until 2018, Galileo is a GNSS (brand) name to be best acquainted with today, as it will be an integral part of our life in the years to come. Just like DVB, UMTS and the World-wide-web are already today!

# 5. Technology Transfer Players: From High Energy Physics (CERN) to manned Spaceflight (ESA) and Energy Research and Implementation (JRC-IET)

Now that we have had a look onto the different Technology Transfer Domains, namely space exploration and space application, to assess the areas in which technology transfer is conducted, it is time to have a closer look at the players and their programmes and projects to analyse what are the requirements and constraints that govern this process.

Given the complexity of the framework, a generic assessment approach will not be easily possible. Technology transfer is not a "clear cut", as it does often span over several domains, such as communication, propulsion, navigation, energy, etc., governed by requirements and constraints like highest safety, best performance, lowest cost, etc., which cannot be easily rated in terms of importance – not even for a specific application. Therefore, instead of trying to make a direct match between requirements and constraints, which are quite often not as obvious as one would expect, let's have a look at specific players, which are confronted with technology transfer – all with a different flavour to it. The players selected are:

- **CERN, the European Organisation for Nuclear Research**, an international entity and a world-renown particle research laboratory, which perfoms basic research in particle physics. The research project we have selected as a reference is a high-end particle detector making use of VLSI technology. CERN, performing frontier science, is very active in technology transfer, spinning in and off the latest technologies. Achieving the highest scientific performance is the key driver behind these activities.
- **ESA, the European Space Agency, an internatonal space agency**, conducting a broad set of spaceflight programmes in an international context. The project we will have a closer look at has a strong focus on communication technologies and is governed by manned spaceflight requirements and constraints, which rates the safety of the astronauts as the top priority that every other design aspect has to adhere to.
- **JRC-IET, the Joint Research Center, Institute for Energy and Transport**, a European research center, devoted to set-up international codes and standards in the area of energy and transport research. The activity we will examine further concerns the development of hydrogen fuel cells and tanks in support of the Hydrogen Economy. Simplicity of use and highest safety at low cost are the main drivers.

*Figure 5-1: Aerial view of CERN, located north of Geneva airport visible at the right. The largest ring represents the two most powerful particle accelerators ever built: LEP (1989-2000) and the LHC (2008 - now)*

CERN, located at the border of Switzerland and France stands for world-class science in high energy physics, which has implications for several other scientific domain such as astrophysics and cosmology, biology, computer and material sciences. At the heart of its activities are the particle accelerators, like the Large Electron-Positron Collider (LEP) and the Large Hadron Collider (LHC), and their associated detectors, such as ALEPH, OPAL, L3 and DELPHI at LEP or CMS and ATLAS at the LHC. Located at specific collision points of the 27 km long accelerator rings, all these detectors use different techniques to track particles in the different reactions which are created by the particle collisions. The registration of all particles in terms of their energy, momentum and charge is key to understand the particle reaction that had happened and the elementary particles which were involved. Naturally not all particles are easily detected and traced, hence only cutting edge methods and materials with the highest performance are utilised to increase the chances of success to gather statistical data. **'Performance' being the top requirement at CERN** translates to the necessity to precisely register each particle track; from the vertex to the exit point. The aim to place the right sort of particle detector at the right point within the whole assembly leads to an 'onion-like' design of all these detectors as demonstrated by the cut-away view of the DELPHI Detector outlined in Figure 5-2.

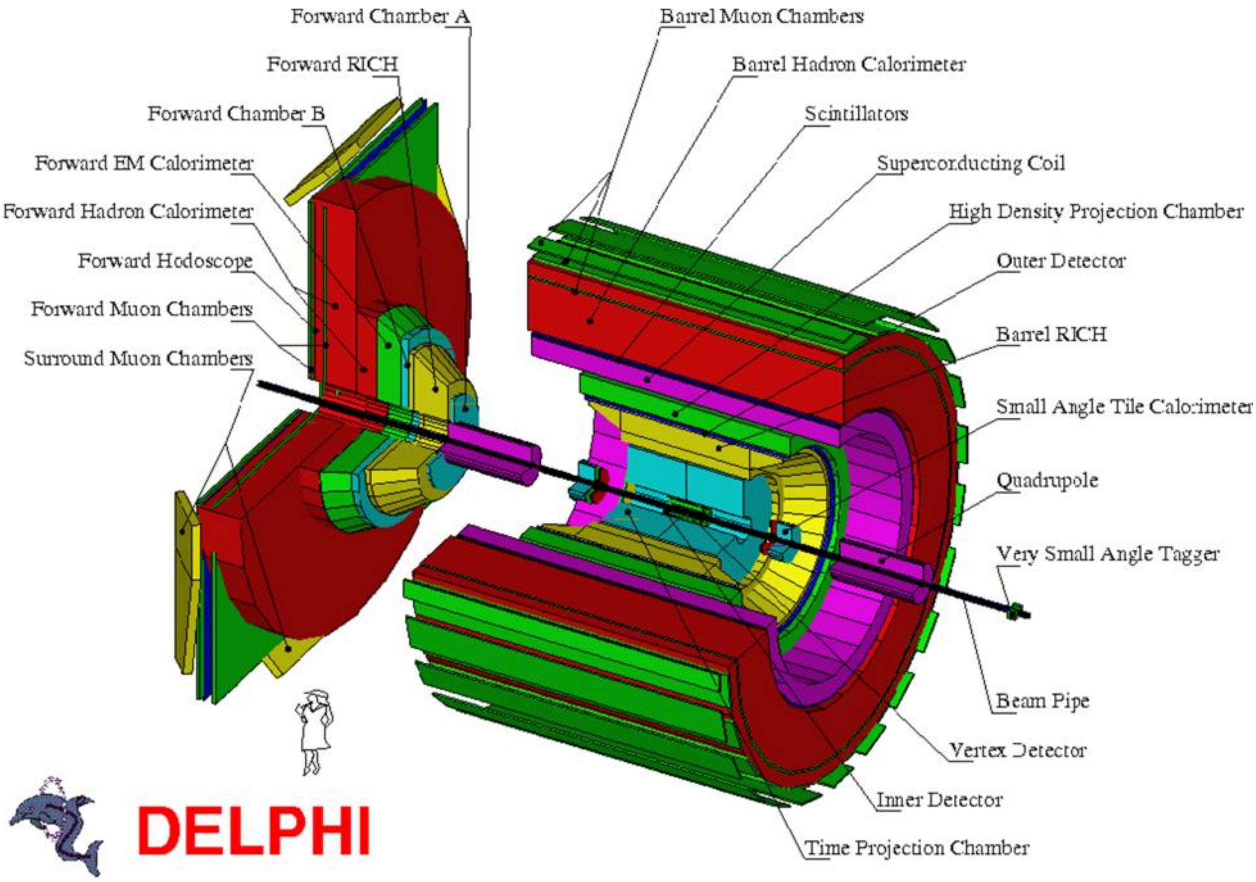


*Figure 5-2: Assembly of the DELPHI Detector*

At the very center of DELPHI is the Vertex Detector. Its close position to the collision point has been chosen to ensure a good first position fix, which is key for a perfect tracing of the particles streaming away from the vertex. At the same time however this close position does also mean that the Vertex Detector is exposed to high radiation intensities. Maintaining the balance between perfromance and survival forms therefore the framework for this type of high-tech detector.

## 5.1 *Scientific Performance above all: "The DELPHI Slicon Tracker at LEP2" ([D] The DELPHI Silicon Tracker Group, 1998)*

Published in The DELPHI Silicon Tracker Group: The DELPHI Silicon Tracker at LEP2, in *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* (1998), pp. 304-328 [D]

The DELPHI Silicon Tracker, an ensemble of microstrips, ministrips and pixels, was completed in 1997 and has accumulated over 70 $pb^{-1}$ of high energy data. The Tracker is optimised for the LEP2 physics programme. It consists of a silicon microstrip barrel and endcaps with layers of silicon pixel and ministrip detectors. In the barrel part, three dimensional *b* tagging information is available down to a polar angle of 25°. Impact parameter resolutions have been measured of 28 µm ⊕ 71/($p$ $\sin^{3/2}\theta$) µm in *R*¤ and 34 µm ⊕ 69/ µm in *Rz*, where *p* is the track momentum in GeV/c. The amount of material has been kept low with the use of double-sided detectors, double-metal readout, and light mechanics. The pixels have dimensions of 330 x 330 µm² and the ministrips have a readout pitch of 200 µm. The forward part of the detector shows average efficiencies of more than 96%, has signal-to-noise ratios of up to 40 in the ministrips, and noise levels at the level of less than one part per million in the pixels. Measurements of space points with low backgrounds are provided, leading to a vastly improved tracking effciency for the region with polar angle less than 25°.

### 5.1.1 Introduction

The DELPHI Silicon Tracker presented in this paper has been optimised to cope with the requirements posed by the physics programme at LEP2. The design [1] had to take into account the following features of the processes studied or searched for:

- Four fermion processes, important for both standard and non-standard physics, are relatively frequent; hence a larger angular coverage in polar angle[26] is required compared to $Z^0$ physics.
- In the processes with the largest cross sections, such as $e^+e^- \Rightarrow q\bar{q}\gamma$ or $e^+e^- \Rightarrow$ ¥¥, the particles are produced predominantly in the forward direction.
- The search for the Higgs boson  and for supersymmetric particles are important physics objectives for LEP2, so a good tagging of *b* quarks down to low polar angles is important in order to reduce background from standard processes such as $W^+W^-$ production.

[26] In the standard DELPHI coordinate system, the z axis is along the electron direction, the x axis points towards the center of LEP, and the y axis points upwards. The polar angle to the z axis is called θ and the azimuthal angle around the z axis is called ϕ; the radial coordinate is R = $\sqrt{x^2 + y^2}$.

### 5.1.2 Design Considerations

The Silicon Tracker uses different kinds of technologies in each angular region in order to achieve the performance goals discussed above. Two main tasks can be distinguished:

- **Vertexing in the barrel region**

  The central part of the Silicon Tracker must have a *b*-tagging performance which is at least equivalent to that of the 1994-95 Vertex Detector [2], and in addition be extended down to around 25°, beyond which multiple scattering starts to dominate the impact parameter resolution for *b* hadron decay products. This is achieved with three layers of microstrip modules, termed Closer, Inner and Outer, at average radii of 6.6 cm, 9.2 cm and 10.6 cm. In the *R*¤ plane the resolution is around 8 µm, and in the *Rz* plane the readout pitch is changed for plaquettes at different angles to give the best resolution possible perpendicular to the track, varying between about 10 µm and 25 µm for tracks of different inclination. The material is kept to aminimum by the use of double-sided detectors and light mechanics. This part is called the Barrel.

- **Tracking in the forward region**

  In the forward region, the emphasis is on improved momentum measurement and standalone pattern recognition. The detector must improve the overall hermeticity of DELPHI and provide a better extrapolation of tracks towards the forward RICH [3] detectors, leading to a better particle identification in this region. The momentum measurement is limited by Coulomb scattering and a resolution of about 100 µm is suffcient. These requirements are met [1] by adding silicon endcaps, consisting of two layers of pixel detectors, with pixel dimensions of 330 x 330 $\mu m^2$, and two layers of back-to-back ministrip detectors with a readout pitch of 200 µm and one intermediate strip. The pixel detectors have a noise level of less than one part per million which is crucial to eliminate ghost tracks, and the ministrips operate at a signal over noise of more than 40. To help the pattern recognition the ministrips are mounted at a small stereo angle. The angular accuracy is about 1 mrad, and the extrapolation accuracy at the forward tracking chambers of DELPHI is a few mm. This part is called the Very Forward Tracker (VFT).

Throughout the detector there is great emphasis on the overlap of sensitive silicon, within each layer of detectors, and between the different layers. This provides redundancy and allows a self alignment procedure, but places great constraints on the assembly, since silicon plaquettes from different layers are often separated by less than 1 mm.

To make the project affordable, components and systems were re-used from the previous silicon vertex detectors of DELPHI, namely some of the plaquettes and hybrids [2] and the data acquisition and service systems [4]. The complete Barrel and a large part of the VFT (the full set of ministrip detectors and 60% of the pixels) was in operation during the 1996 data taking. The complete detector was installed in DELPHI for the data taking in 1997.

The Silicon Tracker is illustrated in Figure 5-3. The three concentric layers of the barrel detector cover the angular region 21°-159°. Two pixel layers, the first one being located inside the barrel, and two ministrip detector endcaps cover the angular region 11°-26° and 154°-169°. As an illustration of its physics capabilities we show in figure 2 an event registered in 1996 at the energy $\sqrt{s}$ = 161 GeV, where a jet with ¯ = 35° is tagged as a *b* jet.

Full technical descriptions of the detector and the individual layers can be found in [5] - [9]. In what follows we give a summary only, mentioning in particular the new features.

### 5.1.3 Silicon Components

The characteristics of the silicon plaquettes used are summarised in Table 5-1and Figure 5-5. The suppliers used were Hamamatsu[27], SINTEF[28], CSEM[29] and MICRON[30].

Multiple scattering at the first measured point dominates the track impact parameter resolution. In order to minimise the amount of material, the Closer layer is composed of double-sided detectors. This layer is taken from the 1994-95 Vertex Detector [2]. For the Outer layer, where multiple scattering is less crucial, a cheaper back-to-back solution was chosen. This layer is completely new, and has a novel *Rz* measurement which is made with single-sided detectors with $p^+$ implants, with the signals being routed to the ends of the detectors with a double-metal technique. The diodes are either read out singly, or singly with one intermediate strip, or ganged in pairs, with two connected intermediate strips. This gives a choice of pitches, allowing the resolution to be optimised for tracks passing through at different incidence angles. The Inner layer is built up of both double and single-sided detectors, allowing the re-use of double-sided detectors from the previous vertex detector.

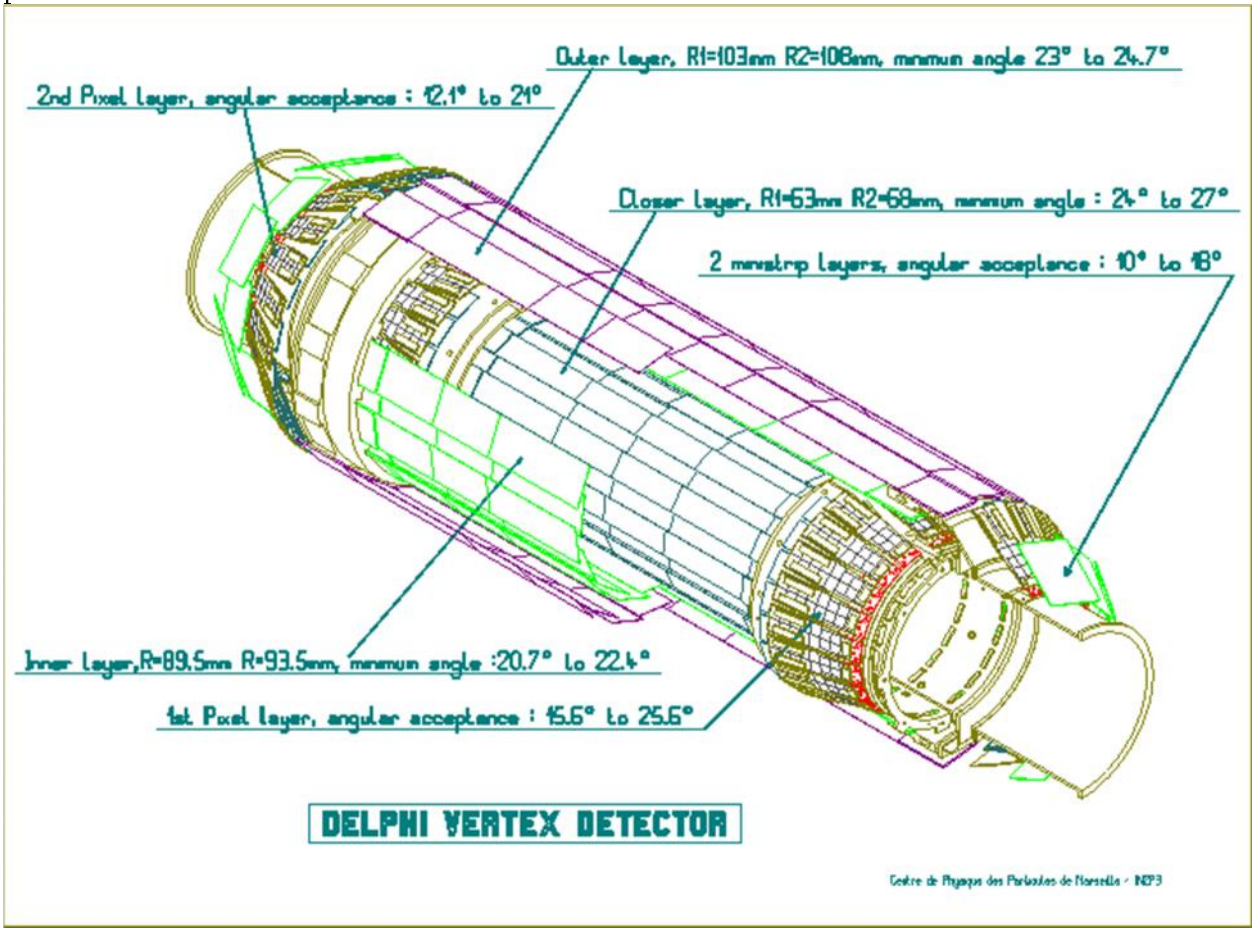


*Figure 5-3: Layout of the DELPHI Silicon Tracker*

27 Hamamatsu Photonics K.K., Hamamatsu City, Japan
28 SINTEF, Oslo, Norway
29 CSEM,Rue de la Maladiere 41, CH 2007, Neuchatel, Switzerland
30 MICRON Semiconductor Limited, Sussex BN15 8UN, England

The pixel plaquettes are divided into ten regions of 24 x 24 pixels at large radius and six regions of 24 x 16 pixels at smaller radius. Each region is read out by an SP8 [10] chip bump-bonded to the detector (see section 4). The pixel size is 330 x 330 µm², and pixels at the boundary between neighbouring read-out chips have increased dimensions, so that blind regions in the active area are avoided. The ministrip plaquettes have a readout pitch of 200 µm with one intermediate strip.

### 5.1.4 Assembly into Modules and Crowns

The concept of the Silicon Tracker is modular: the plaquettes in each region are assembled into electrically independent modules or crowns, which are subsequently connected to their repeater electronics and mounted onto the support structure. The characteristics of these modules and crowns are summarised in Table 5-2.

In the barrel the modules take the form of ladders 4 or 8 plaquettes in length, each of which forms an electrically independent half of a barrel module. The front-end electronics are mounted onto double-sided BeO hybrids at each end of the modules, and multilayer kapton cables join the hybrids to the repeaters. In each quarter of the detector there is one repeater card per layer, serving 10 or 12 modules. Bond wires connect the signal and bias lines between the detectors and hybrids. In the Inner layer this leads to one bias line connecting together diodes with polysilicon resistor and FOXFET biasing, which has been operating successfully.

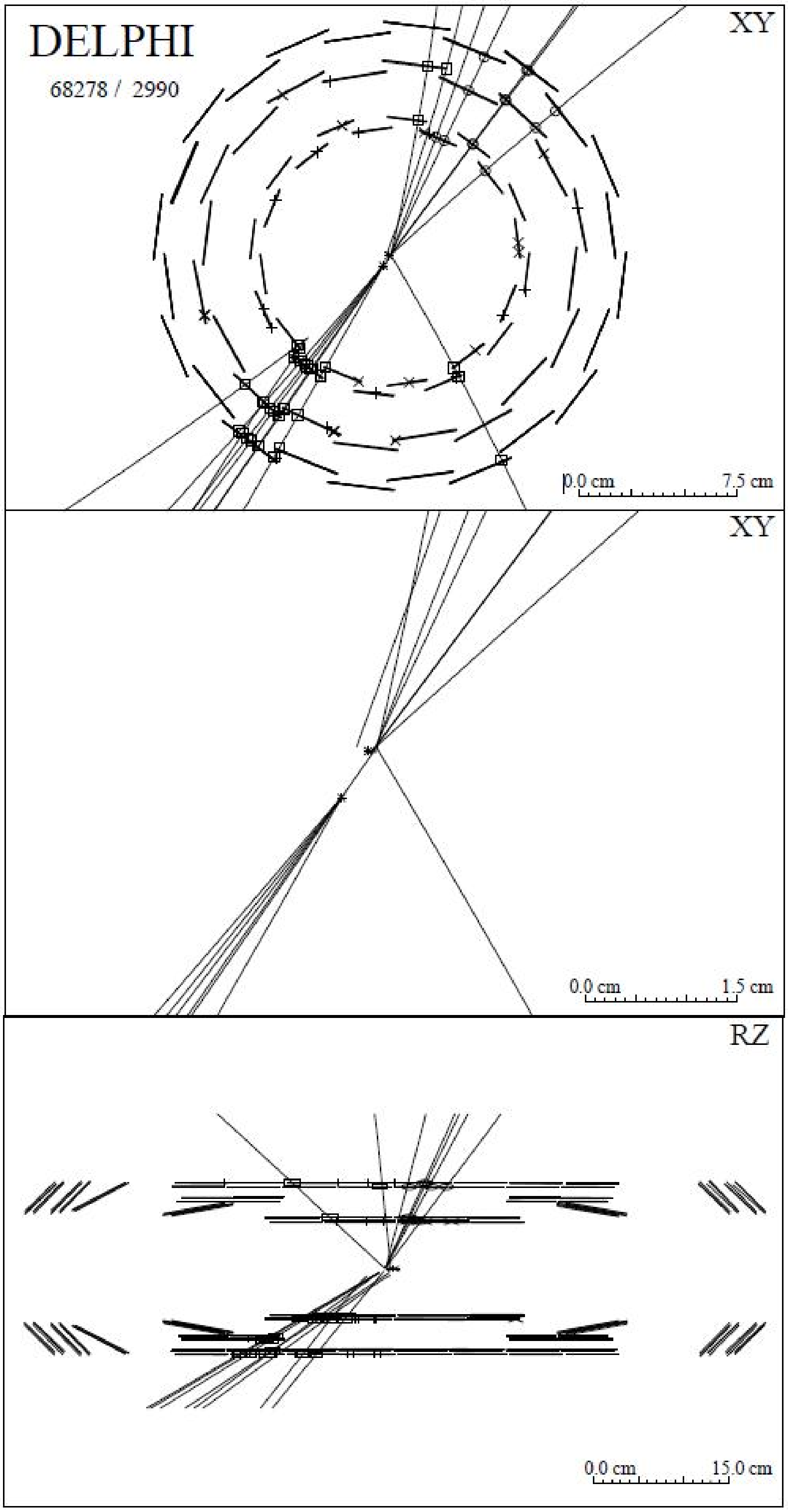


*Figure 5-4: Event registered during the 1996 161 GeV run. The top two views show the R¤ projection on two different scales. The displaced vertex is clearly seen. The bottom view displays the Rz projection. In 1996 only one quarter of the second pixel layer was installed.*

| Characteristics of silicon plaquettes | Barrel | | | | VFT | |
|---|---|---|---|---|---|---|
| | **a** | **b** | **c** | **d** | Pixels | Ministrips |
| supplier | Hamamatsu | SINTEF | Hamamatsu | SINTEF | CSEM | MICRON |
| single/double-sided | ss | ss | ds | ds | ss | ss |
| double-metal p-side | no | yes | no | no | - | no |
| n-side | - | - | yes | yes | - | - |
| length (cm) | 5.99 | 5.99 | 5.75 | 6.07,7.91 | 6.9 | 5.3 |
| width (cm) | 3.35 | 3.35 | 3.35 | 2.08 | 1.7 – 2.2 | 5.3 |
| sensitive area ($cm^2$) | 18.6 | 17.9 | 34.2 | 22.2,29.4 | 9.9 | 27.0 |
| pitch ($\mu$m) p-side | 25 | 44 | 25 | 25 | $330 \times 330$ | 100 |
| n-side | - | - | 42 | 49.5,99,150 | - | - |
| readout pitch p-side | 50 | 44,88,176 | 50 | 50 | $330 \times 330$ | 200 |
| ($\mu$m) n-side | - | - | 42,84 | 49.5,99,150 | - | - |
| blocking strip (n-side) | - | - | $p^+$ | field plate | - | - |
| # readout channels | 640 | 640 | $640 \times 2$ | $384 \times 2$ | 8064 | 256 |
| wafer thickness ($\mu$m) | 290 | 310 | 320 | 310 | 290 – 320 | 300 |
| implant width ($\mu$m) | 8 | 8 | 12,14 | 6,8 | - | 60 |
| biasing | FOXFET | Polysilicon resistors | Polysilicon resistors | Polysilicon resistors | DC | FOXFET |
| readout coupling | AC | AC | AC | AC | DC | AC |
| resistivity ($k\Omega$cm) | 3 – 6 | 3 – 6 | 3 – 6 | 3 – 6 | 10 | 10 |
| operating voltage (V) | 60 | 60 | 65 | 60 – 95 | 40 – 60 | 60 |

*Table 5-1: Characteristics of silicon plaquettes. There are 888 plaquettes in the full detector. The different types of plaquettes in the barrel, **a**, **b**, **c** and **d**, are arranged as shown in Figure 5-5. Sensitive area counts R¤ and Rz sides for cases of double-sided detectors.*

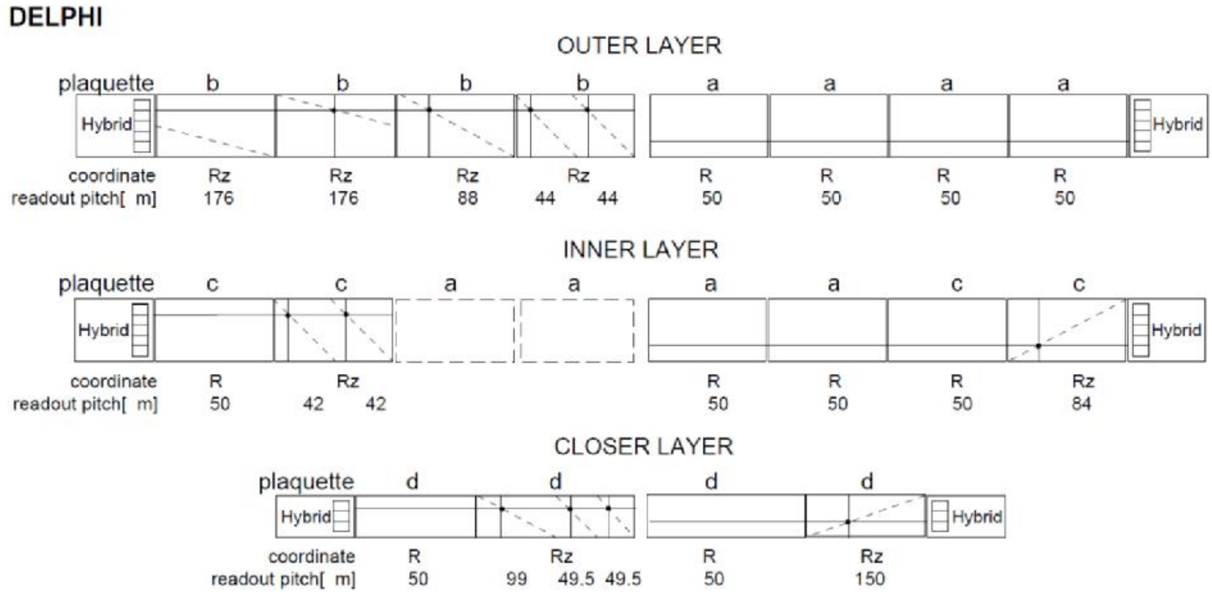


*Figure 5-5: Arrangement of the detectors **a**, **b**, **c** and **d**, as defined in Table 5-1, in the barrel. The left hand side of the figure illustrates the sides of the modules which face away from the beampipe, and the right hand side of the figure shows the sides of the modules which face towards the beampipe. The solid lines indicate the directions of the strips, and the dotted lines the layout of the contact holes in the case of double metal read-out. A full technical description of the components of the barrel and the readout conventions can be found in [11].*

For the Closer and Inner layers the front end amplifer used is the MX6 [12], taken from the previous detector, and for the Outer layer the new TRIPLEX [13, 14] chip, with an Equivalent Noise Charge ENC = (283 + 17 x $C_{load}$) electrons, where $C_{load}$ is the load capacitance in pF. On the *Rz* side of this layer there is a charge loss in some plaquettes (up to a maximum of 25% in the most external plaquettes) due to the combination of the double-metal readout with intermediate strips [9], but due to the high S/N performance this leads to a negligible loss in resolution. The use of double-sided and back-to-back modules led to the choice of kevlar for the strengthening beams, with the addition of carbon fibre at the top of the beams to reduce the mechanical sensitivity to changes of humidity [15].

In the VFT, the pixel and ministrip plaquettes are mounted onto semicircular aluminium supports, with inclinations with respect to the z axis of 12° and 32° for the pixel and 49° for the ministrip plaquettes. The electronics are connected to the repeaters with kapton cables, with one repeater per crown for the ministrips and two repeaters per crown for the pixels.

The pixel plaquettes, each with 16 bump-bonded SP8 chips [10], are arranged in groups of 19 onto each pixel crown. Bus lines bringing the data and control signals to each of the chips are integrated onto the detector substrate using a double-metal process. This design reduces the amount of material and allows at the same time a reduction in the amount of signals by multiplexing on the integrated bus. On the other hand, it is a highly demanding design in terms of failure rate of the interconnection technique. The connection between the bus lines and the corresponding pad on the chip is achieved by the same bump-bonding technique used for the pixel interconnection. The IBM C4 (Controlled Collapse Chip Connection) bump bonding process [16] was used, and a $(2.4 \pm 0.2) \times 10^{-4}$ failure rate was achieved for a bump size of 100 µm. The remaining power busses are supplied via a flat kapton cable glued on top of the readout chips. On two cells per chip, a *p*-well underneath the input pad defines a 30 fF calibration capacitance. Because of the large number of pixels and the expected low occupancy, a selective readout scheme was implemented on the chip [17], identifying and outputting the addresses of the hit pixels. The connections between the detector substrate and the flat kapton cable, and then to the long kapton cable which is connected to the repeater electronics, are made with wire bonding. The assembly of a pixel plaquette is illustrated in Figure 5-6a.

The ministrip crowns each contain 6 pairs of back-to-back plaquettes. As for the barrel, MX6 chips were used, glued to 300 µm thick BeO hybrids. Due to the lack of space the hybrids are glued directly on top of the single-sided plaquettes. A ceramic or glass fan-in was used to match the 50 µm electronics pitch with the 200 µm readout one. The back-to-back detectors are rotated by 90° with respect to each other, to give a two dimensional readout. The implanted strips have an angle of 2° with respect to the edge of the detector, so by rotating modules in adjacent crowns a 4° stereo angle is created between the strips, helping the pattern recognition. The assembly of a back-to-back ministrip component is illustrated in Figure 5-6b.

### 5.1.5 Readout Electronics

The repeaters are multilayer printed circuit boards mounted in the form of rows of semicircular discs at the ends of the Silicon Tracker. They contain buffers, control circuits and power lines, and communicate with the readout systems in the barracks approximately 20 m away.

| Characteristics of modules/crowns | Barrel | | | VFT | | |
|---|---|---|---|---|---|---|
| | Outer | Inner | Closer | Pixel 1 | Pixel 2 | Ministrip |
| # modules/crowns | 24 | 20 | 24 | 4 | 4 | 8 |
| # plaquettes | 16 | 8 | 4 | 19 | 19 | 12 |
| sensitive area ($cm^2$) | 292 | 208 | 103 | 189 | 189 | 324 |
| dimensions (cm) | $55.9 \times 3.4$ | $55.5 \times 3.4$ | $36.0 \times 2.1$ | $r_{min} = 6.9$ $r_{max} = 8.4$ | $r_{min} = 7.5$ $r_{max} = 11.2$ | $r_{min} = 6.8$ $r_{max} = 11.2$ |
| support material | kevlar + carbon | kevlar +carbon | kevlar +carbon | Aluminium | Aluminium | Aluminium |
| chip | TRIPLEX | MX6 | MX6 | SP8 | SP8 | MX6 |
| power/chip (W) | 0.2 | 0.2 | 0.2 | 0.017 | 0.017 | 0.2 |
| # chips | 20 | 20 | 12 | 304 | 304 | 24 |
| % overlap | 12 | 13 | 15 | 37 | 12 | 15 |
| rad tolerance (krad) | 50 | 50 | 50 | 10 | 10 | 50 |
| angle to z-axis (deg) | 0 | 0 | 0 | 12 | 32 | 49 |

*Table 5-2: Characteristics of modules and crowns. Sensitive area counts R¤ and Rz sides for cases of double-sided detectors. The VFT detectors are supported with ceramics in the case of the pixels, and aluminium plates in the case of the ministrips.*

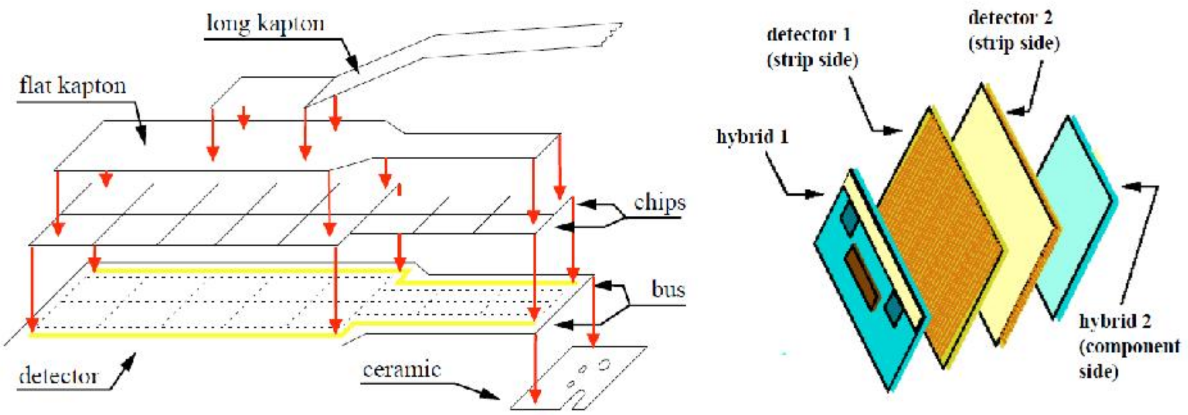


*Figure 5-6: Assembly of the pixel (left side) and ministrip (right side) components of the VFT crowns.*

The readout electronics of the barrel and ministrip parts of the Silicon Tracker are similar enough to be steered and read out by a common system. At each second level DELPHI trigger 174080 analogue values from the barrel and ministrip parts of the Silicon Tracker are presented to the readout system. These data are analysed in real time by an on-line computer farm made of 128 DSP56001 Digital Signal Processors. Each DSP is conveniently assigned to one, two or four detector modules and receives between 1280 and 1536 analogue readouts for the analysis. For every DSP the readout is performed in a serial form at the speed of 1 MHz. As all modules are read out in parallel, it takes about 1.6 ms to read out all the strip detectors. Each DSP measures the pedestal and noise of every channel by averaging data over several events. The channels with significant signal are chosen, and signals on adjacent channels are correlated to match the typical charge spread patterns. The DSP's together with the digitization electronics are built into SIROCCO FASTBUS modules [18], which accommodate two DSP's each. The zero-suppressed data are collected from these modules by a standard DELPHI readout processor and later are joined to the common data stream. The suppression ratio achieved is of the order of 5/1000.

The pixel readout system consists of 16 repeaters read out in parallel by the same number of FASTBUS readout units. The readout units themselves are read sequentially by a FASTBUS crate processor which combines the data stream. A custom designed card provides all necessary timing signals for the SP8 front-end chips [19]. The 16 front-end chips of one plaquette are addressed sequentially and accessed separately one by one. This allows the skipping of malfunctioning chips. With each second level trigger, the readout is started and all timing and clocking signals are activated. The sparse data scan readout in the front-end chips selects the addresses of hit pixels only and transfers them to the crate processor with a 5 MHz clock. The total readout time for a full repeater with 160 front-end chips is typically 1.5 ms, including all bus transfer. A small fraction of pixels are systematically noisy. The total number depends on the threshold settings, and is shown in Figure 5-7 for a range of settings. The crate processor supresses these noisy pixels during acquisition time with the use of a mask which is set in advance using calibration run data. This mask is updated every few months and in case of major changes in the detector settings. The sparse data scan and the noisy pixel suppression together reduce the event size considerably with a typical event size being a few hundred pixels. This number is dominated by the remaining noisy pixels, which are flagged by the online monitoring and later removed off-line (see section 0).

### 5.1.6 Mechanics

#### 5.1.6.1 Mechanical Design

The principal challenges which had to be overcome for the mechanical design were as follows:

- Limited space is available (see Figure 5-9). The space constraints are provided by the 116 mm inner radius of the Inner Detector and the 56.5 mm external radius of the flange connecting the different sections of the beam pipe.
- The structure must be able to be installed inside DELPHI, which limits the total length of the detector to 1050 mm.
- The Silicon Tracker including the detectors and repeater electronics is 1033 mm long. Within this there are modules which can be as long as 50 cm, mounted in parallel with much shorter modules. The mechanical design must be sufficiently rigid to support all components and suffer as little stress as possible from the varying deformations of the different components with changes of temperature, humidity, etc. At the same time, the extra support material must be kept to a minimum, so as to maintain the previous performance for the *R*¤ impact parameter resolution in the barrel section.
- The mechanics must be able to re-use all double-sided modules from the previous detector, and accommodate the design accordingly.

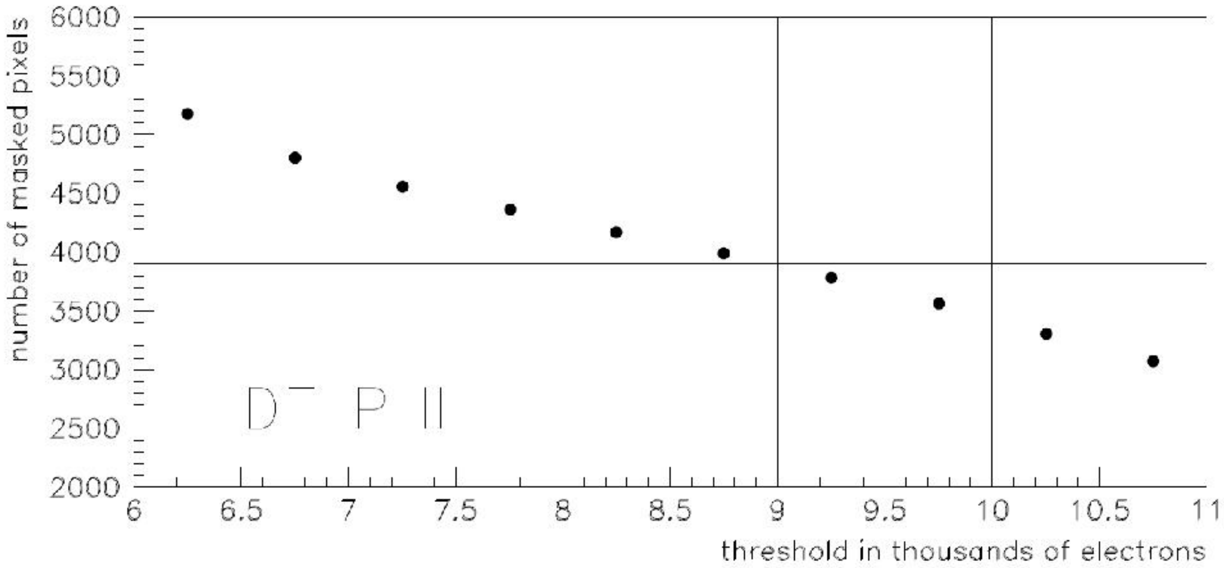


*Figure 5-7: Number of masked pixels as a function of the discriminator threshold for the 1997 detector configuration.*

#### 5.1.6.2 Support Structures

Figure 5-8 shows diagrammatically a cross section of the modules and supports for one quadrant of the detector. The barrel support consists of light aluminium endrings joined by carbon-honeycomb half cylinders [20]. The Inner and Outer layers are screwed to either side of this endring. The Closer layer has its own endring, which is connected to the barrel via an intermediate composite piece, which also serves to support the internal pixel layer. The thermal expansion coefficients between the components are matched to reduce mechanical stress [21]. The arrangement of the barrel detectors on the endrings is illustrated in Figure 5-9. It can be seen that in order to fit into the space, the support beams on the Outer layer are glued to alternate sides of the modules. An adaptor piece connects the barrel to the forward cylinders. The forward cylinders support 3 crowns of VFT detectors, and also serve to route the kapton cables towards the repeaters. The cabling is arranged in such a manner that using a rotating jig it is possible to mount each section of the detector together with its cabling and repeaters. The resulting structure
(see Figure 5-10) maintains the amount of material in the barrel at a similar level to the 1994-95 Vertex Detector, and moves forward material to significantly lower polar angles than previously.

A photograph of part of the detector can be seen in Figure 5-11.

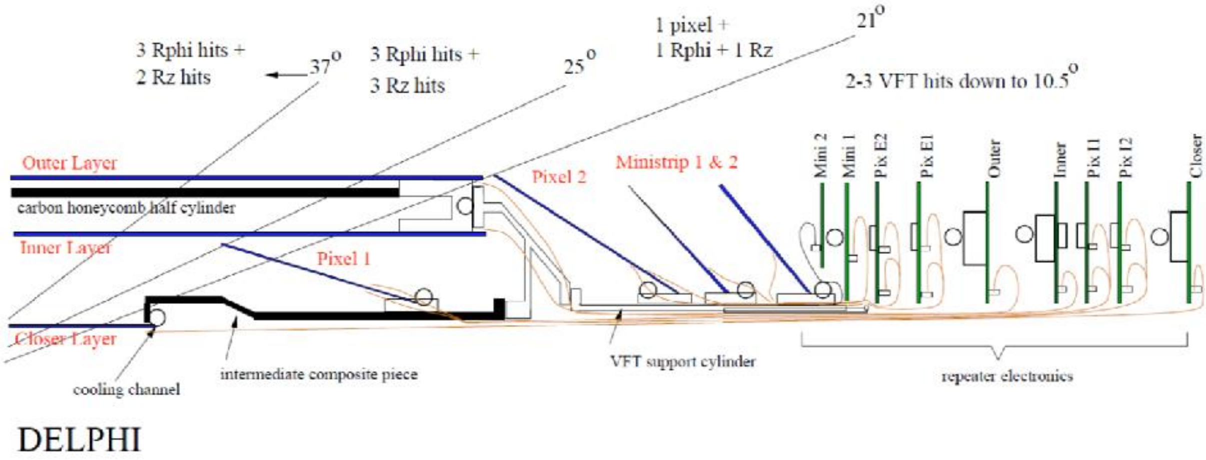


*Figure 5-8: Cross section of one quadrant of the Silicon Tracker for z>10cm*

#### 5.1.6.3 Cooling Considerations

The Silicon Tracker as a whole dissipates about 400 W in an almost completely confined space. In order to remove the heat, a system of cooling with water at 20°C was chosen. The water is delivered to each section of the detector in 0.5 mm thick aluminium tubes with an internal diameter of 3.5 mm. The geometry of the cooling system is based on mechanical considerations and the different power characteristics of each section. In the barrel, the greatest amount of power is developed in the Inner and Outer layers, which have a total of 880 chips dissipating 0.2 W each. These layers are cooled with one tube per quarter. The shorter Closer layer is cooled in parallel, to avoid mechanical stresses due to temperature differences between the layers. The heat transfer between the cooling tubes and the hybrids is optimised with the use of heat paste[31] between all connections. Laboratory tests showed gradients of 4°C for the Inner and Outer hybrids, and a maximum of 6°C for the Closer layer, which has less contact with the endrings. For the pixel detectors, the power dissipation is about 40 W, however the electronics are not localised on the hybrids but distributed over the detector. Here, the cooling functions by both conduction and convection, and the maximum gradients observed can be as high as 12°C. The pixel and ministrip crowns are also cooled in parallel, as well as the repeater electronics, which are cooled with one tube per quarter looping through 5 of the 9 repeater cards.

[31] supplied by SCHAFFNER, 5, Rue Michel Carre, 95100 Argenteuil, France

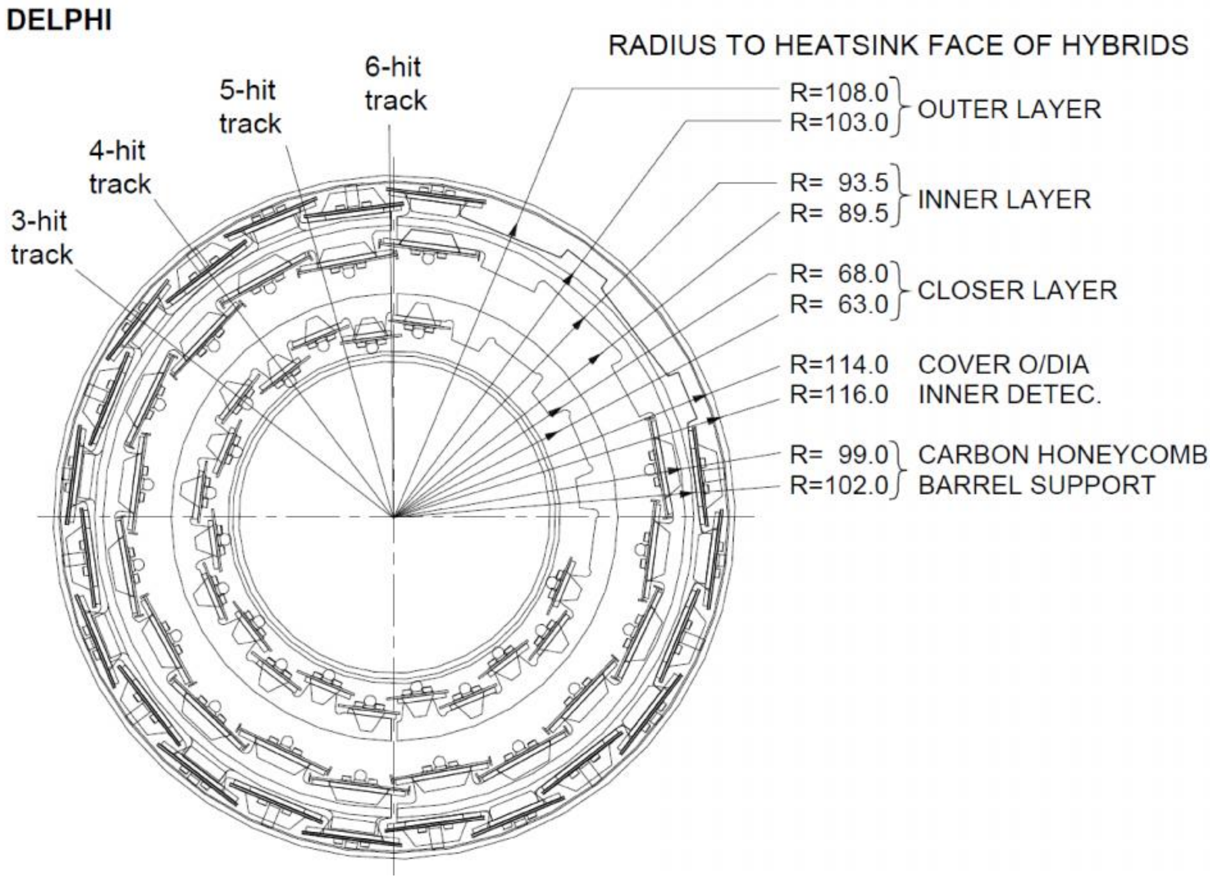


*Figure 5-9: Cross section of the Silicon Tracker showing the aluminium support rings of the Closer, Inner and Outer layers with the shape of the modules including the hybrids overlaid. There is a high degree of overlap in all layers, particularly the Closer layer which has roughly 15% overlap. The Inner layer has 20 modules only, as these modules come from the Outer layer of the 1994-95 Vertex Detector and previously formed a ring of 24 modules at higher radius. Spacers are screwed onto the Outer module hybrids to support the cover, which is made from 900 µm thick woven glass fibre with epoxy. The interior cover is supported with screws in 6 Closer layer hybrids. It is made from 1 mm thick Rohacel foam, with a 30 µm thick aluminium shield. The spheres used in the survey (see Section 0) are shown for the Closer and Inner layers. All spheres are removed before the installation into DELPHI. Note the overlaps between the top and bottom detectors, spanning the space where there is a gap in the support mechanics.*

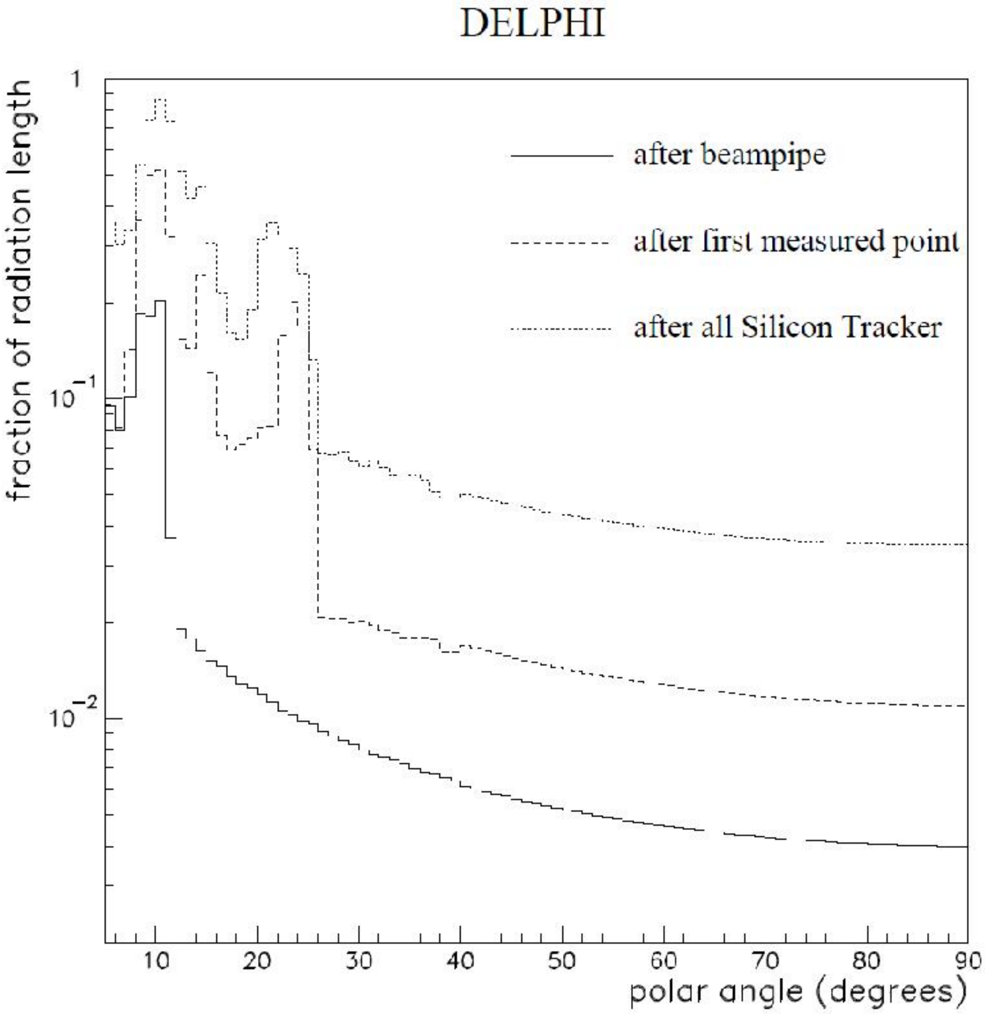


*Figure 5-10: Material of the Silicon Tracker as traversed by particles at polar angles ¯. The most important term for the impact parameter distribution is represented by the dashed line, which shows the material just after the first measured point. The values at ¯ = 90° are 0.4%, 1.1% and 3.5% for points after the beam pipe, the first measured point and the whole Silicon Tracker respectively.*

The cooling is operated on a siphoning principle, with the resultant underpressure protecting the detector from leaks in the system. The water pump used[32] is driven by pressurised air, so there is no heat flow into the system, and the water is cooled by a system of fridges. Problems of algae developing have been avoided with the use of Kemazur 1636[33]. The system has a total of 20 independent cooling tubes, and bifurcation of the tubes inside the detector is avoided, except for short sections in the VFT crowns. This means that sections can be operated independently, and allows for a total water flow of 16 l/min.

[32] supplied by YAMADA EUROPE, Topaasstraat, 7554 TH Hengelo, The Netherlands
[33] produced by Degremont-Erpac, 69263 LYON CEDEX 09, France

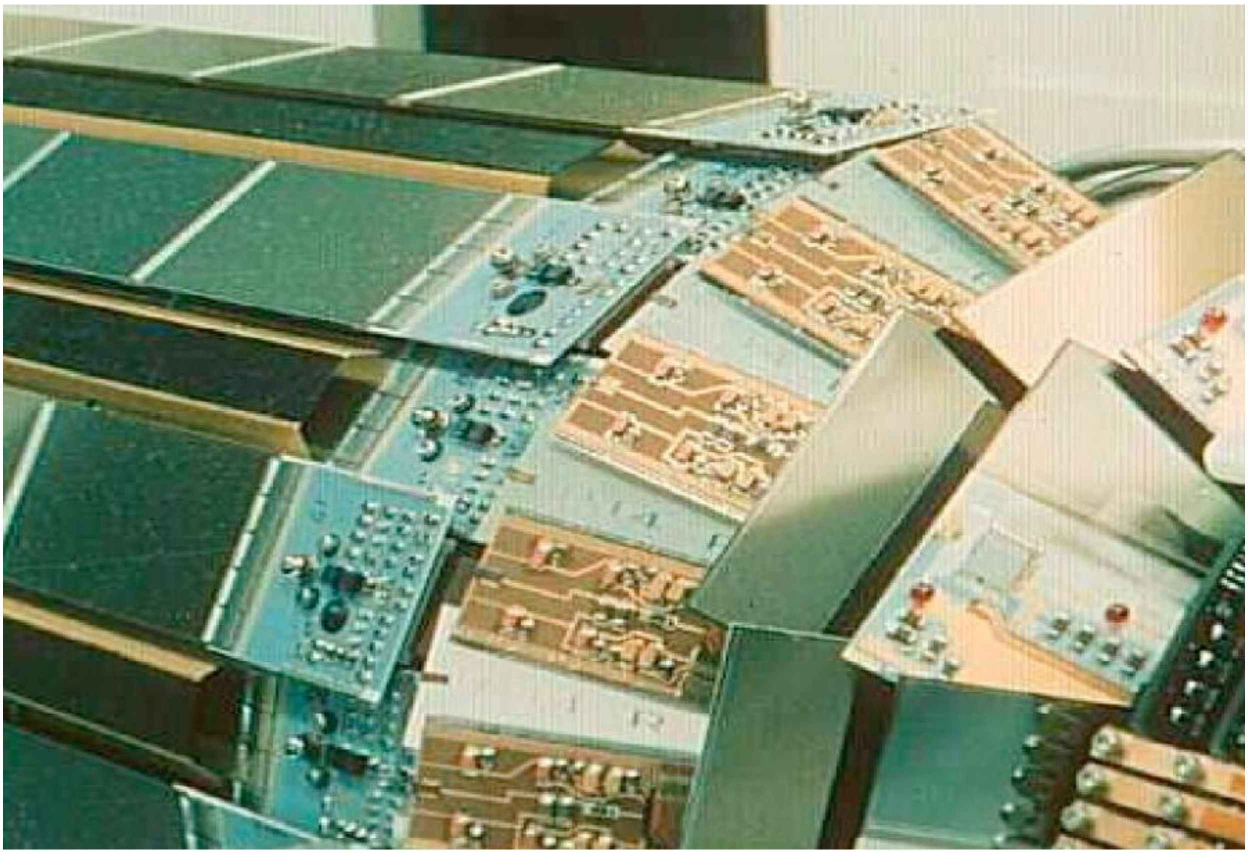

*Figure 5-11: Photograph of part of the detector showing from left to right Rz detectors of the Outer layer with their hybrids, the second pixel layer, two ministrip layers and part of the repeater electronics.*

#### 5.1.6.4 Installation

The detector is installed inside DELPHI with the beam pipe already in place. The weight of the detector is supported on carbon fibre rails via two aluminium skates per half shell. The skates are 3 mm thick at the place where they pass between the barrel detectors and the second pixel layer, and widen to 8 mm at the foot. In the horizontal plane there are also side skate supports, made from 2 mm thick aluminum, with Teflon coated heads, which rest on side rails. Extra skates support the repeater electronics. In order to pass the support ring of the beampipe the rails are pulled apart, separating the two halves. The halves must be reassembled before entering the centre of DELPHI, which limits the total length of the detector to 1050 mm. The detector is pulled into DELPHI with cords, and the two halves (each weighing around 3.5 kg) are brought together with a precision of 100 µm using locating pins mounted in the aluminium endring of the barrel. A complete mockup of the centre of DELPHI was built and test installations performed with the true Silicon Tracker.

### 5.1.7 Detector Performance

#### 5.1.7.1 Real Time Control of the Detector

##### *5.1.7.1.1 Operational Control*

Stable and safe operation is a critical issue for the running of the Silicon Tracker. There is an automated response to changes in the data taking conditions or possible misbehaviours of the detector, running within the framework of the general DELPHI slow controls system [22]. From the safety point of view the temperature of the detector is the most critical parameter. This is monitored with the use of 44 PT100 platinum thermometers[34], placed at the entry and exit of various parts of the cooling system. In the case of the pixels some are mounted on the detectors themselves. The temperature variations seen on the inlet and outlet of the cooling are between 4°C and 7°C and are stable to 0.1°C. Thresholds are set both in software and hardware to check for failures in the cooling system. Other parameters, such as bias voltages and currents, low voltages to electronic drivers and ambient humidity, are also continuously recorded.

For the pixels a CAEN[35] controller supervises power supplies and threshold settings. A procedure was developed to detect and to react to an anomalous number of hit pixels, associated to either a high background or to a misbehaving chip. It is necessary to protect the detector against accidental very high occupancies because the power consumption of a cell connected to a hit pixel increases by a factor of about 10. If the required power exceeds the supply characteristics the detector may then trip off, leading to a jump in temperature of around 12°C, affecting badly the detector stability. A typical situation where this can arise is during the LEP injection, when the occupancy can be up to more than 2 orders of magnitude greater than nominal. When the occupancies are abnormally high the crate processor supervising the data acquisition notifies the slow control system, which raises the thresholds [23]. In addition, for the special period of LEP injection when the backgrounds are expected to be high, the discriminator thresholds are always automatically raised.

#### *5.1.7.1.2 Monitoring Data Quality*

Online data quality checking is essential for commissioning the detector and for fast feedback during LEP physics conditions. The Silicon Tracker monitor program [24] reads the data stream of the entire detector, working within the environment of the DELPHI online monitoring system [25]. The routines can quickly detect dead, noisy or inecient modules. A simplied track search has been implemented for the barrel detector. An online calculation of the residuals between tracks and hits gives information on the stability of the layers. For the pixel detector the occupancy of the modules supplies information on the threshold settings and the quality of the noisy pixel suppression mask.

Trace plots document the development of several quantities as a function of time. As an example, Figure 5-12shows residuals as measured online in 1996 for the Outer layer of the barrel detector. The LEP high energy periods at $\sqrt{s}$ = 161 GeV and 172 GeV can be distinguished, separated by the summer break to install further cavities in LEP.

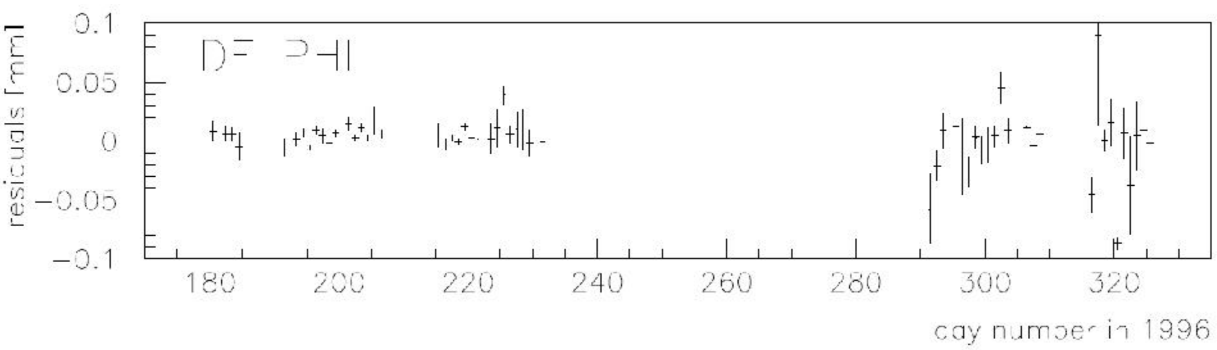


*Figure 5-12: Trace plot of online calculated track residuals in the Outer layer of the barrel detector.*

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[34] from MINCO Products Inc., Minneapolis, Minnesota, USA

[35] Costruzioni Apparecchiature Elettroniche Nucleari S.p.A.,Via Vetraia, 11, I-55049 Viareggi, Italy

### 5.1.7.2 Noise and Efficiency

#### *5.1.7.2.1 Signal over Noise of Strip Detectors*

Figure 5-13 gives a summary of the most probable signal over noise (S/N) values for the minimum track length in the silicon shown as a function of the strip length seen by the amplier. Due to the flipped modules on the Closer and the Inner layers one can distinguish, on each side of the module, between the *R*¤ and *Rz* signals. The highest S/N value is measured for the ministrip detectors, which have relatively short strips. Note that the strip length is only one of several sources of noise affecting the S/N level. Other sources could be inter-strip capacitances depending on the detector pitches, detector current, capacitances between metal layers for the double-metal layer detectors, noise from the voltage supply or charge loss effects from intermediate strips to the second metal layer. The noise performance of the detectors without n-side readout is well described by an offset and a linear capacitance dependence taking into account the length of the strips and routing lines. The additional n implants cause an extra noise contribution which dominates the other contributions (for other discussions see [9, 26]).

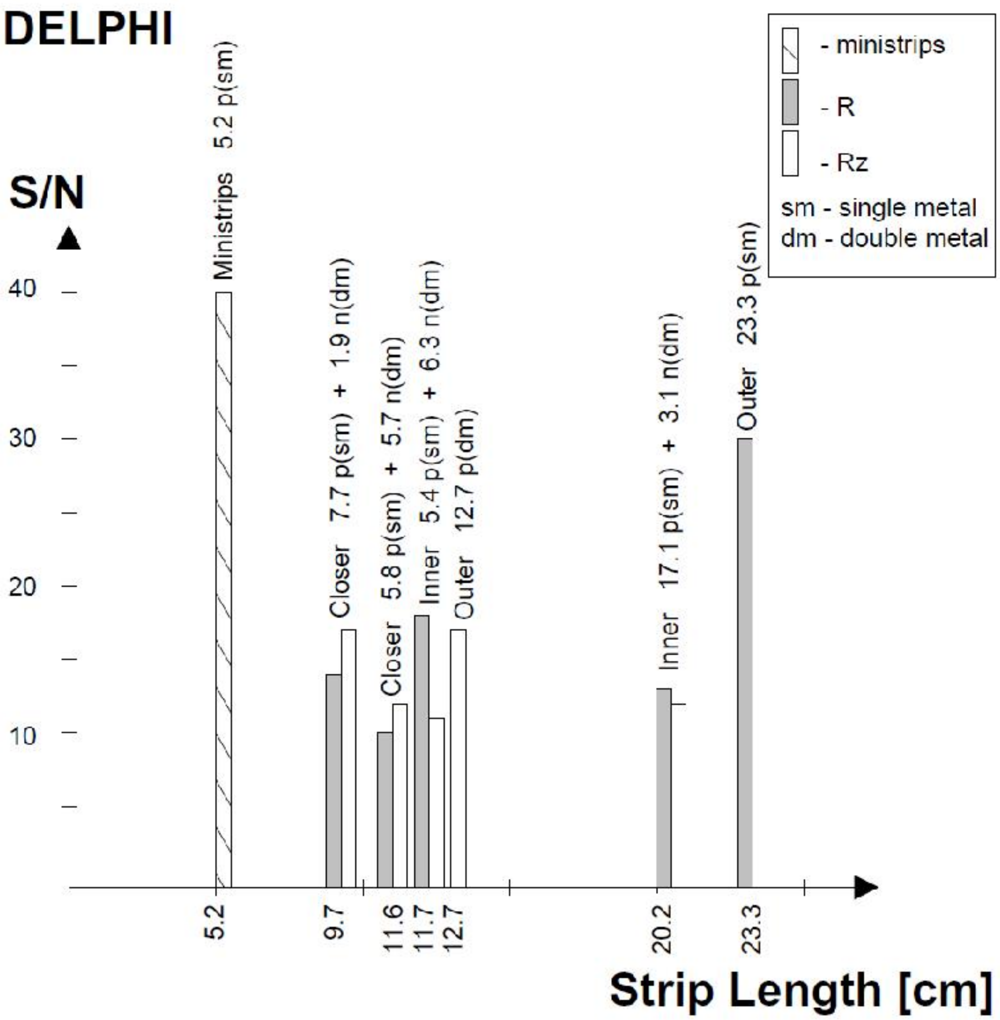


*Figure 5-13: Signal over noise performance of the strip detectors. For each measurement the corresponding length of p and n strips connected to the amplifer is shown, and it is indicated if a double-metal layer is used. The number shown is the most probable value of the S/N.*

### *5.1.7.2.2 Pixel Noise*

The threshold settings for the pixel detector are placed at a level where the expected sensitivity to charged particles is 99%. The level of systematically noisy pixels for this threshold setting is around 0.3%, as can be seen in Figure 5-7. Most of the noisy pixels are removed by masking in the crate processor, and the remaining ones, defined as those which respond to more than 1% of triggers, are flagged and removed off-line. Figure 5-14 shows day by day the mean number of noisy pixels which were flagged during the runs at $\sqrt{s}$ = 172 GeV. With the suppression mask unchanged, their number rises slightly in time. On day 324 a new mask was applied.

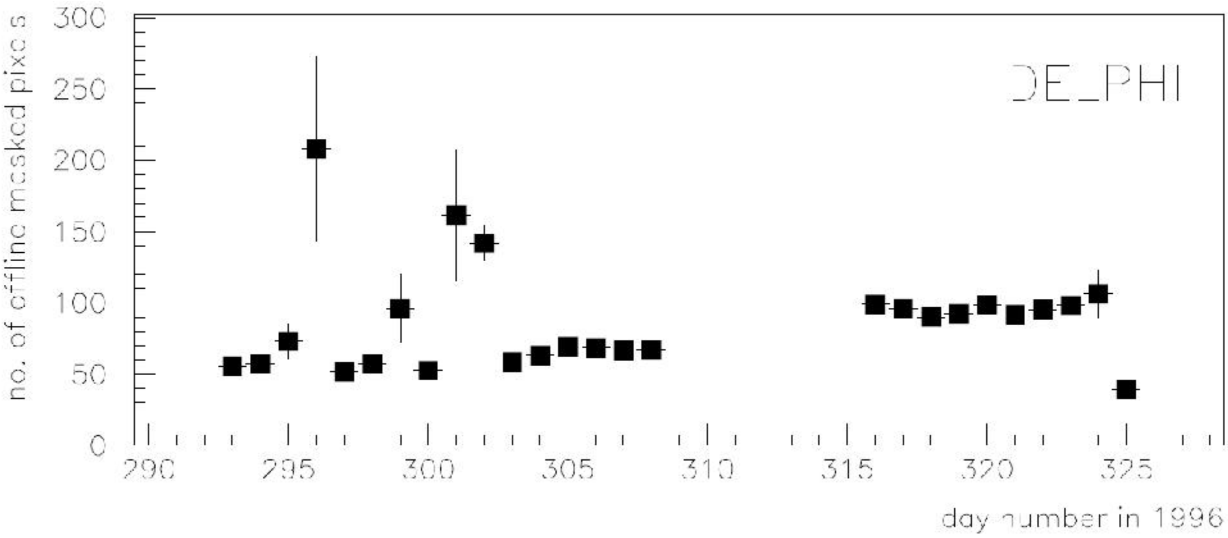


*Figure 5-14: Trace plot of the mean number of pixels agged as being noisy in addition to those masked in the crate processor. They are removed from the data offline.*

After the noisy pixel removal, the hits which remain originate from particles traversing the detector and from random noise. The number of pixel hits is shown in Figure 5-15 for three classes of events. Hadronic events, where some tracks pass through the forward region, have a mean number of pixel hits of about 4.5. Background events, which are triggered events with no tracks pointing to the primary vertex, include beam gas interactions with large showers at small angle and result in a tail extending to very large numbers of hits. Such events become more prevalent at higher energies. A class of events was also selected with just two charged tracks reconstructed in the barrel. These events should produce no physics background in the forward region, and the mean number of pixel hits places an upper estimate on the random noise of 0.5 ppm.

### *5.1.7.2.3 Efficiency*

The efficiency of the barrel part was studied using good quality tracks from hadronic events. The tracks were required to have a minimum momentum of 1 GeV/c, be reconstructed with a minimum number of track elements from other detectors, and lie within the polar angle range 27° < ¯ < 153° Tracks with a hit in two layers were taken and extrapolated to the third layer, where a hit was searched for. An identical analysis was performed on a Monte Carlo sample simulated with a fully efficient Silicon Tracker, and all results were normalised to this. Excluding dead and noisy detectors, the chance of finding the *R*¤ hit associated with a track for the 1996 data was found to be 93.5%, 98% and 99% for the Closer, Inner and Outer layers respectively, and 99.4% of tracks have at least two associated *R*¤ hits. The problematic detectors made up a total of 10%, 2% and 2% in the three layers, and had a lower average eciency of around 60%. The probability of finding the *z* hit associated with a track which has an *R*¤ hit associated in the same layer was found to be 96% for the Closer layer and 98% for the Outer layer.

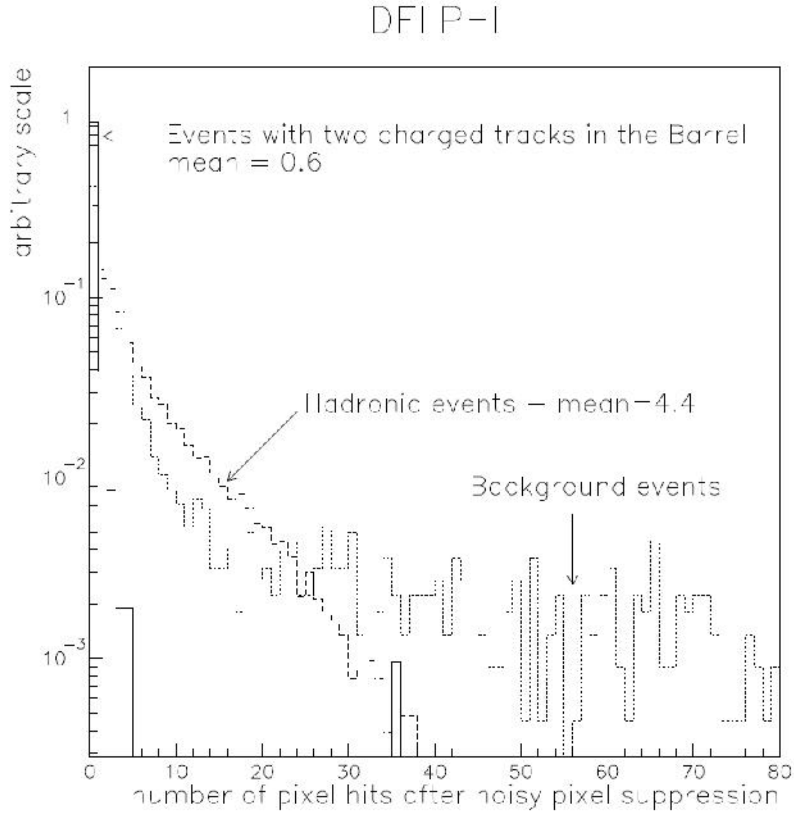


*Figure 5-15: Mean number of pixels per event for hadronic events, background events, and events with two charged tracks only in the barrel. The data are taken from the 1997 $Z^0$ running period. The normalisation is arbitrary.*

The efficiency of the pixels was studied using tracks which pass through a region where neighbouring plaquettes overlap and have at least one hit in a silicon layer other than the one being studied. If a track registers a hit in one plaquette, a second hit is searched for around a 3σ window in the neighbouring plaquette. Figure 5-16a shows the average efficiency measured in each pixel crown using this technique. It was possible to measure the efficiency for 130 plaquettes. Of the remaining plaquettes, 16 were dead or partially dead, and the remaining 6 were overlapping with bad detectors or did not have a good enough alignment. The average efficiency excluding bad plaquettes was 96.6%.

The eciency for the ministrip part of the detector is determined using electrons from the dominant process of t-channel small angle Bhabha scattering. The electrons are required to be tagged by the shower signature in the forward electromagnetic calorimeter, and have at least one hit in a silicon layer other than the one being studied. A set of 18000 Bhabha events was selected for the analysis. When a track registers a hit in the overlap region between two plaquettes a hit was searched for in a 3σ window in the neighbouring plaquette. The results of this measurement are shown in Figure 5-16b where the efficiency based on 90 ministrip plaquettes is shown for each ministrip crown. An average efficiency of 98.5% was measured. The remaining 6 dead plaquettes were excluded from the measurement.

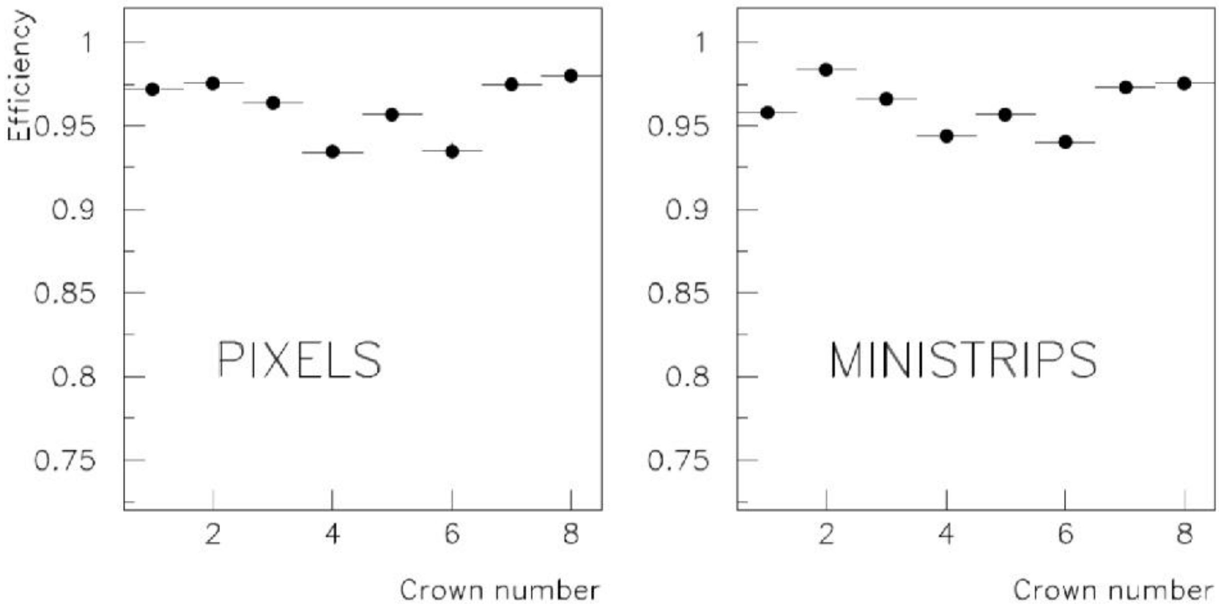


*Figure 5-16: Efficiency for the pixel and ministrip crowns as measured in the 1997 data using tracks (see text). The average quoted eciencies do not take into account dead modules.*

#### 5.1.7.3 Alignment

The Silicon Tracker is the basis of alignment in DELPHI. To avoid propagation of errors from the other tracking detectors, the only measurement taken from outside the Silicon Tracker when performing the alignment is the momentum of the tracks.

The alignment of the full Silicon Tracker is performed in four steps.

The first one consists of an optical and mechanical survey of the individual components and of the whole structure of each half-shell. Being made before the installation inside DELPHI, the survey gives no information on the relative position of the two half-shells. Also the geometry of either half-shell after installation might slightly differ from the results of the survey, due to possible deformations of the mechanical structure.

The second step uses cosmic tracks to commission the detector before the start of LEP running and to make a rough prealignment of the two half-shells with respect to each other and to the other tracking detectors of DELPHI.

The last two steps, final alignment of the barrel and of the VFT, uses tracks from $e^+e^-$ collisions, to perform 4 tasks: parametrisation and correction of the mechanical deformations, refinement of the survey for each half-shell, relative alignment of the two half-shells and external alignment of the whole Silicon Tracker. The alignment procedure for the barrel is similar to that used for the 1994-95 Vertex Detector, which has been described in detail elsewhere [27].

#### *5.1.7.3.1 Survey of the Silicon Tracker*

The survey stage [28] is different for the different detector components and it requires both optical and mechanical measurements. Barrel and ministrip modules are individually measured by a camera[36] mounted on the same 3D machine[37] used for the mechanical survey. This measurement provides the position of all strips on either side of a module with respect to high precision reference spheres fitted onto the hybrids.

After assembling all modules into half-shells and half crowns, a 3D survey of detector layers and reference spheres is made with a high precision touching probe system, which provides the relative positions of all modules within one substructure.

The pixel detectors are surveyed in two steps. After the chips are bump-bonded and the ceramic support is glued to the detector, the two-dimensional position of the external detector corners and the ceramic are determined with a microscope with respect to pads close to the detector corners. These pads have a well known position on the detector mask and dene the position of the pixel array. They are chosen as a reference as they remain visible during the assembly. The kapton cables are then attached and the tested module mounted on the support. Its position, given by the location of the two corners plus the measurement of the module's plane, is related to that of three spheres mounted on the support. After all modules are mounted, the VFT crowns are joined to the barrel support and the positions of the spheres with respect to the barrel are measured.

The intrinsic accuracy of the survey is below 10 µm, but the overall precision of the description of the actual detector in DELPHI is limited by deformations which occur after the survey. The main kinds of coherent deformations which can be expected are:

- There may be a twist of the barrel around the *z* axis or a tilt of the barrel endrings which maintains them parallel to each other (as the distance between the endrings is fixed by the module length). The effect of such distortions on the VFT crowns is illustrated in Figure 5-17.
- The pixel detectors are mechanically bound to the support at one end only, and experiencing the pressure of the kapton cable may bend in polar angle. This can affect the local *z* coordinate by up to a few hundred microns.
- The modules in the barrel may develop a bowing relative to the survey. The effect is small for the Closer layer but its amplitude might be as large as large as 150 µm in the middle of a module of the Inner or Outer layer. This effect is related to stress during installation and to variations in humidity.

[36] Mondo Machine Developments Ltd., Leicester, UK.
[37] POLI S.p.A., Varallo Sesia, Italy.

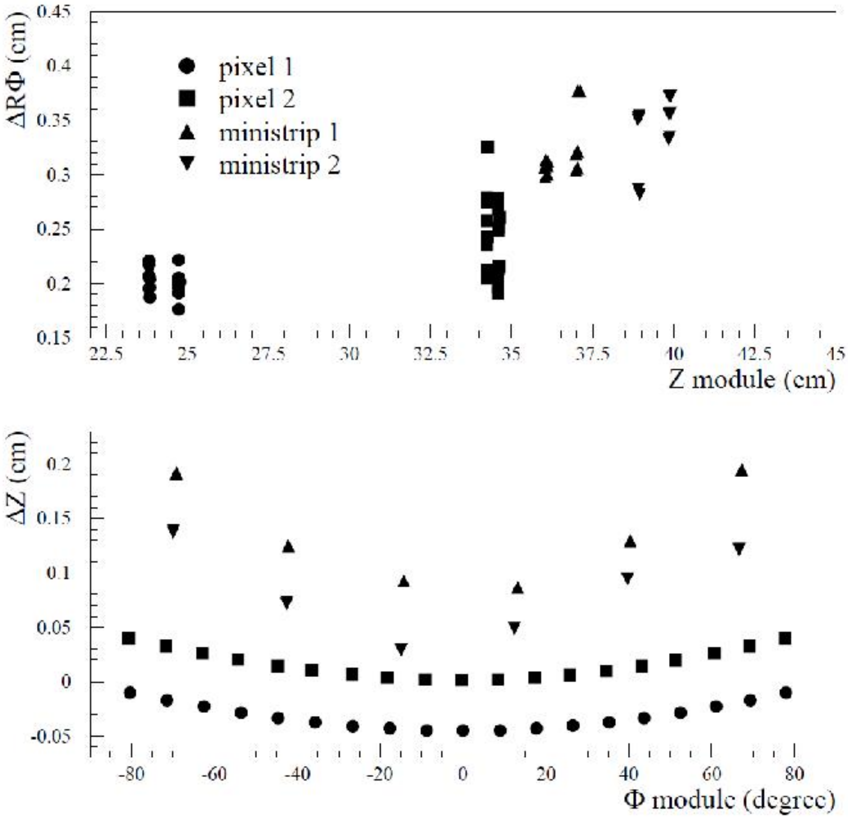


*Figure 5-17: Differences between the survey and the final VFT alignment for the fully equipped quarter of 1996; the biggest movements found are a torsion of the structure, visible as an R¤ shift dependent on the z of the layers, and a rotation of the crowns about the vertical axis, which shows up as a systematic dependence of the translation in z on the position of the module.*

The study of the actual distortions of the Silicon Tracker structure after installation into DELPHI is performed with reconstructed tracks as described in the next sections.

#### 5.1.7.3.2 Alignment of the Barrel

The Barrel alignment procedure uses three following classes of tracks: $e^+e^- \Rightarrow \mu^+\mu^-$ events at the $Z^0$ pole, tracks passing through the overlap regions of two adjacent modules and tracks passing through only one module of each layer. The only information taken from the other tracking detectors of DELPHI is the track momentum.

The survey is used as a starting point, and before the alignment begins, the following effects are parametrised and corrected for:

- It appears that the barycentre of the holes (and electrons) created by a particle crossing a detector and collected by the implant lines does not correspond exactly to the mid-plane of the detector, but are shifted towards the p-side by 10-20 µm. This effect was first established with data from the 1994-95 Vertex Detector [27, 29].
- The shape and amplitude of the bowing mentioned in Section 0 is parametrised using overlap residuals.
- A possible time or fill dependent acolinearity and momentum imbalance of the LEP beams affects the trajectories of the muon pairs at the $Z^0$ pole used for alignment. Both effects are measured by the LEP machine group.

The alignment procedure then uses tracks through overlaps to align the Outer layer, muon pair tracks to align the Closer layer with respect to the Outer layer, and finally the Inner layer is aligned with respect to the other two layers. The actual procedure deals with 408 degrees of freedom and consists of a complex sequence of elementary steps repeated iteratively [27].

At LEP2 the integrated luminosity delivered at the $Z^0$ peak is a factor of 50 below that of previous years, resulting in a limited number of muon pairs useful for alignment. The performance of the alignment procedure is hence statistically limited for the impact parameter resolution at large momenta. However in the momentum interval relevant for *b* hadron decay products the effect is negligible. The lack of dimuon events is partially compensated with the use of cosmic tracks.

As an illustration of what is gained by the internal alignment together with the correction of elastic deformations, Figure 5-18 displays the distribution of the residuals between the two hits of a track passing through the overlap of two adjacent modules, before and after internal alignment, for *R*¤ hits and for *Rz* hits.

### *5.1.7.3.3 VFT Alignment*

The VFT alignment procedure uses track elements already reconstructed with the use of the other tracking detectors. The procedure optimises the VFT module positions by minimising the $\chi^2$ of tracks refitted over all track elements. The weight of the track in the fit depends on the polar angle and the combination of tracking detectors contributing to the track. In addition, the intrinsic VFT resolution and the constraints from overlapping modules are exploited. The global parameters at the level of each quadrant are determined first, then the individual plaquette parameters are fitted, allowing 6 degrees of freedom per plaquette. The overlap between the first pixel layer and the Barrel Inner layer at 20° < ¯ < 25 provides the link between the Barrel and the VFT global alignment.

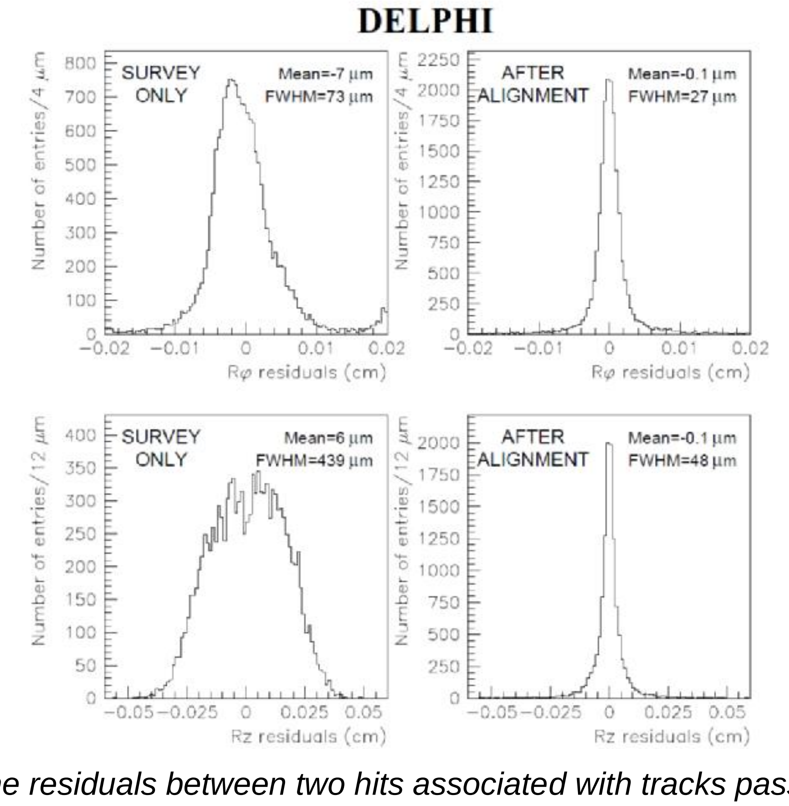


*Figure 5-18: The residuals between two hits associated with tracks passing through the overlaps between modules. R¤ residuals (upper plots) and z residuals (lower plots) are shown for the detector positions obtained from the survey (left side) and given by the final alignment (right side).*

#### 5.1.7.4 Alignment Performance

In the barrel, the precision of the alignment can be checked using residuals between overlapping modules, track hit residuals, and impact parameter distributions. The best hit precisions are found in the Outer layer, as these are used as constraints in the alignment procedure. The distributions are shown in Figure 5-19 for the *R*¤ and *Rz* projections. Taking the appropriate geometrical factor into account, the hit precision found is 9 µm in the *R*¤ projection and 11 µm for perpendicular tracks in the *Rz* projection. The Closer layer shows similar distributions with a hit precision of 11 µm in the *R*¤ plane and 14 µm in *Rz*.

The excess of these numbers over the Outer layer precision indicates the quality of the alignment. The Inner layer makes a less important contribution to the impact parameter resolution and is important mainly for pattern recognition and redundancy. In *R*¤ the hit precision in this layer is measured to be 13 µm and in *Rz*, measured for polar angles below 37° only, is 70 µm in the detector plane.

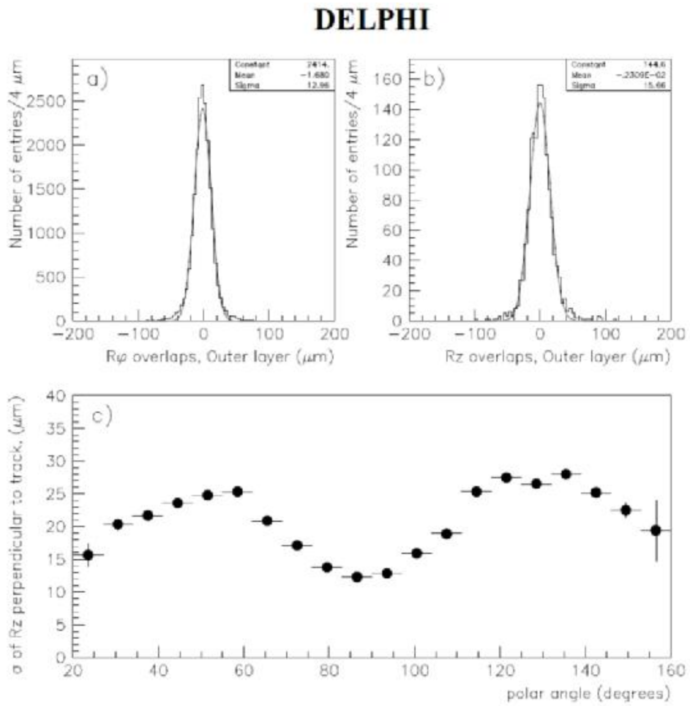


*Figure 5-19: Plots a) and b) show residuals in overlapping detectors of the Outer layer in the R¤ and Rz projections. The width must be divided by $\sqrt{2}$ to obtain the single hit precision. Plot c) shows the Rz precision of hits in the Outer layer in the direction perpendicular to the track.*

An independent check of the alignment is provided by the impact parameter resolutions, displayed in Figure 5-20. The top plot shows the impact parameter in *R*¤ as a function of momentum, and is fitted with the function 28 µm $\oplus$ 71/($p$ $\sin^{3/2}\theta$) µm, where *p* is the track momentum in GeV/c. The bottom plot shows the impact parameter resolution in *Rz* for perpendicular tracks and is tted with the function 34 µm $\oplus$ 69/$p$ µm. In both these cases the first term is the asymptotic value and the second term contains the effects of multiple scattering. Taking into account the correct geometrical factors one estimates effective hit precisions of 8 µm and 9 µm in the two coordinates. Figure 5-20b combines tracks at all theta angles and fits the *Rz* impact parameter resolution with the function 39 µm $\oplus$ 75/($p$ $\sin^{5/2}\theta$) µm

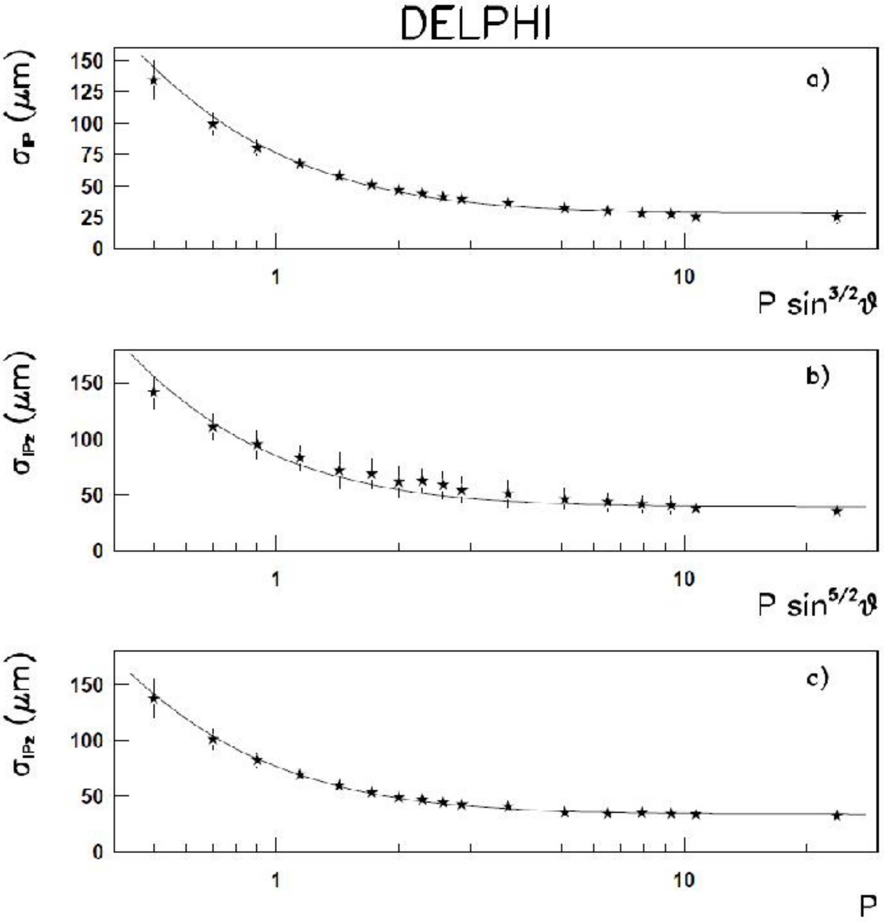


*Figure 5-20: Impact parameter resolutions as a function of momentum, for: a) R¤, b) Rz (all tracks), and c) Rz (perpendicular tracks) projections.*

The internal alignment of the VFT is also checked using tracks passing through overlapping detectors. For the pixels, the expected resolution depends on the cluster size, which is a function of the track incidence angle. Tracks from the primary vertex traverse the first and second pixel layer at incidence angles $\psi$ in the polar direction of 57.5° and 40.5° respectively. The incidence angle in the $R$¤ direction is close to 90°. The majority of produced clusters are either single hits or double pixel hits split in the polar direction. Neglecting charge diffusion effects, the angular dependence of the single pixel hit rate is given to first order by the following equation:

$$N = (1 - \frac{d}{\Delta}); \qquad d = \omega \times \tan\psi - \frac{t}{c} \times \omega \times \sin\psi \qquad (1)$$

*Equation 5-1: Angular Dependence of the single Pixel Hit Rate*

where ω is the thickness of the depletion layer, Δ is the pixel pitch, c is the charge deposited by a minimum ionising particle and the parameter t is given by the detector threshold (about 10ke$^-$ is used). Knowing this rate, a simple geometrical consideration of ionisation charge sharing in the pixel sensitive volume leads to the following expression for the expected detector resolution:

$$\sigma^2(\psi) = \frac{1}{12}\frac{(d^3 + (\Delta - d)^3)}{\Delta} + (\frac{\kappa}{c} \times \omega \times \sin\psi)^2 \qquad (2)$$

*Equation 5-2: Calculation of the expected Detector Resolution*

Here $\kappa$ is a parameter describing the effect of charge fluctuations (about 5ke⁻ is used), and the other symbols are the same as in equation 1. The expected distributions are displayed in Figure 5-21 as a function of $\psi$. The resolutions in the data are measured in the detector plane for the *z* local (polar) direction and the x local (*R*¤) direction. The values extracted are overlaid on the prediction. For the x local points the incidence angle is the same for the pixel I and pixel II layers, and these points are shown together. The measured points are seen to be very close to those predicted by the simple model.

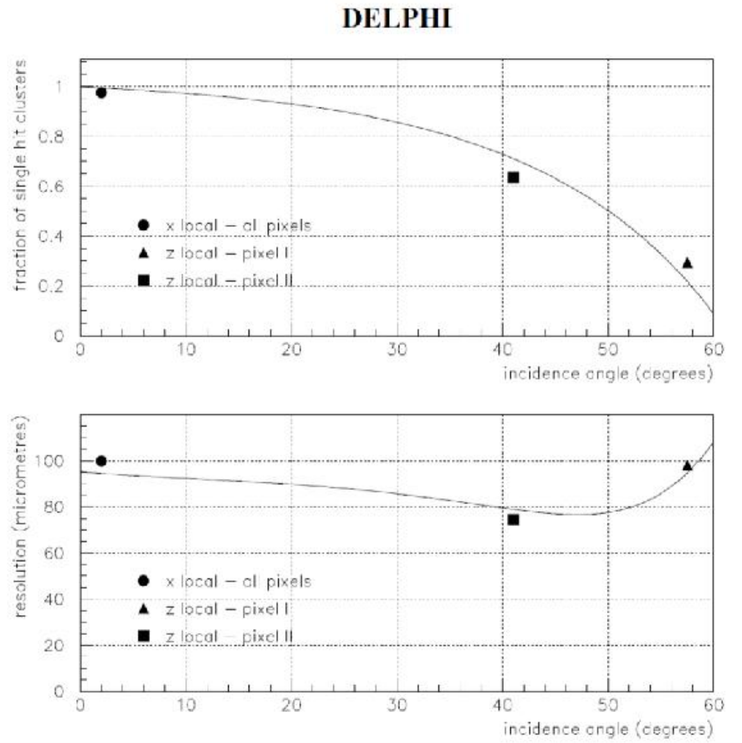


*Figure 5-21: Resolution expected in the pixels as a function of track incidence angle (solid line) shown together with the values measured in the data.*

Figure 5-22 shows the residuals for the ministrip overlaps. The internal hit precision derived from this plot is 30-33 µm, as expected from previous studies [26].

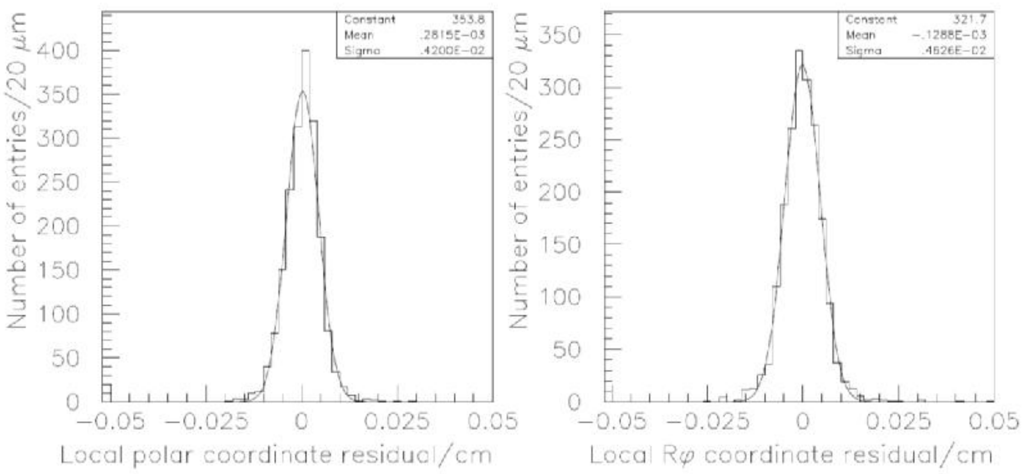


*Figure 5-22: Local alignment residuals for ministrip modules. To derive the internal hit precision the widths must be divided by $\sqrt{2}$.*

### 5.1.8 Physics Performance

#### 5.1.8.1 Performance of *b*-Tagging in 1996 Run

For the Barrel the *b*-tagging performance of the Silicon Tracker is important for physics analyses. Figure 5-23 shows the *b*-tagging eciency [30] as a function of the polar angle of the event thrust axis. The full line is the performance of the 1994-95 Vertex Detector, which had a 3-layer coverage down to a polar angle of 42° and a Closer layer coverage down to 25°, and the points show the performance in 1996 of the new Silicon Tracker. It can be seen that the new extended barrel maintains the performance of the previous Vertex Detector in the central region, while there is a clear gain in the region between 25° and 42°.

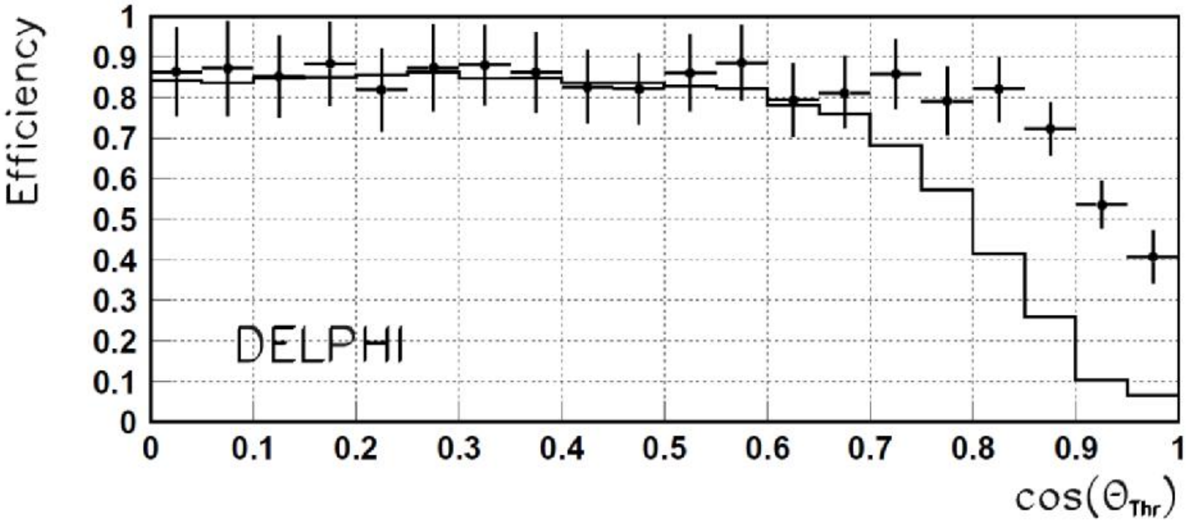


*Figure 5-23: The efficiency versus cos(¯$_{Thr}$) for the new microvertex detector (points) and the previous shorter one (full line).*

One of the main physics goals of LEP2 is the Higgs search. A good efficiency for the signal and a good background rejection can be reached as shown in Figure 5-24, where the efficiency for an event tag in the region |cos(¯)| ≤ 0.9 is shown for ZH, hA, WW events and the QCD background.

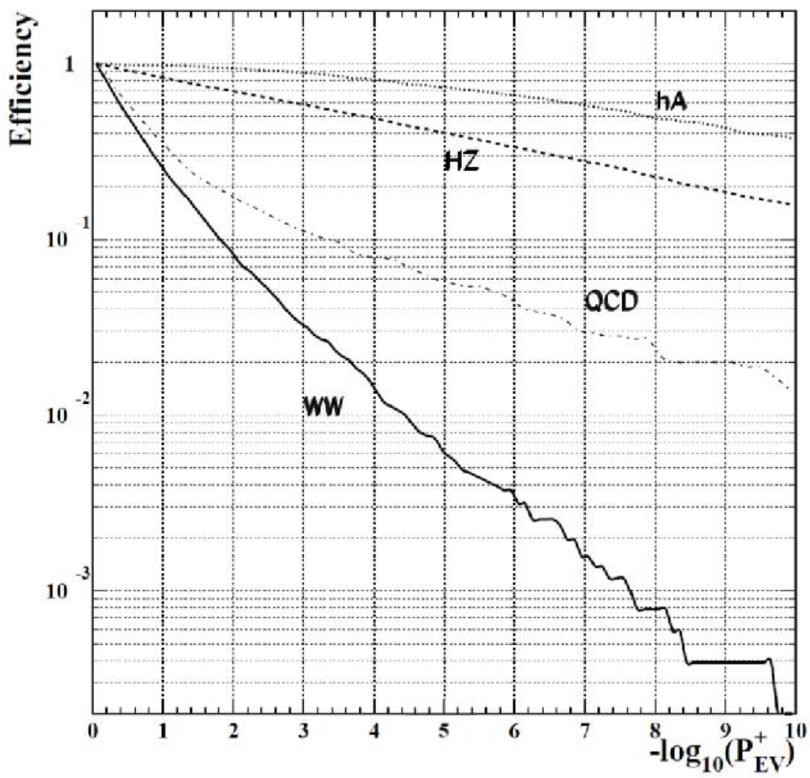


*Figure 5-24: The efficiency for an event tag $P_{EV}^{+}$ is shown for hA, ZH, WW events and the QCD background (taken from [31]).*

#### 5.1.8.2 Improvement of Tracking in the VFT Region

The tracking situation in the forward region is considerably different to the barrel part of the Silicon Tracker. A description of the DELPHI tracking detectors may be found in [3]. In the forward the TPC measures only short track elements of particles leaving through its endcap, and there are fewer *R*¤ points provided by the jet chamber of the Inner Detector. Additional tracking information is provided by the forward chambers before and after the Forward RICH and by the measured track elements in the drift tube of the Forward RICH itself. However the track finding efficiency using these chambers alone is limited by interactions in the material in front of them. The situation in the forward region is summarised in Figure 5-25 which shows the number of coordinate points reconstructed by the inner tracking chambers as a function of polar angle. The overlap between the various detectors can be seen, as well as the decreasing importance of the TPC and Inner Detector in the forward.

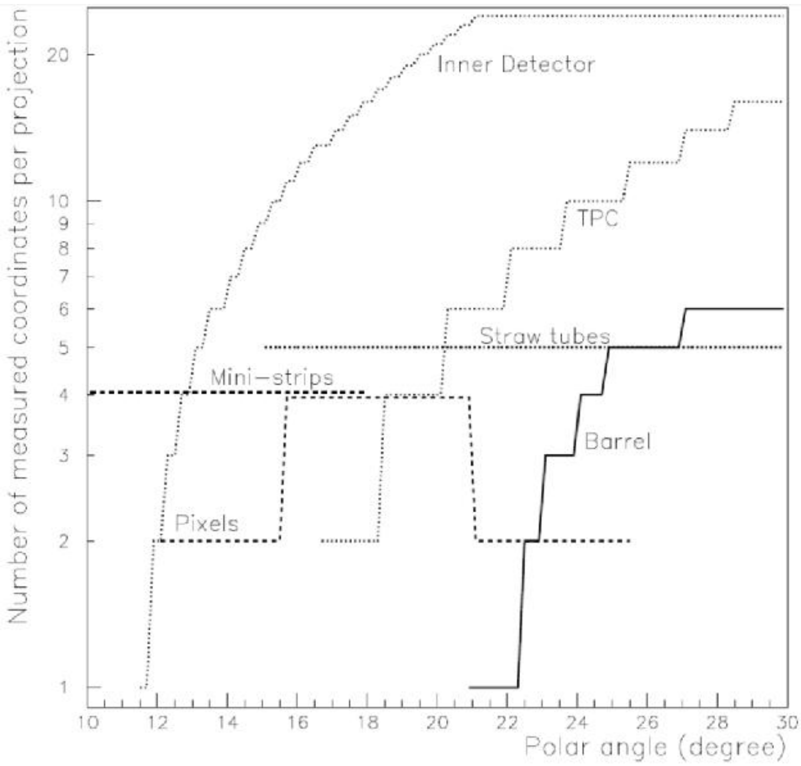


*Figure 5-25: Number of coordinates measured by the innermost tracking detectors shown as a function of polar angle for the forward region. One entry is shown for each R¤ and each Rz measurement. The vertical scale is logarithmic. The detectors shown are the TPC (minimum radius 40 cm), the Inner Detector Jet Chamber (R¤ information, minimum radius 12 cm), the straw tubes (R¤ information, minimum radius 23 cm) and the layers of the Silicon Tracker. The outer tracking detectors not shown in this plot provide measurements at |z| > 160cm.*

The VFT space point measurements are fully integrated in the DELPHI reconstruction. The VFT standalone pattern recognition is used to reconstruct track elements pointing to the primary vertex out of multiple hits in the different layers. These elements are used in the global reconstruction as a seed for the track finding. Measurements in the ID are extrapolated to the VFT to pick up the correct track element before extrapolating to the other detectors. The extrapolations may also be improved by constraining the VFT track element to the primary vertex.

Figure 5-26 shows the improvement due to the VFT in the number of tracks reconstructed in the forward region. Simulation studies show that for 91% of the particles crossing the VFT the hits are associated to the tracks, and the purity of the associations is 94%. This compares with a purity of 98% for the Barrel.

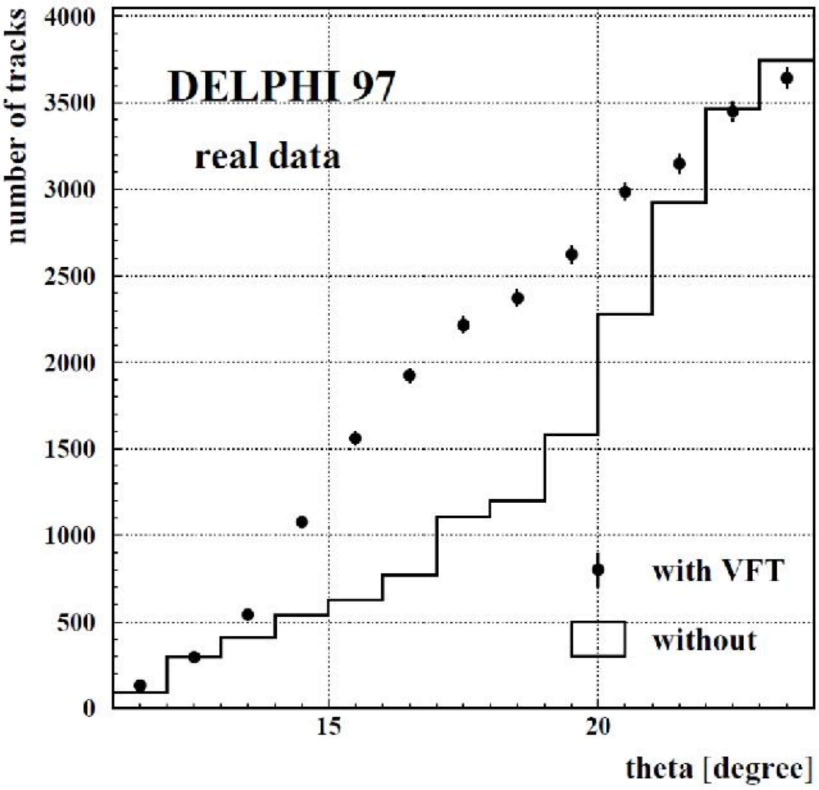


*Figure 5-26: Number of reconstructed tracks useful for physics analysis reconstructed with the VFT (dots) and removing the VFT from the tracking (line) shown as a function of polar angle [32].*

### 5.1.9 Conclusions

The final upgrade of the DELPHI Silicon Tracker, to enable DELPHI to meet the physics requirements of LEP2, was completed in 1997 and has accumulated about 70 $pb^{-1}$ of high energy data. The Silicon Tracker contains 888 detecting elements having a total active surface of about 1.6 m² of silicon, has 1399808 readout channels and covers polar angles between 11° and 169°. It consists of the Barrel, extending from 21° to 159° and playing the role of vertex detector, and the Very Forward Tracker (VFT) in the form of two silicon endcaps, providing standalone pattern recognition and increasing the track reconstruction efficiency between 11° and 25°.

The Barrel contains 640 AC coupled microstrip silicon detectors, arranged in three layers at average radii between 6.3 and 10.8 cm. The 149504 electronics channels read signals collected on the strips which give *R*¤ measurements with a readout pitch of 50 µm and *Rz* measurements with pitches varying between 42 µm and 176 µm. The material in the sensitive region is kept to a minimum by the use of double-sided detectors, double-metal readout and light mechanics.

Each of the two VFT endcaps contains two layers of silicon pixel detectors and two layers of ministrip detectors. The pixels have dimensions of 330 x 330 µm² and there are 1225728 in total. They are connected to the readout electronics channels using an industrial bump bonding method and their readout is performed by a sparse data scan circuit. The AC coupled ministrip detectors (96 in total, corresponding to 24576 electronics channels) have a strip pitch of 100 µm and a readout pitch of 200 µm.

The complete Silicon Barrel and a large part of the VFT was already in operation during the 1996 data taking at LEP2, and the complete Silicon Tracker was installed in 1997.

### 5.1.10 Acknowledgements

The detector could only be constructed thanks to the dedicated effort of many technical collaborators in all laboratories participating in the project. We wish to express our appreciation to all of them and in particular to R. Boulter and A. Rudge.

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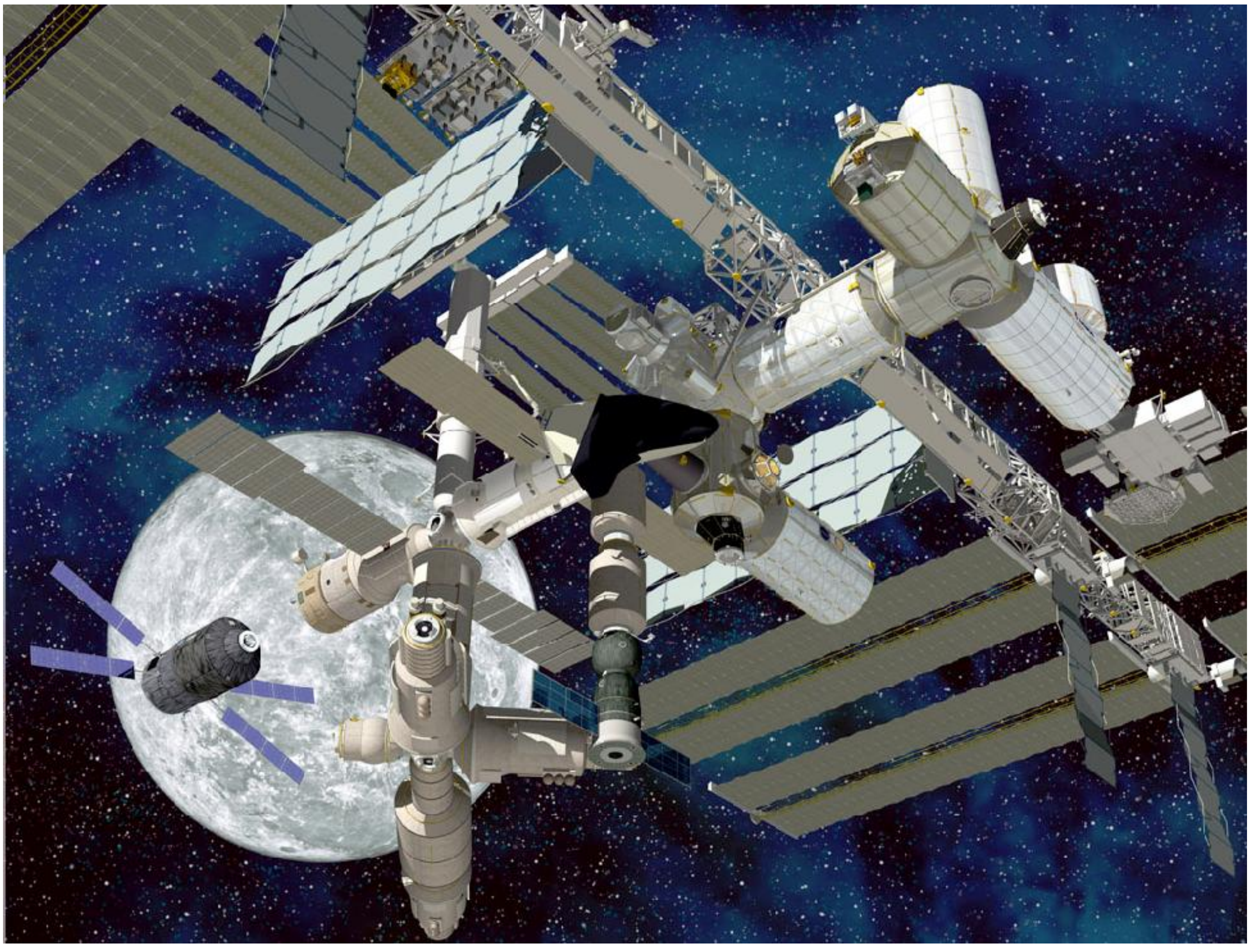

*Figure 5-27: The ATV as it approaches the International Space Station*

The following paper presents the Navigation and Communication System of the ATV (Automated Transfer Vehicle). The ATV is a project of ESA, intended to re-supply and re-boost the International Space Station (ISS). What makes this project so special is that for the first time a spacecraft will initiate and commence a docking maneuver in fully autonomous mode, only relying upon on-board calculations, derived from Absolute/Relative GPS Data and Information from an Optical Rendezvous System for the final docking sequence. **ISS crew safety is the uttermost principle leading to exceptional requirements**, constraints and design drivers for the Navigation and the Communication Subsystem of the ATV.

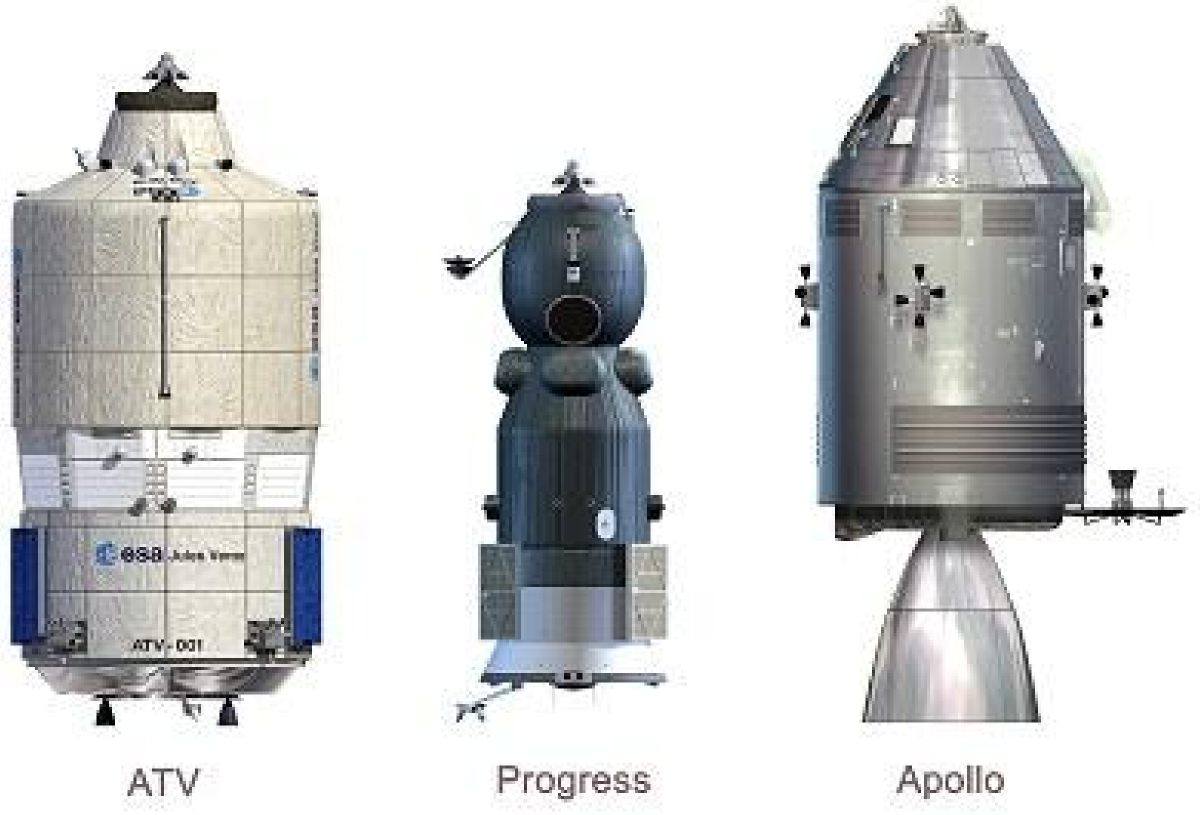


*Figure 5-28: ESA's ATV in comparison with other vehicles utilised for space station supply; the Russian Progress and NASA's Apollo System*

## 5.2 *Safety and Redundancy: "The Navigation and Communication Systems for the Automated Transfer Vehicle" ([E] Aguilar-Sanchez, Paris, Allard, & Frischauf, 1999)*

Published in Aguilar-Sanchez, I., Paris, D., Allard, F., Frischauf, N.: The Navigation and Communication Systems for the Automated Transfer Vehicle, in *Vehicular Technology Conference, 1999 IEEE 49th* (1999), pp. 1187-1192 [E]

### 5.2.1 Introduction

The ATV project is designed to contribute to the logistics servicing of the International Space Station, allowing the European Space Agency to meet part of its obligations as a partner in the ISS Programme.

#### 5.2.1.1 The ATV Mission

The ATV mission consists of:

- Delivery of dry cargo in a pressurized cargo (up to 5500kg), water (up to 840kg) and gases (up to 100kg)
- Disposal of ISS waste (up to 5500kg in the pressurized environment and 840kg of liquids)
- Refueling of the ISS (up to 860kg of propellant
- ISS re-boost and contribution to attitude control of the ISS (up to 4950kg of propellant are foreseen for this, ATV mission depending), corresponding to an ISS altitude increase of approximately 50km.

The net transportation capability of the ATV amounts to 7.6t to 8.2t, depending on the type of mission to be flown. The precise combination of cargo items is defined by the ISS needs at the time of flight and is specified in the flight and cargo manifests. 9 ATVs will be built to fly at average intervals of about 12 months.

The ATV is launched by an ARIANE 5 and is designed to dock at the Russian Service Module, part of the Russian segment of the ISS. Upon departure from the ISS, the ATV is designed for destructive re-entry. The phasing of operations is described in the figure below:

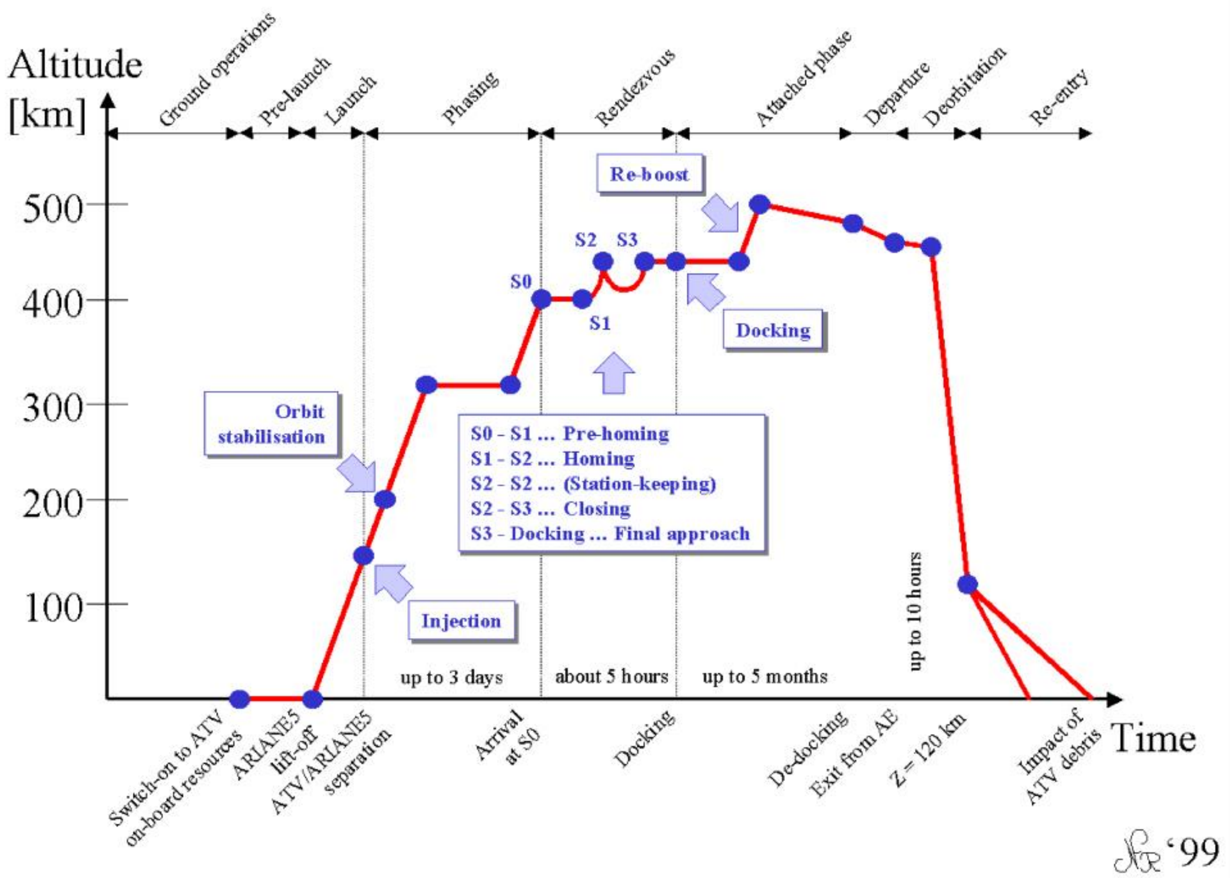


*Figure 5-29: ATV Operations Profile*

The ATV shall successfully complete a planned mission with a 98% probability.

Since Rendezvous and Docking is one of the most critical periods during the mission, safety issues of the ISS and its crew are the main drivers for the mission requirements associated with this phase. Therefore the ATV design includes systematic redundancy and Failure Detection Isolation and Recovery (FDIR) capabilities. The latter enables the ATV to fulfill its mission after any first failure and ensures ISS safety after any second failure.

#### 5.2.1.2 The ATV Spacecraft

The ATV is designed to rely on its on-board automation and resources, to interact with the ATV Control Center and the ISS and to use external resources such as GPS data and communication links via TDRS. Implementing these capabilities makes the design and development of the ATV a challenging endeavor and has an effect on:

- Mission and vehicle management
- ATV motion control (GNC)
- Docking System (Russian Docking System – RDS)
- Power generation and storage, including 4 Sun-tracking solar arrays
- Thermal control
- S-Band Communications with ISS and TDRS
- ISS services and cargo accommodation

The ATV is presented below:

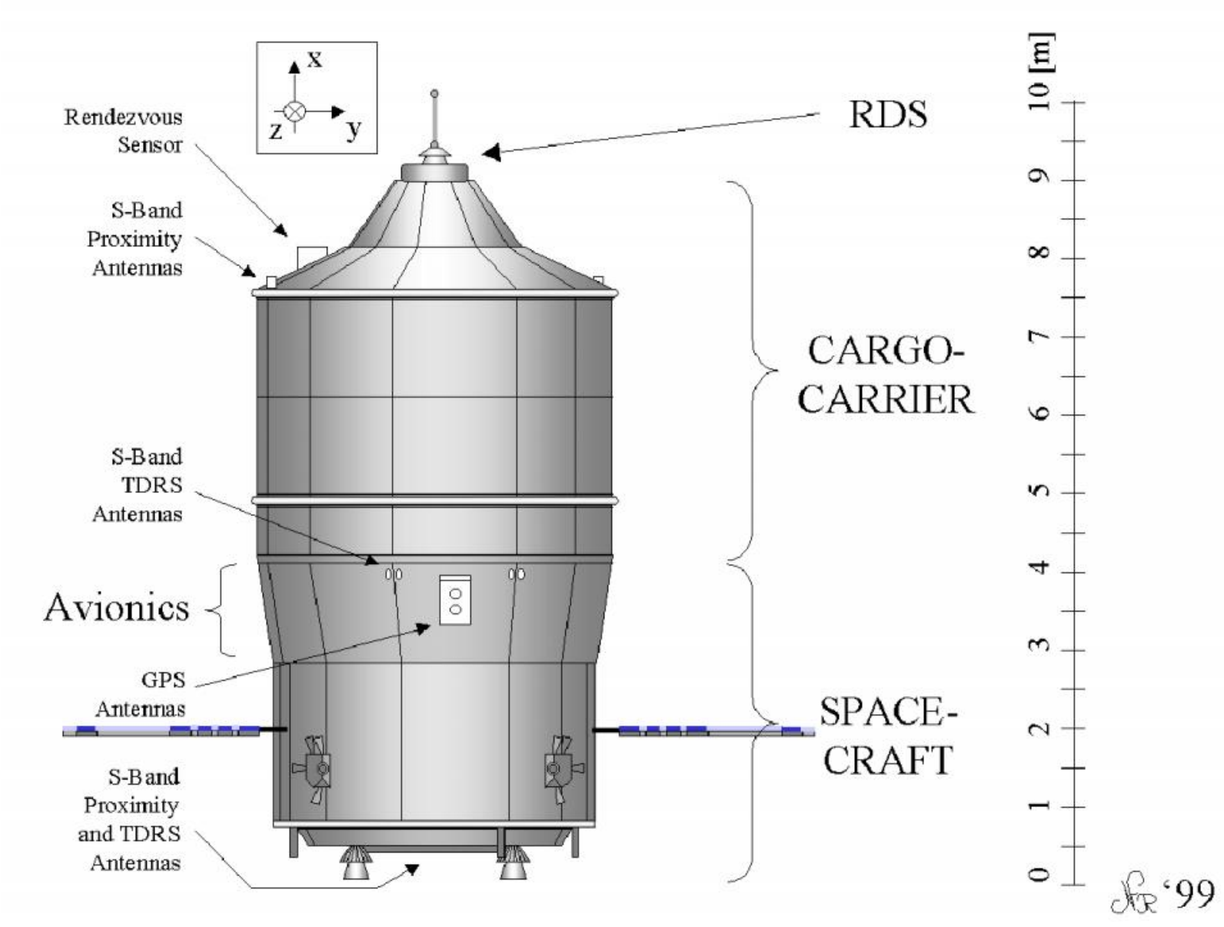


*Figure 5-30: Main Elements of the ATV*

The Rendezvous and Docking phase requires novel capabilities. It is during that phase that the most intensive use is made of two key ATV capabilities: GNC and Communications.

The GNC sensing capability is based on relative GPS (comparing the ATV GPS data with the ISS one) and attitude sensors (gyros, Earth sensors and Sun sensors). Rendezvous sensors are used when the ATV is close enough to ISS (less than 500m).

The Communication capability is based on two S-Band links: one with the ATV-CC via TDRS to ensure a Telecommand/Telemetry link with the ground, the other one directly with ISS to receive ISS commands (such as the abort command) and ISS GPS data.

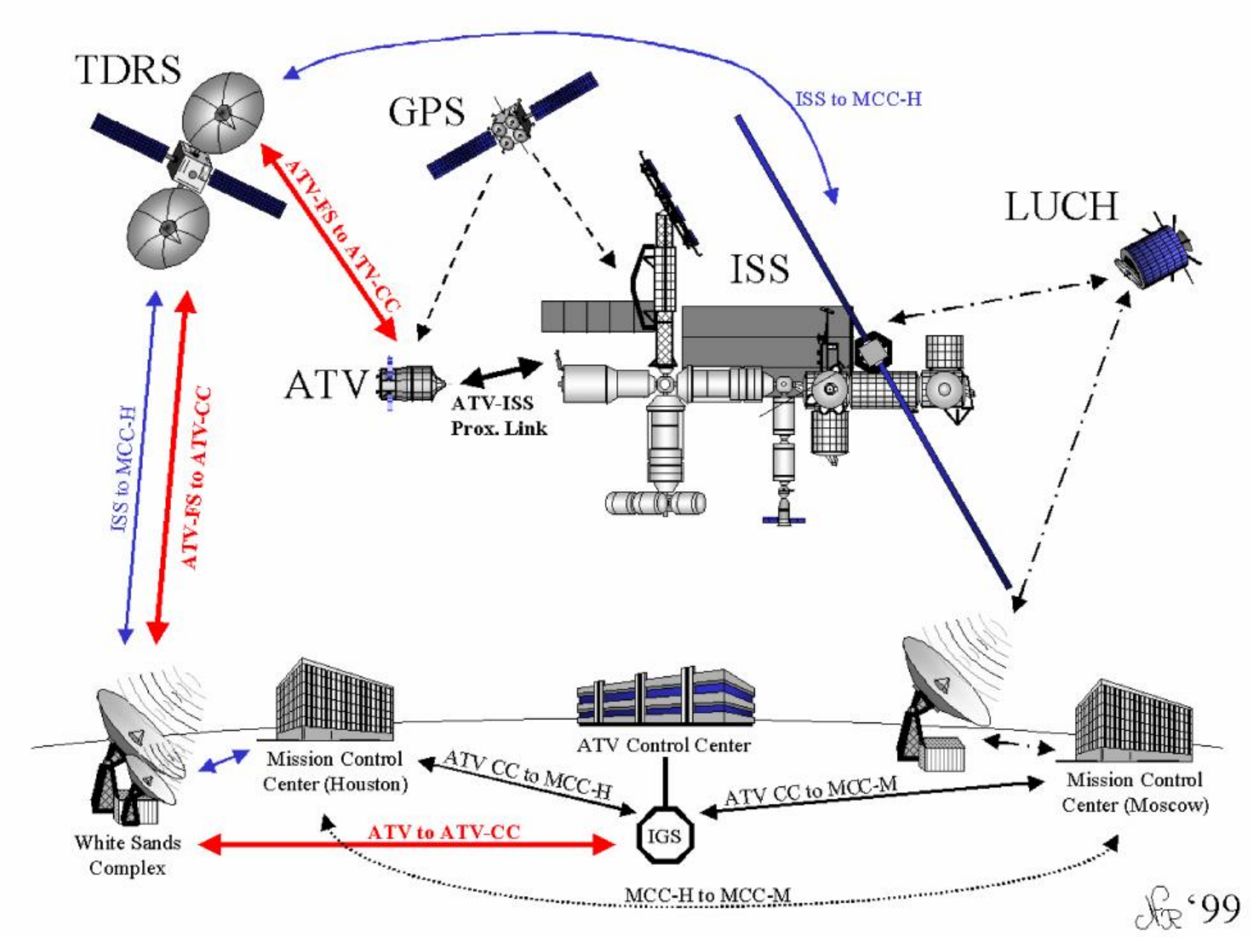


*Figure 5-31: The Communications Environment of the ATV*

## 5.2.2 The ATV Navigation System

The navigation system is in charge of generating the estimated absolute and Relative State vector (attitude, attitude rate, position and velocity) in accordance with the needs of the various flight phases of the ATV/ISS- rendezvous. This paper has been produced to present the required ATV GPS navigation technology.

### 5.2.2.1 Absolute GPS Navigation (AGPS)

The AGPS navigation filter determines the orbital position of the ATV during the rendezvous phase. This information is used as the primary means of navigation at the beginning of the rendezvous when the proximity link between ATV and ISS is not yet established or when this link cannot be maintained like it is possibly in case of an ATV wave-off command.

The AGPS filter structure is based on an extended Kalman filter, which uses the raw measurements of a GPS receiver in order to update a propagated orbital state vector. The navigation vector also includes the GPS receiver clock drifts. The processed measurements are the GPS pseudo-range (accuracy: 5 m, 1$\sigma$) and the Doppler which is used to estimate the pseudo range rate (accuracy: 5 cm/s, 1$\sigma$). Full observability of the AGPS state vector is ensured only with at least 4 GPS satellites visible. An all-in-view processing is applied for AGPS.

The major drivers for the achievable AGPS performance are the Selective Availability and the ionospheric effects. The typical order of magnitude of AGPS 1σ-accuracy is better than 60 meters in position and 0.1 m/s in velocity.

#### 5.2.2.2 Relative GPS Navigation

Relative GPS navigation (RGPS) is the primary navigation means for the long-range leg of the rendezvous operations, i.e. from acquisition of the proximity link between ATV and ISS at 30km down to 500m (because of the concern about the GPS Multipath effects). The RGPS-navigation filter architecture is shown below:

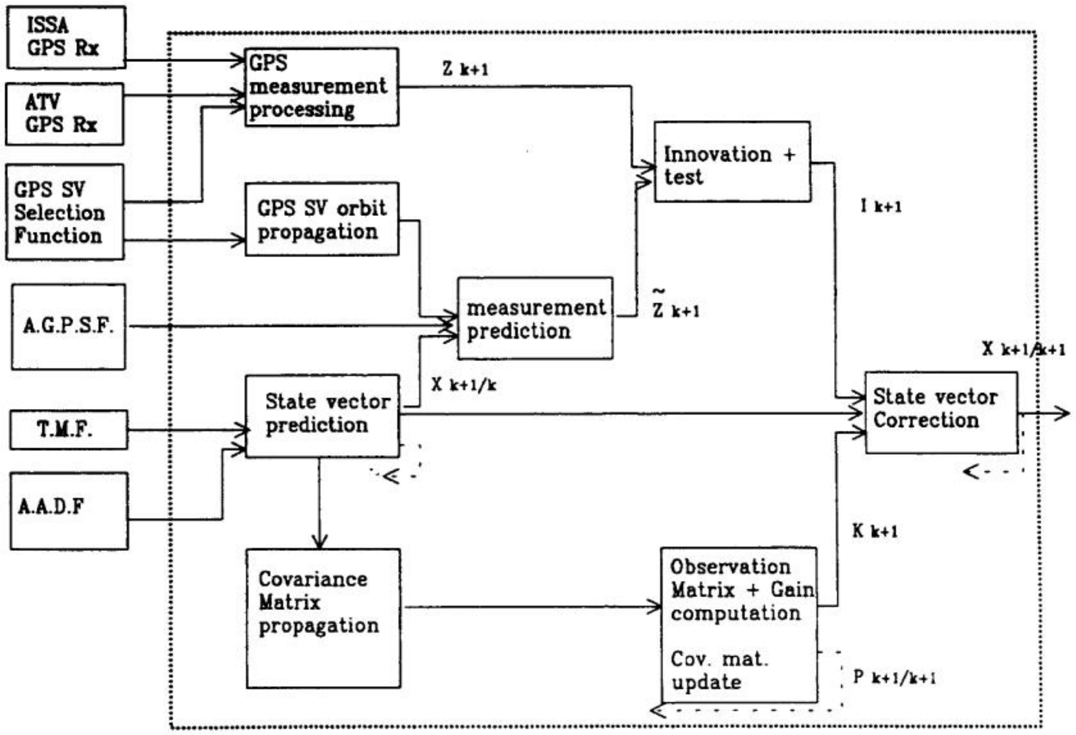


*Figure 5-32: Relative GPS-navigation Filter Architecture*

The basic principle is to use the single differences of the GPS raw data, obtained quasi-simultaneously by the ATV and the ISS GPS receivers. This allows a direct cancellation of common error sources in the GPS signal as seen by both vehicles like selective availability, ionospheric effects.

A linearized Kalman filter scheme is used in order to perform optimal hybridation of the GPS differential observables with a relative dynamics model (first order Clohessy-Whiltshire model). The processed measurements are the GPS pseudo-range and the carrier cycle count (accuracy: 6 mm, 1σ) which is back differentiated in order to estimate the average range rate over the last measurement interval.

The RGPS State vector is of dimension 8 as it includes not only the relative state vector but also the relative clock bias and drift. Full observability of the RGPS state vector is obtained only with at least 4 common visible GPS satellites. This drives the antenna concept on ATV and ISS (structural blockages and Multipath effects), the attitude profile of each spacecraft and the number of channels for each receiver (more than 6). The selection of satellites is based on the best configuration of 4 (simplified volume criteria).

The relative dynamics prediction model uses the commanded thrust accelerations. The absolute S/C-attitude is needed as input for the filter in order to compensate for the lever arm between GPS antenna and center of mass. The state update algorithm contains also a rejection filter like AGPS based on innovation estimations.

The RGPS filter is run at 1-Hz frequency. The de-synchronization between the two receivers must be limited to 100 milliseconds. The RGPS filter is also capable to cope with an acquisition delay of the ISS GPS data through the proximity link of up to 2s.

With good visibility conditions and synchronization of both receivers, the typical performance of RGPS 3σ-accuracy is 5m in position and 5 cm/s in velocity when accounting for the rendezvous maneuvers. RGPS convergence time is typically a few minutes.

### 5.2.3 ATV Communication System

Both TDRS and Proximity links shall remain operational during Rendezvous, docking and departure phases.

#### 5.2.3.1 The TDRS link

Shortly after ARIANE 5 fairing jettison, the ATV will establish communication with the Ground through the NASA Tracking and Data Relay Satellite System (TDRSS) (3).

The frequencies used for this S-band link are:

- 2106.40625 MHz for the Forward (FWD) link,
- 2287.5 MHz for the Return (RET) link.

These frequencies correspond to the so-called S-band Multiple Access (SMA) service of TDRSS.

However, SMA service presents two fundamental shortcomings. First, FWD link service is time shared with other TDRSS users. Secondly, both FWD and RET services provide for limited data rates.

The so-called S-band Single Access (SSA) service, with higher EIRP and G/T performances, overcomes the above shortcomings. ATV plans to use SSA service for the most critical mission phases, e.g. launch, rendezvous.

Preliminary results indicate a coverage between 65% and 91%, according to the vehicle attitude and TDRSS constellation considered (4).

***Signal structure***

ATV will use both DG1 mode 1 (coherent) and DG 1 mode 2 (non-coherent) signals.

They have the following structure:

| FWD link |
|---|
| SQPSK<br>I channel: Gold PN code, $2^{10}$-1, 3 Mchip/s<br>Q channel: Truncated 18-stage shift register PN code, ($2^{10}$-1)*256, 3 Mchip/s |
| **RET link** |
| SQPSK<br>DG1 mode 1: Truncated 18-stage shift register PN code, ($2^{10}$-1)*256, 3 Mchip/s<br>DG1 mode 2: Gold PN code, $2^{11}$-1, 3 Mchip/s |

The following data rates have been determined: 1 kbps for FWD link; 8 and 64 kbps for RET link (5).

***Data services, protocols and command protection***

The TDRSS communication link with ATV will support the following data services: Command, Telemetry, Data load, Data dump as well as Packet Utilization Services (PUS).

Data tables, files and software replaceable units will be uploaded using Data load service. Spacecraft telemetry previously stored during non-visibility periods will be downloaded in high data rate mode with Data dump service. Various Packet-based services (PUS) will be implemented, e.g. command verification, command execution status.

Those data services will be developed using ESA’s standardized Packet Telecommand and Telemetry protocols.

The Packet Telecommand protocol includes a mode with automatic retransmission mechanism for Packet segments, the so-called Command Operation Procedure (COP-1). This mode, which ensures the highest grade of service, is used only for the TDRSS link.

The physical link protocol has been adapted to the use of a TDRS link. The acquisition of the FWD link, because of the Spread Spectrum modulated signal requires a more complex procedure (3).

NASA requires that vehicles visiting the ISS shall be protected against unauthorized command. ATV will implement for the first time for an ESA S/C a Triple Data Encryption Standard on its Telecommand link.

ESA Packet Telecommand and Telemetry standards recommend a Bit Error Rate (BER) of $10^{-5}$ for the space link. Both Block Codes (BCH FWD, RS RET) and Convolutional Coding (rate ½) are used.

***Range and range rate tracking***

The TDRSS communication link supports the provision of spacecraft range and range tracking services. Using two-way range and Doppler measurements, ATV position and velocity can be determined.

#### 5.2.3.2 Proximity link

The Proximity Communications link between ATV and the Russian Service Module of the ISS is needed during the Rendezvous, Docking and Departure mission phases in order to support the so-called Proximity Operations and in particular RGPS.

The frequencies used for this S-band link are:

- 2030.4375 MHz for the Forward (FWD) link,
- 2205 MHz for the Return (RET) link.

The selection of these frequencies took into consideration frequency compatibility not only with ATV-to-TDRS link but also with existing and planned S-band ISS communications systems (6).

A new signal structure had to be defined. Power Flux Density limits as well as RFI immunity implied the use of a spread spectrum signal. The main characteristics of these signals are:

| **FWD link** |
| --- |
| SQPSK<br>I channel: Gold PN code, $2^{10}$-1, 3 Mchip/s<br>Q channel: Gold PN code, $2^{10}$-1, 3 Mchip/s |
| **RET link** |
| SQPSK<br>I channel: Gold PN code, $2^{10}$-1, 3 Mchip/s<br>Q channel: Gold PN code, $2^{10}$-1, 3 Mchip/s |

***Range and range rate tracking***

The S-band signal is required to support the independent determination by ISS of the relative position and velocity of ATV, with accuracies of 1m (1$\sigma$) and 5mm/s (1$\sigma$) respectively.

***Data services and protocols***

In addition to Command and Telemetry, GPS raw measurements taken by the ISS GPS receiver are to be transmitted to ATV.

Data protocols for Proximity link are similar to the ones for the TDRSS link. FWD link is to be established first at PN code, subsequently with data modulation. RET link shall be established with data modulation.

Telecommand re-transmission mechanism is limited to packet level.

***Quality of service***

BER is $10^{-5}$. Communication interruption shall be minor than 3s at distances more than 100m from the station. At closer distances no interruption shall occur.

The required coverage is shown below:

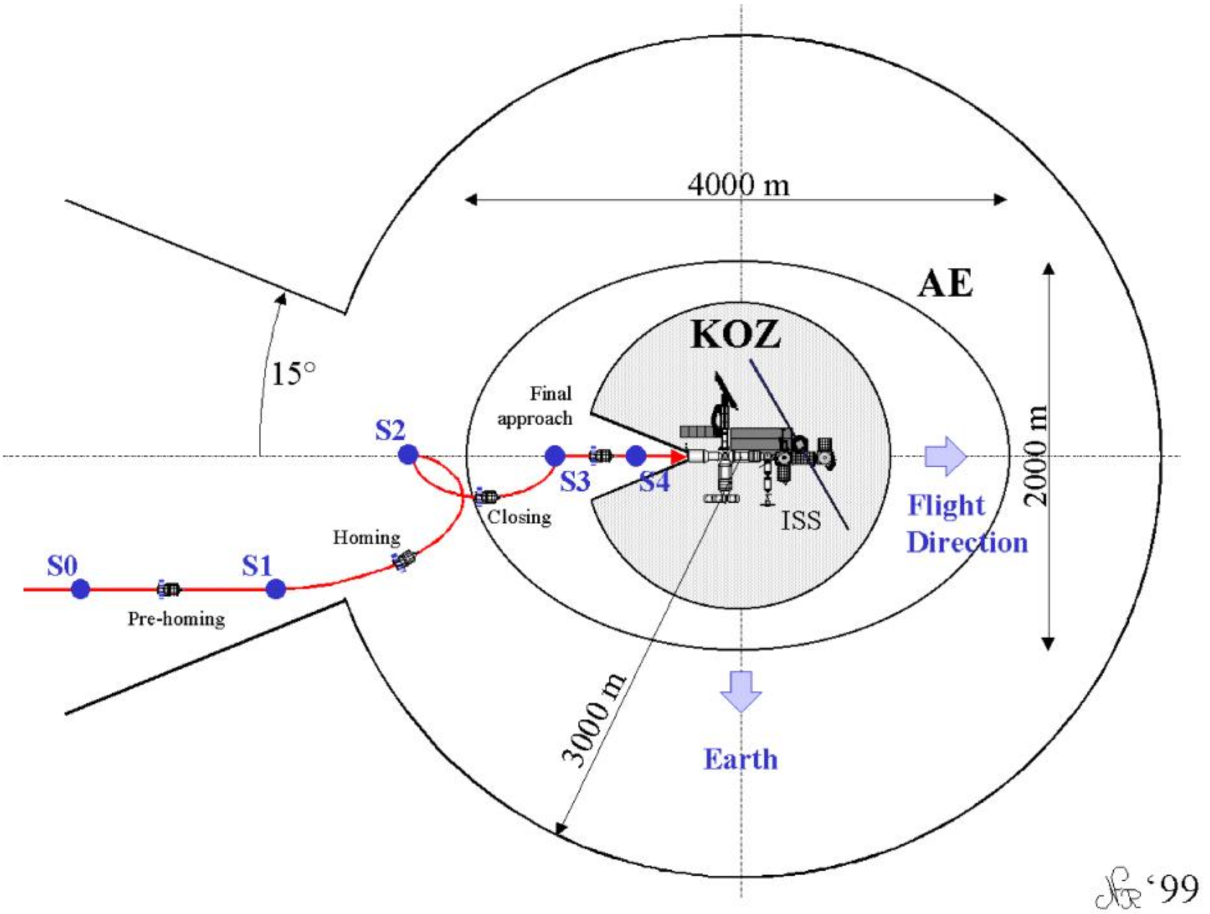


*Figure 5-33: Approach Pattern of the ATV to the ISS*

The link design and coverage analyses have presented some unusual challenges for a space communications link. Because ISS is a large structure with plenty of reflecting, shadowing, and scattering surfaces, the signal propagation is affected to a certain extent by Multipath fading. Simulations had proved this effect to be negligible for the nominal approach trajectory of ATV. This Multipath fading can be important for the spherical coverage. GTD simulations showed that coverage requirements could be attained with the RF parameters selected (6).

Both FWD and RET data rates are 20kbps.

A figure of 2s (at max.) for the time delay between GPS raw measurement at ISS GPS receiver and reception by ATV has been required.

### 5.2.3.3 Spacecraft Comms Subsystem Architecture

For the TDRS communications the following architecture is baselined (5). Two antennas, installed in the Avionics Bay of the vehicle are foreseen for nominal operation. An additional antenna for survival mode communications is installed on the Propulsion bay. A 30W Solid State Power Amplifier feeds the antennas via a diplexer. The transponder handles signal processing, including convolutional coding and decoding. The Communications Processor implements the frame and segment protocols. It is interfaced with the spacecraft computers via a MIL-1553 Bus. The spacecraft computers handle the communications management. For the Proximity chain, a similar concept is baselined. 4 antennas in total are foreseen; 2 on the front and 2 on the propulsion bay. The transponder delivers 5W RF power. An independent section of the communication processor handles Proximity protocols and I/F via a MIL-1553 Bus with the spacecraft computers.

### 5.2.4 Follow-on Work

The ATV Project has recently started the development phase. Major system choices in the areas of Navigation and Communications have been described. The following sections provide recommendations as well as a snapshot of what remains to be done.

#### 5.2.4.1 R-GPS Navigation

In the frame of the ATV rendezvous predevelopment program (ARP) ESA has predeveloped a prototype of the RGPS filter concept described in this paper (1, 2). This RGPS technique was experimented in flight on the occasion of the Orbiter to MIR missions STS 84 and 86 in order to validate this concept. ARP program has allowed deriving important recommendations for the ATV project in order to guarantee a minimum risk approach for RGPS application:

- Need to optimize the visibility of common GPS satellites between ATV and ISS by proper antenna implementation and orientation on both spacecraft
- Need to guarantee a minimum level of “twiness” between ATV and ISS GPS receivers
- Need to ensure RGPS filter robustness to occurrence of cases with less than 4 visible satellites, interruption of communications between ATV and ISS and GPS receiver carrier phase cycle slips
- Need to take care to predict about multipath effects, structural blockages especially for ISS.

These issues are presently under analysis between ESA and RSC ENERGIA/NASA.

#### 5.2.4.2 Communications

Coverage and system studies for TDRS and Proximity links will be both reviewed and completed. Main areas are:

- Launch phase coverage and operation,
- Use of TDRSS Zone of Exclusion (ZOE) satellite,
- Maximum transmit RF power during launch (corona),
- TDRSS link margins during various mission phases and operational conditions, including RFI losses,
- Proximity link coverage and frequency compatibility analyses with final Russian antenna network implementation.

Finally, communications subsystem development, integration and verification will make a reality the ATV Communications

### 5.2.5 References

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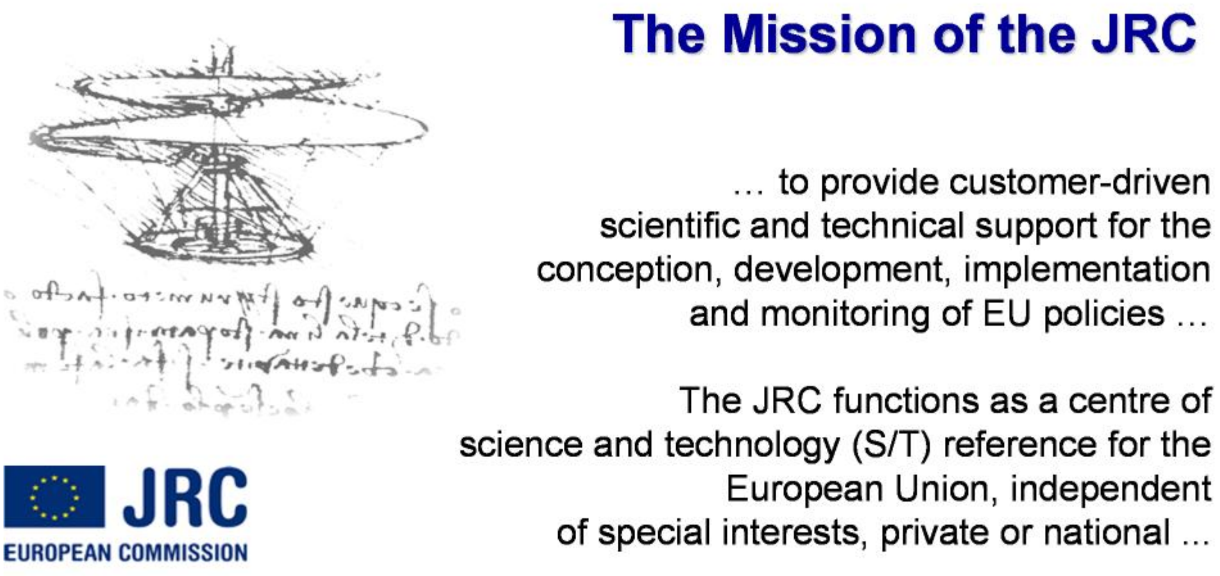


*Figure 5-34: Mission Statement of the JRC*

CERN and ESA showcase two different approaches when it comes to the development and application of technologies for their own cases, ranging from the utilisation of cutting edge technologies to achieve the highest performance to developing technologies to such a confidence level that they even may be used for manned spaceflight. **The JRC puts another flavour to this discussion; here technology development is an item of creating a “clever regulator”, hence an entity that knows the strengths and weaknesses of a particular technology to define a framework for its future commercial utilisation in the market**.

A technology that needs to be thoroughly assessed in terms of its strengths and weaknesses and in the way it should be best utilised in the market is Hydrogen, which is nothing more than the “fuel of the future” for a society with high mobility demands. The implications are of such magnitude that one speaks of the ‘Hydrogen Economy’, an economic system, which satisfies the energy demand of humanity by the production, storage, distributon and utilisation of hydrogen.

The biggest driver for this paradigm shift is the automotive industry, which is currently preparing for the generation change from the fossil fuel internal combustion engines to hydrogen based fuel cells. These fuel cells are the key element of the Hydrogen Economy, without them an efficient energy conversion is not possible. Although fuel cells originate from space, the current development for their terrestrial cousins happens at a much higher pace, s sooner or later the pendulum of technology transfer will fully swing to the spin-in side, when the space sector will acquire terrestrial fuel cells to odify them for space applications.

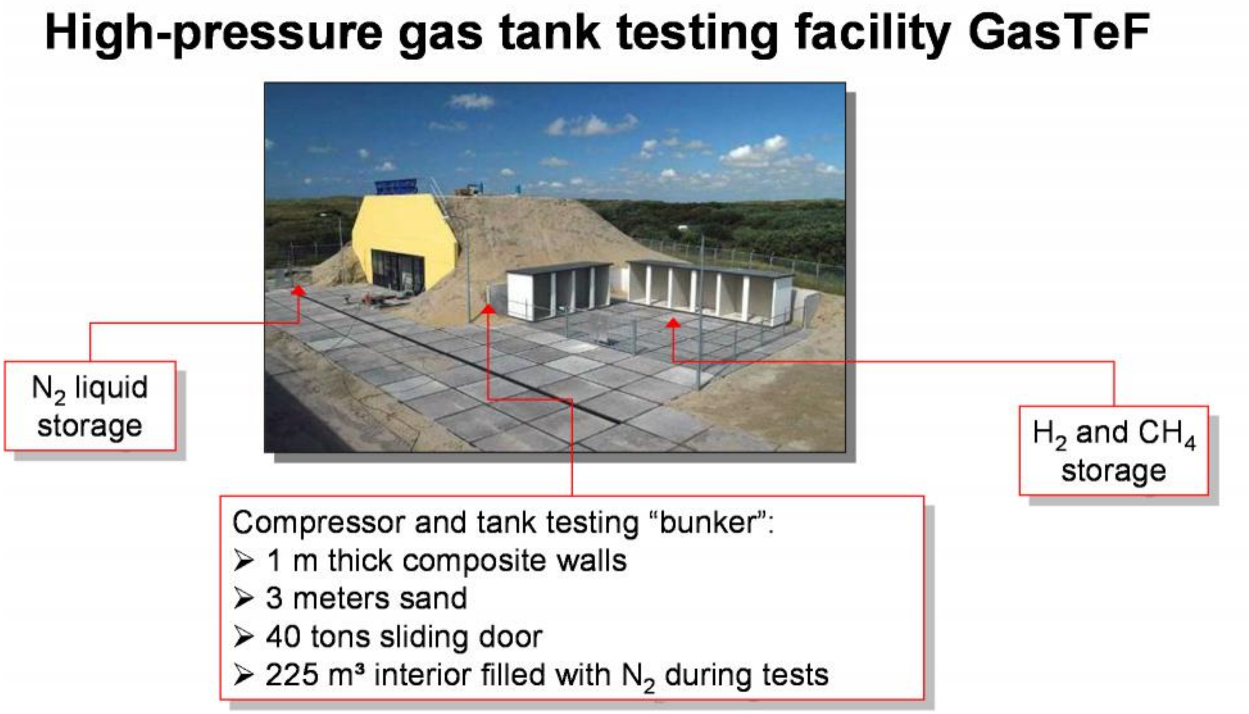


*Figure 5-35: The JRC-IET's GasTeF is a key element in assessing the opeational contraints of future hydrogen storage elements*

## 5.3 Technology Research for the Regulator: "The Role of the JRC-IE in Support of the upcoming Hydrogen Economy and its Potential Applications for Space Activities" ([F] Frischauf, et al., 2010)

Published in Frischauf, N. et al: The Role of the JRC-IE in Support of the upcoming Hydrogen Economy and its Potential Applications for Space Activities, in *IAC-2010, Prag, Czech Republic* (2010) [F]

### 5.3.1 Introduction

Hydrogen can be stored in many ways as metal hydride tanks, compressed gas, cryo-liquified, carbon nanotubes, gas micro spheres, liquid carrier or chemical storage. Which storage methodology is finally utilised is driven primarily by the application concerned. Rockets, with cryogenic engines for example demand big amounts of hydrogen with very high flow rates – hence the storage of cryo-liquified hydrogen has established itself as state-of-the-art. The automotive sector, which does not require the throughput of vast amounts of hydrogen in a short timeframe, is much more driven by safety and cost issues. While safety is imperative for the aerospace sector as well, the distinction is that it is very well trained personnel that fill the rocket with the liquid hydrogen, while it is the man on the street that will refill his own car – hence the safety aspects for automotive tanks are of a completely different nature. With this in mind and the fact that the lots in the transport sector are much bigger and customers are much more price sensitive, the automotive sector, as the biggest driver of hydrogen technology, has settled on storing gaseous hydrogen in high pressure tanks Therefore, for on-board applications, both compressed gas for automotive and liquid hydrogen for aerospace applications have established themselves as state of the art.

### 5.3.2 International Hydrogen Safety Standards and the Role of the JRC-IE

The storage of gases under pressure, including hydrogen, is a well-known technology. Nonetheless, the use of hydrogen tanks in vehicles and in particular the challenge of using very high pressures, demands stringent regulations supported by safety and performance studies. Requirements to qualify storage systems for on-road passenger vehicles have been under development primarily by the SAE International and ISO committees (respectively SAE-J2579[1] and ISO15869[2]). The push to develop safety standards for hydrogen storage well before commercialization is driven by two factors. First, by acknowledging that on-road safety is of highest priority, requirements are being developed a-priori, without waiting for any lessons learned from on-road experience. Second, taking into account that there is a high need for rapid insertion of new technologies into the marketplace, storage requirements must be capable of qualifying novel technologies for reliable and durable performance under broad conditions of use. Setting up qualification test campaigns with conditions that take into account historical failure mechanisms is helpful but not sufficient. Instead a comprehensive approach to defining extreme conditions of on-road vehicle service is required. Storage systems must function both under the stresses of normal vehicle operation and under externally imposed stresses.

Today's state of the art for hydrogen storage comprises 35 MPa (350 bar) and 70 MPa (700 bar) compressed gas tanks. Carbon fiber fully wrapped-reinforced tanks are already in use in prototype hydrogen-powered vehicles. Two types of inner liners are typically used: metal (aluminium, Cr-alloys) ones in "Type 3" storage pressure vessels and high molecular weight polymer in "Type 4" tanks, as described in ISO 15869[2]. The application of such materials comes from the need of guaranteeing impermeability of the inner liner to the hydrogen molecules whilst having the tank being as lightweight as possible.

Both SAE 2579 and draft ISO 15869 propose the following tests for compressed hydrogen storage tanks:

- Sequential exposure to impact, chemicals and cyclic stresses
- Sequential exposure to static high pressures (simulates vehicle parking) and fuelling stresses
- Exposure to hydrogen fuelling under extreme ambient temperatures
- Simulated fuelling failure (i.e. overpressures) at the end of vehicle service

It is up to specific research institutes and the industry to perform and further develop these test regimes as scientific knowledge progresses. And it is imperative to do this on global level so that the “Hydrogen Economy” vision can be realised. A major actor on European level, contributing to science, R&D and engineering, is the JRC-IE.

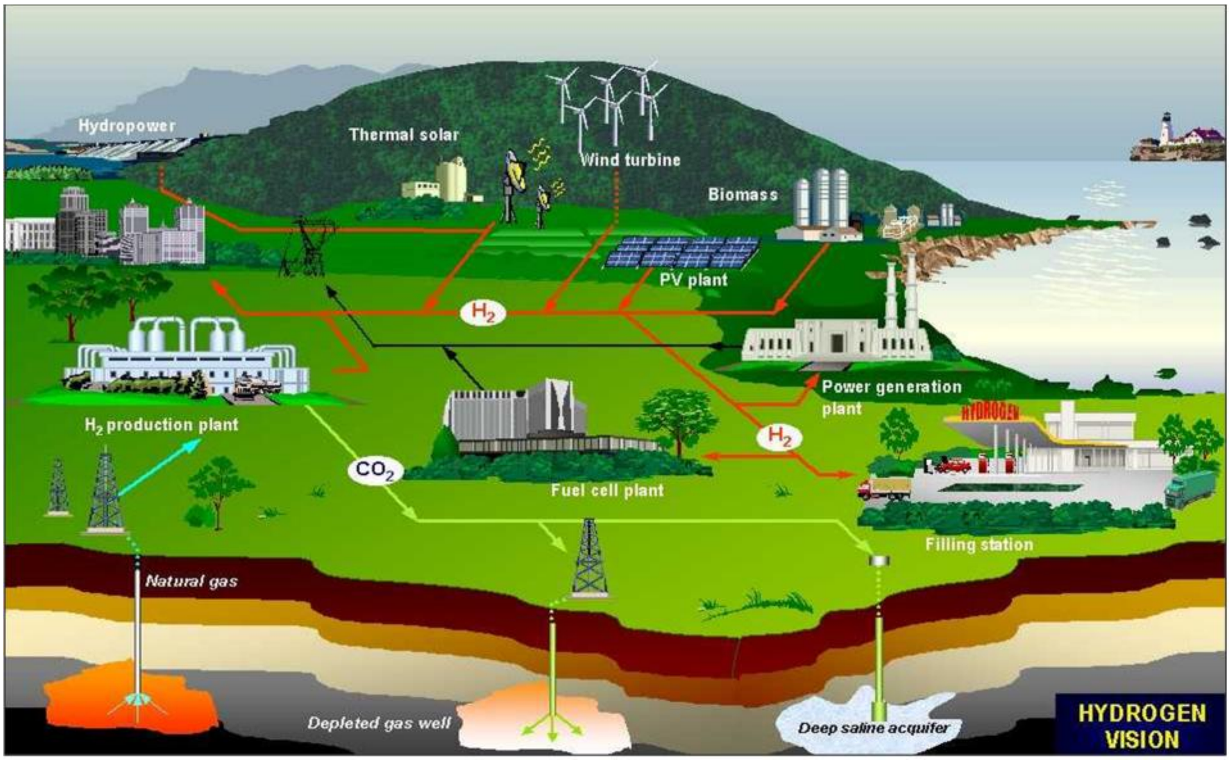


*Figure 5-36: Hydrogen Economy Vision*

The Institute for Energy (IE) is part of the Directorate General Joint Research Centre (JRC) of the European Commission. Its mission is to provide scientific and technical support for the conception, development, implementation and monitoring of community policies related to energy. Hence, the JRC-IE is involved in the European Union’s 20-20-20 strategy[3], which is a major milestone on the roadmap to the Hydrogen Economy.

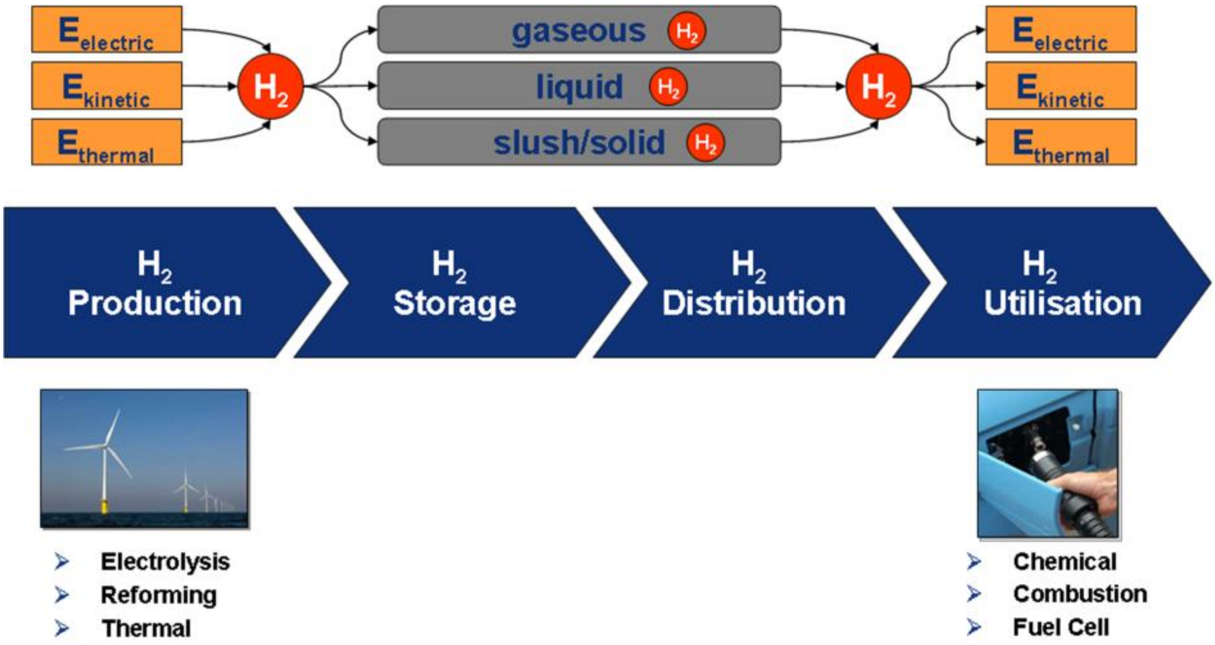


*Figure 5-37: The Hydrogen Value Chain*

The JRC-IE performs research in solar and nuclear power, power management, as well as hydrogen generation and storage, detection and usage, hence covering the whole hydrogen value chain (Figure 5-37). This paper will cover some of the JRC-IE's activities along the $H_2$ value chain, such as:

a) Hydrogen storage test activities by GasTeF,

b) Hydrogen sensor experiments by SenTeF and

c) Fuel Cell tests by the FCTEST facility

### 5.3.3 GasTeF

To carry out "expected-service performance verification tests" on full-scale high pressure vehicle tanks for hydrogen or natural gas, the JRC-IE has set up a facility, dubbed GasTeF (for Gas Testing Facility). In addition, the testing of any other high-pressure components, such as valves and pipes, is also possible.


*Figure 5-38: GasTeF – also called "the bunker"*

#### 5.3.3.1 GasTeF Description

The JRC-IE compressed hydrogen gas tanks testing facility (GasTeF) consists of a half-buried concrete bunker with an attached gas storage area. The bunker is similar to bunkers designed for the storage of explosives such as dynamite; it has double walls of heavy-concrete and is covered by a three meter thick sand layer armoured by geotextile every thirty centimetres so that it could endure a sudden energy release equivalent to 50 kg TNT[4]. In this way the impact of a potential $H_2$ explosion in the vicinity to the nuclear installation on site is fully mitigated.

The bunker is divided into three parts: a service room, the compressor room and the test room, refer to Figure 5-39. All the relevant equipment inside the bunker is explosion proof zone 2 according to the ATEX 137 EC directive[5].

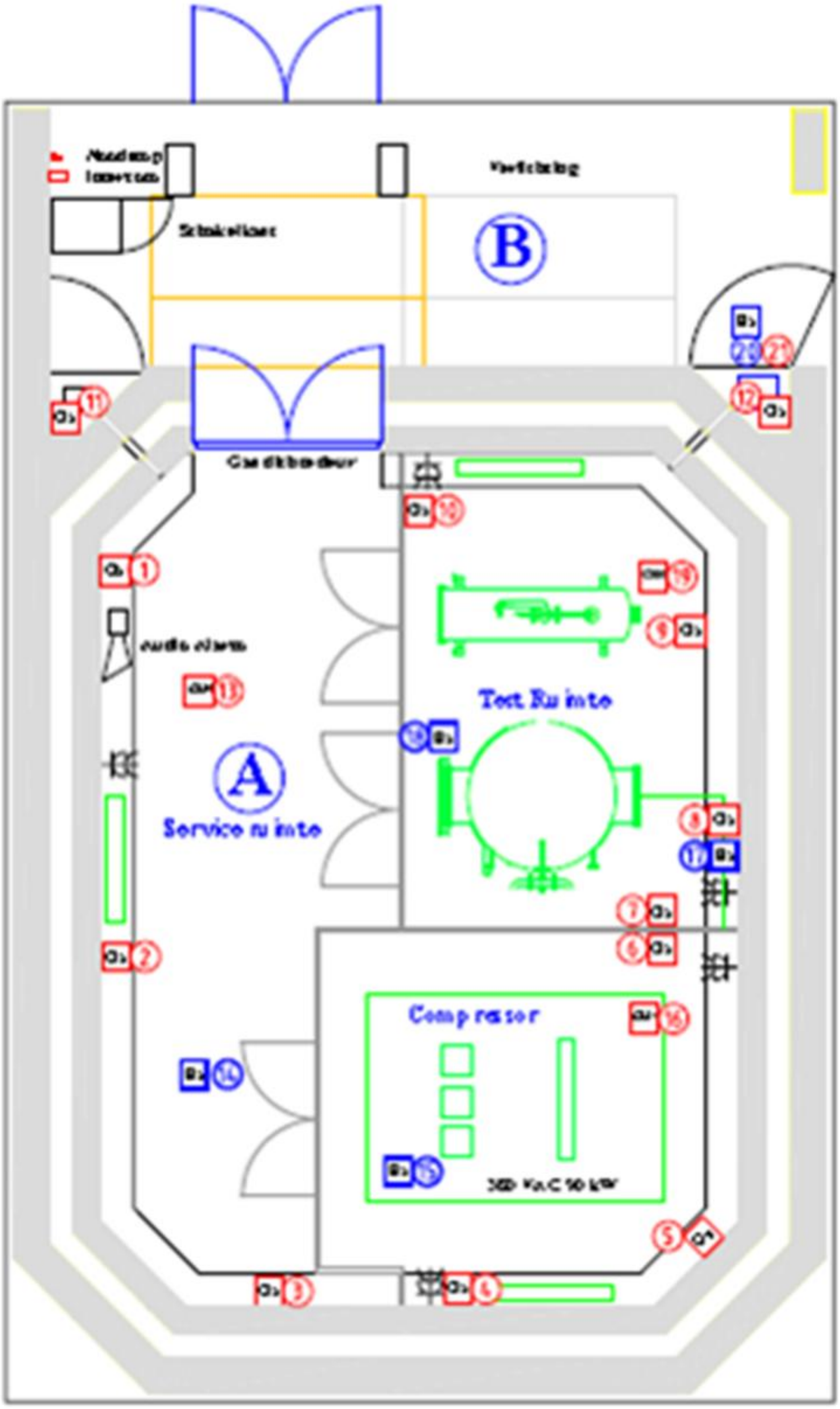


*Figure 5-39: Overview of the Inside of the GasTeF Rooms and Surveillance/Safety Devices*

The compressor room houses a two piston compressor enabling hydrogen or methane to pressurize and depressurize the test tank (i.e. fuelling and defuelling), Figure 5-40. The compressor is a reciprocal machine built by Hofer and is able to fill a gas tank to a pressure of 88 MPa with a power consumption of 55 kW within 3 minutes. It is cooled using a closed water circuit that includes an air/water heat exchanger located outside the bunker. The compressor is equipped with its own PLC (Programmable Logic Controller) for full remote control. The PLC collects all signals from the machine and the cooler and performs its own continuous functional checks. Part of the information collected by the compressor PLC is transferred to the main control and automation PLC of the facility via a bi-directional link.

*Figure 5-40: GasTeF Compressor*

In the test room a pressure vessel containing the component to be tested is placed (Figure 5-41). The tanks to be tested are inserted inside a sleeve which contains an inert gas (Helium or Nitrogen) and serves as a chamber for determining hydrogen permeation through the test tank walls. The hydrogen level in the sleeve is accurately determined using a gas chromatograph. The sleeve is placed into the safety pressure vessel which is filled with nitrogen at 5 kPa, so that hydrogen leakages will stay safely contained within a small volume. In the case of hydrogen/methane leakages outside the pressure vessel, into the test room, the emergency shut down procedure will automatically start.

*Figure 5-41: GasTeF Safety Pressure Vessel*

The compressor and the test installations are linked with high pressure stainless steel piping. Besides control valves and pressure and temperature indicators, the system is equipped with safety valves and pressure reducers for emergency venting. The facility features also stacks for the controlled or urgent discharge of gases in the air.

The bunker is closed by a gas-tight inner door and after that by a hydraulically operated 40 tons massive concrete door sliding on Teflon plates. During tests, the bunker is deprived of oxygen by purging with nitrogen gas in order to prevent the occurrence of an explosive atmosphere created in the event of leakages. In normal operation the facility is run fully automatically and the tests are operator controlled from a control room situated in an adjacent building.

Inside the bunker a number of gas detectors are strategically situated as Figure 5-39 shows. There are three types of sensors: Oxygen, hydrogen and methane content detectors, whereby all are placed inside each room in the bunker. The gas detectors form the heart of the safety monitoring system of the bunker, so special attention has been paid to their working logic:

1) In each room there are three oxygen sensors from which the signal of at least two must be valid in order to carry out the testing (the red squares in Figure 5-39). When the bunker is closed and filled with nitrogen, the oxygen content must be kept to a value less than 0.9%. On the contrary when the test is finished, the oxygen sensors have to measure more than 19%, before the bunker is allowed to be opened.
2) $H_2$ and $CH_4$ Sensors: There is a hydrogen and a methane detector inside each room and in the left niche of the bunker where the gas chromatograph is located (blue squares in Figure 5-39). In addition there are other $H_2$ and $CH_4$ sensors in the line going out from the sleeve to the gas chromatograph and to the exhaust stack. If one of the detectors measures an $H_2$-

content exceeding 80% of LEL[38] the emergency shut down procedure is immediately triggered.

The emergency shut down procedure ensures that the three bunker rooms and all installation parts (piping, etc.) are purged with Nitrogen gas. When all the hydrogen/methane has been vented-off, the ventilation system will fill all bunker rooms with air to regain a breathable atmosphere after which the concrete door can be opened and the bunker accessed.

#### 5.3.3.2 $H_2$ Tank Performance Testing

GasTeF has been designed to carry out the following experiments on both Type 3 and Type 4 tanks:

- Fast-filling cycling, in which storage tanks are fast filled and slowly emptied using hydrogen pressurized up to 70 MPa, for at least 1000 times to simulate their lifetime in a road vehicle. During the cycling process the tank is monitored for leaks and permeation rates using gas chromatography.
- Static permeation measurements as a function of time on tanks filled up to 70 MPa and temperatures to 85 °C.
- Temperature profile measurements inside the tanks to validate CFD models of the temperature distribution when filling and emptying at various rates

Figure 5-42 shows an example of a fast filling experiment performed in GasTeF. In this case the target filling pressure was 350 bar and it took 2.5 minutes to fill a 30 litres Type 4 tank. The emptying time was about 40 minutes. Figure 5-42 shows how the tank temperature increases during the first filling cycles to reach a stable value of approx. +23 C° after six filling/emptying cycles.

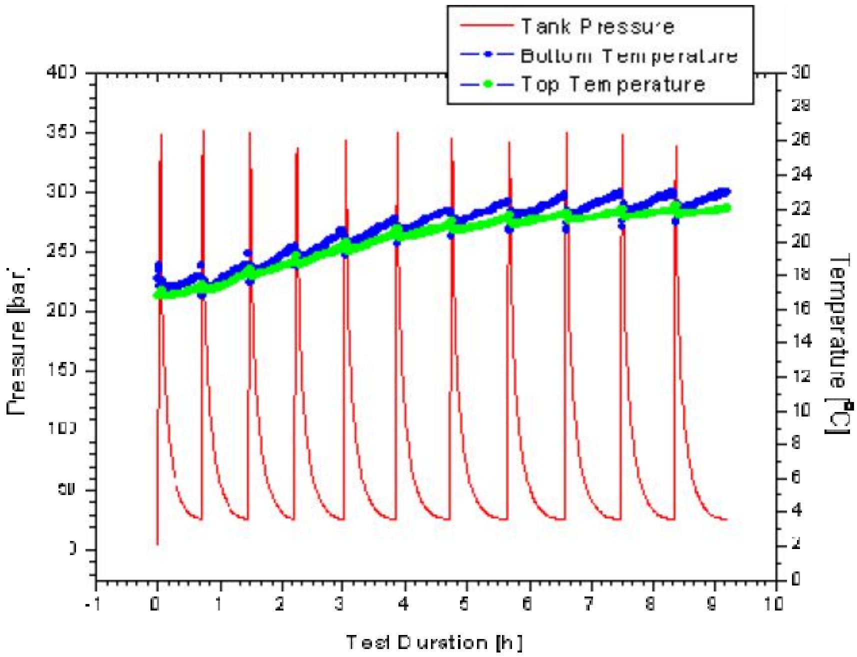


*Figure 5-42: Example of a fast Filling Test*

[38] LEL is the Lower Explosive Limit. The LEL of $H_2$ in air is 4%.

An example of a "permeation type" test carried out after the cycling depicted in Figure 5-42 can be seen in Figure 5-43. Here the tank pressure decreases sharply within the first 30 minutes and reaches an equilibrium pressure of 300 bar after 1.5 hours. The pressure drop seems to be primarily caused by the temperature decrease of the tank.

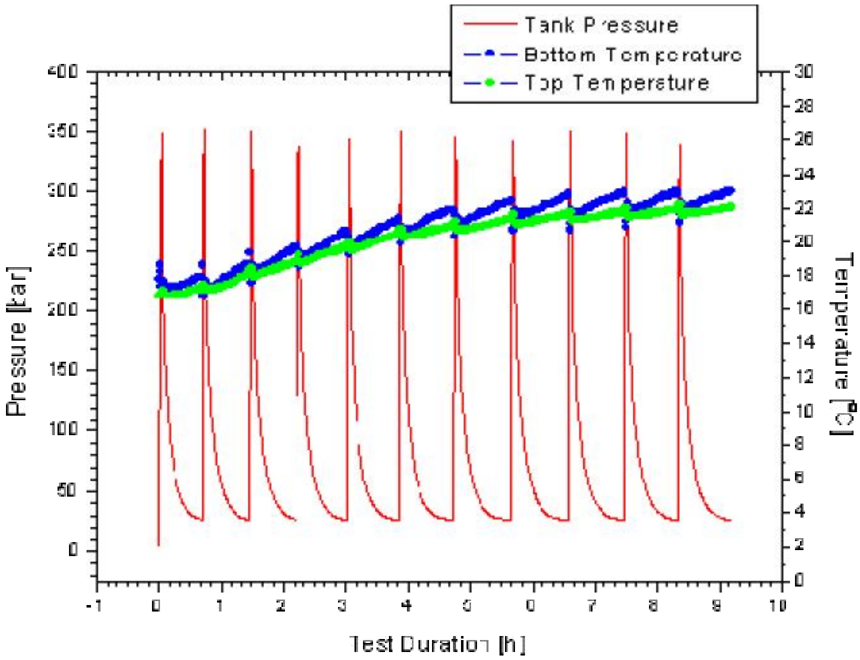


*Figure 5-43: Example of a Permeation Test*

These tests are part of a more general effort aiming at assessing from a safety point of view existing and future regulation in the field, and in particular the measures drafted in the implementing European regulation on type-approval of hydrogen vehicles[6]. The GasTeF results are applied to validate existing and future standards and are used as input to pre-normative research for the development and improvement of performance characterization methodologies for high pressure hydrogen storage.

### 5.3.4 SenTeF

The SenTeF (SENsor TEsting Facility) was designed and built to test the performance of gas sensors and more specifically hydrogen safety sensors. A detailed description of the facility is available from the referenced document[7], its salient features follow hereunder.

The facility comprises a test chamber, a gas handling system, a control and data acquisition system, a gas analyser and some subsidiary devices for temperature management and power supply. Central to the facility is the double walled, stainless steel test chamber in which sensors are mounted. The vessel, with an inner volume of 2.4 litres, is internally coated with HALAR® polymer for chemical resistance and is further contained inside another vessel, which can be closed and purged with an inert gas flow. In this way the test chamber is isolated from the laboratory environment, thereby improving thermal stability and ensuring safety of operation when toxic or flammable gas mixtures are used. Depending on the size of the sensors being tested up to six samples can be mounted in the chamber, out of contact with the walls. All electrical signals are transferred into and out of the chamber by means of two 25-pin feedthroughs.

*Figure 5-44: The SENsor TEsting Facility (SenTeF)*

A series of mass flow controllers are used to control the flow rates of up to four gases or gas mixtures into the system. This method of online gas mixing allows a wide range of gas compositions to be produced and introduced into the chamber. Temperature in the chamber is controlled by circulating a thermostatic fluid between the chamber walls. Ambient temperature in the chamber is measured by means of three Pt100 thermometers connected to the LabVIEW® data collecting system. The gas stream is humidified by evaporating water into the test gas using a Bronkhorst® controlled evaporator mixer (CEM). The test gas humidity is measured by means of a chilled mirror dew point meter. The test gas is introduced into the bottom of the test chamber and leaves from the top and a small fan positioned inside the chamber ensures homogeneity of temperature and gas composition.

The precise composition of the gas is continuously analysed during tests by a multi-column, multi-detector (thermal conductivity and flame ionisation detector) compact gas chromatograph (Interscience B.V.).

The facility is controlled by National Instrumens® hardware and is managed through software programmed in LabVIEW®. The software controls both gas and liquid mass flow controllers and, pressure settings via an Ethernet 100 port with the Fieldpoint 2000 communication and control block (National Instruments). At the same time, it acquires and stores data on flows, pressures, dew point, temperature and sensor signals through 8 analogue inputs with 12-bit resolution.

### 5.3.5 FCTEST

The state-of-the-art Fuel Cell TEST (FCTEST) facility allows testing of Polymer Electrolyte Fuel Cell (PEFC) stacks, components and entire systems with a capacity of up to 100 kW electrical power output. Its main purpose is to establish a reference laboratory for fuel cell pre-normative research (PNR) and performance verification open to the scientific community and industry. The facility supports developments in Regulation, Codes and Standards (RCS) globally within the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). The facility is also used for carrying out test campaigns on Polymer Electrolyte Fuel Cell (PEFC) stacks for EUfunded research projects and for the validation of fuel cell testing procedures and measurement methodologies as input to standards on fuel cell performance currently drafted by international standardisation bodies, such as ISO and IEC.

The facility provides moreover opportunities for training and exchange of research fellows and scientists and allows for:

- Simulation of a variety of hydrogen feed gases including diluents and typical air & fuel impurities.
- Accurate control of gas parameters such as composition, humidity, pressure and temperature and stack and coolant temperatures.
- Off-grid electronic load and grid-connected 120 kVA DC/AC inverter operation including continuous power metering.
- Simultaneous measurement of cell voltages and HFRs and in-situ electrochemical impedance spectroscopy (EIS) diagnostics of selected cells.
- Online feed gas composition analysis and continuous recording of system emissions.
- Programmable safety and process monitoring.

Figure 5-45 shows a typical example for the validation of a fuel cell testing procedure (FCTESTNET test module TM PEFC ST 5-3)[8] concerning polarisation curves (stack voltage & power vs. stack current density) for a PEFC stack. The different curves represent the average stack voltage and power in dependence of the period of data acquisition taken to calculate the average values and in dependence of hold period applied prior to the period of data acquisition. The test results confirm that the actual durations of measurements are of less significance when applying this procedure. Suggested improvements to the procedure will result in much shorter overall test duration thereby allowing for increased test throughputs.

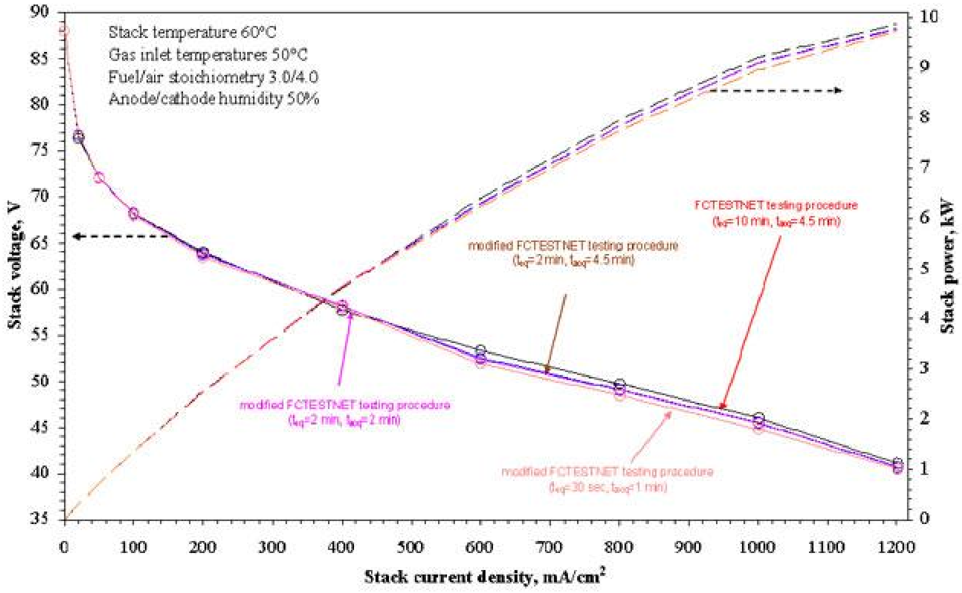


*Figure 5-45: Fuel Cell Testing Validation Procedure at FCTEST*

FCTEST also allows testing under simulated environmental conditions over a wide range of humidity and temperature in the ambient surrounding of the item under test (i.e. PEFC stack). Moreover, the performance of the item can be characterised when subject to artificially generated and real world shocks and vibrations. These additional testing capabilities are accomplished by a unique combination of a hydraulically actuated shaker table housed in a large scale walk-in environmental chamber. The cube shape multi-axial vibration test system may bear payloads in excess of 750 kg. Tests at vibration frequencies ranging up to 250 Hz, accelerations of typically 6 g vertically and 4 g in the other axes at payloads above 250 kg while and more than 10 g in the vertical axis are possible for payloads of less than 250 kg. Other characteristics of this vibration test systems includes a speed of 96 cm/s, a dynamic axial force of 62 kN, horizontal and longitudinal axis displacements of 5 cm and 10 cm in the vertical axis with angular displacements of ±4 ° for pitch and roll and ±6 ° for yaw. The maximum horizontal mountable area is 1.5 meters by 1.5 meters while additional areas to fix the test item are available at the sides of the Six-Degrees-of-Freedom (6DoF) shaker table. The multi-channel data acquisition in combination with 1D and 3D high precision accelerometers ensure control and monitoring of the tests in real time. The explosion proof climate chamber can simulate changes in ambient temperature ranging from about -40°C to 60°C with an accuracy of ±1 K for 20 kW thermal loads at mid chamber space. Its cooling and heating capacity is 80 kW and 35 kW providing respective rates of 2 K/min. The relative humidity of the conveyed air inside the software-controlled chamber may be varied between 15 % and 95 %.

### 5.3.6 Aerospace Applications

Ten years ago, storage and distribution of hydrogen resembled a huge issue – both for the upstream (from the production to the fuel station) as well as for the downstream part (fuel station to the automobile). Today, the issue has been partly closed, with the automotive industry agreeing among its members to use the storage of gaseous hydrogen in high pressure tanks as the technical baseline for the automobiles of the future. With the downstream storage and distribution issue being closed, focus is now put on the upstream part and the question, how the hydrogen will be best transported from the production facilities (e.g. nuclear power plants, wind parks, etc.) to the dispensers of the refuelling stations. It is not a matter of technology per se – but rather a question of cost effectiveness. Only time and continued R&D will tell whether this role is to be fulfilled by hydrogen pipelines, hydrogen trailers and/or localised hydrogen production facilities.

As far as aerospace is concerned, one can foresee that hydrogen will gradually move into energy and propulsion related applications.  This is due to the fact that hydrogen energy systems scale better then solar cells or batteries when bigger power levels are needed – which means that their mass increases at a lower rate per power increment, leading to a lower mass at a certain power level - and that hydrogen constitutes the best propulsive medium that can be used. No other medium is lighter in mass and can therefore provide readily for high specific impulse ($I_{SP}$) levels, which are paramount to save on fuel consumption.

#### 5.3.6.1 $H_2$ based Propulsion Systems

Let us take the example of a Telecom satellite, such as the ASTRA 1K, with a mass of 5250 kg and an anticipated lifetime of 15 years. As a typical telecom satellite, ASTRA 1K will be parked in the geostationary belt, 35786 km above the Earth’s equator. It will be brought to a Geostationary Transfer Orbit (GTO) by a Heavy Lift Launch Vehicle (HLLV) like an Ariane 5 or a Proton, and once it has been released there it will fire its main engines to arrive at its designated slot in the Geostationary Orbit (GEO). This manoeuvre has already taken some fuel, but although the satellite is now in its final parking position, there is more to be spent. The Sun and the Moon, the Earth’s gravity field, all sorts of disturbances act on the Telecom satellite, trying to move it out of its slot. To maintain in the designated position and out of any collision courses with the adjacent Telecom satellites, roughly 50 m/s velocity increment have to be invested every year. This surmounts to 750 m/s in 15 years and dependent on the chosen propulsion system, the required fuel mass ranges from 1181.40 kg for a classical bi-propellant system with an $I_{SP}$ of 300 s, to 245.04 kg for a plasma engine with an $I_{SP}$ of 1600 s and 99.42 kg for an advanced pulsed plasma thruster with an $I_{SP}$ of 4000 s. The dependency of the required fuel ($m_{propellant}$) is described by equation [1], whereby $m_{S/C\_Initial}$ resembles the initial spacecraft mass before the manoeuvre, ΔV is the velocity increment (in our case 15 * 50 m/s) and g is the standard acceleration of gravity, hence 9.81 m/s².

$$m_{propellant} = m_{S/C\_Initial}(1 - e^{-(\frac{\Delta V}{g \cdot I_{SP}})}) \qquad [1]$$

Hydrogen would clearly be the best propulsive medium, were it not for the fact that it features mediocre storage features due to its low density. At the moment the fuel savings are more than offset by the mass penalty of the hydrogen tanks, making it impractical to use $H_2$ as propellant, if the $I_{SP}$ of the engine is too low, besides of HLLVs where matters of thrust-to-weight ratio come into play as well. Once high performance engines become available however, then things might chance and then it will make sense to copy the terrestrial upstream $H_2$ distribution and storage solutions for space, e.g. by utilising hydrogen tanker spaceships to supply remote outposts, as envisaged in the Aurora programme of the European Space Agency ESA (here as feedstock hydrogen for an In-Situ Resource Utilisation plant on Mars, utilising the Sabatier-reaction to produce methane as rocket fuel)[9].

#### 5.3.6.2 $H_2$ based Energy Systems

A somewhat earlier application for hydrogen in space adapts an already existing technology for new purposes. The fuel cells being used in NASA's manned space missions like Gemini, Apollo and the Space Shuttle provide for high power levels and potable water. Combining these with the latest technological developments in the terrestrial automotive sector, it would be possible to design a pressurised manned rover for the exploration of the Moon and Mars. Similar to an automobile on the Earth, the combination of high pressure hydrogen gas tanks, buffer batteries, hydrogen leakage detectors and fuel cells could provide for a manned pressurised rover, allowing 2-4 astronauts to explore planetary bodies like the Moon during a cruise of 5-6 weeks, thereby covering a range of 1000-2000 km. As part of an ESA contract with Thales Alenia Space, the Liquifer Systems Group (LSG) has designed a Rover for Advanced Mission Applications (RAMA)[10].

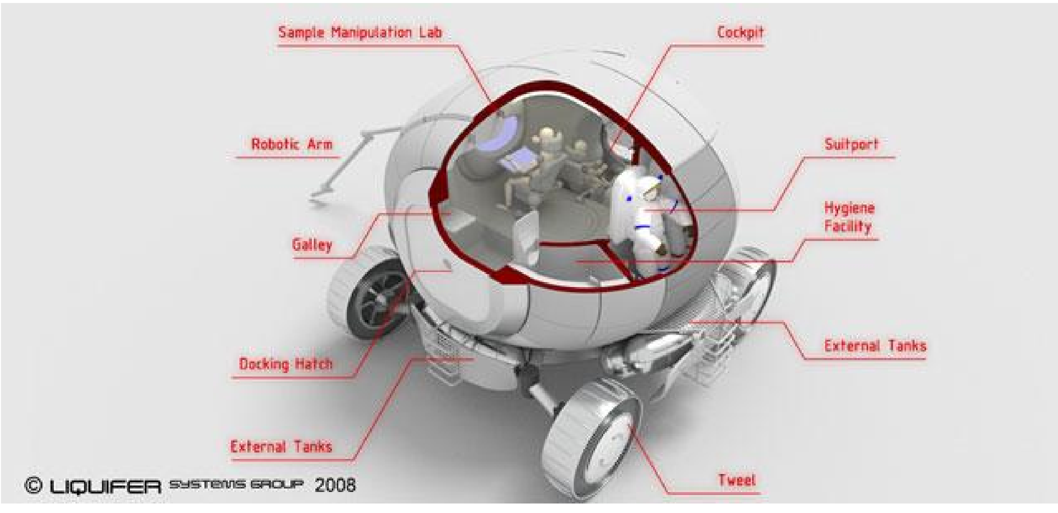


*Figure 5-46: Illustration of LSG's RAMA Concept (Source: Liquifer website)*

RAMA has been designed for surface missions with a crew of two or three lasting up to approximately 40 days, its source of energy, a liquid hydrogen/liquid oxygen fuel cell, allowing it to be driven and operated during the day as well as the night. Guidance, navigation and obstacle avoidance systems are foreseen as standard equipment to allow it to travel safely over rough terrain at all times of the day. The rover allows extra-vehicular activity and a remote manipulator is provided to recover surface samples, to deploy surface instruments and equipment and, in general, to assist the astronauts' field activities wherever and whenever needed. The vehicle has also been designed to have a very high degree of manoeuvrability. In addition, RAMA may be operated and replenished from a fixed site base or co-operate with other rovers of the same type to provide a mobile base. The rover in all cases will be refuelled using the products supplied by an in-situ resources facility.

Transportation and surface exploration requirements define the size and mass of the rover. RAMA has a launch mass of approximately 7000 kg, a dry mass of about 6200 kg and surface mission masses of between 7800 and 8300 kg. The rover can be launched by a future heavy lift launcher similar to the American ARES V concept. The factor most affecting the mass of the rover, other than the quantities of fuel cell reactants and crew consumables, is the amount of radiation shielding integrated in the design of the rover's pressurized shell. The factor most influencing the rover's external and internal configuration is the launcher's payload envelope and the need for the rover's centre-of-mass to be aligned with or close to the launcher's longitudinal axis.

Obviously there is a significant synergy with the fuel cells in the automotive sector, with the major difference being the type of hydrogen storage system; a cryogenic tank in the rover vs. a high pressure gaseous hydrogen tank in the cars. The major reason for this is the current complexity of high pressure compressor systems, which would be required to refill the hydrogen into the rover. With continued progress in the automotive sector however, this type of compressors will eventually become space qualified as well and then a Moon/Mars rover can transfer-in the hydrogen energy systems and power train to the greatest extent – with all possible cost benefits.

Similar considerations have led the German Aerospace Center DLR to install a terrestrial fuel cell and gaseous high pressure hydrogen tank system on an Airbus A320[11]. In July 2007, the first flight experiments were made in which the function of the fuel cells under flight conditions were tested and demonstrated. The system worked consistently below 3g, with enough in store for a standby system. Since February 2008, the same fuel cell system has been used to power a hydraulic circuit pump, with the necessary power to steer the aircraft.


*Figure 5-47: The Airbus A320 ATRA fuel cell experiment (Source: DLR website)*

The A320 ATRA project is embedded in a programme to introduce environmentally-friendly technologies to minimise emissions and to increase passenger comfort. For instance, an auxiliary turbine unit (APU) can in the future be used without conventional air conditioning. Using a fuel cell and an electric nose wheel, an aircraft would be able push back on its own from the gate at the airport, as well as taxiing without the use of the main engines to the runway for take-off and to the gate after landing. In addition, a fuel cell will be able to provide water and to generate heat, which might be used in a next step for on-board processes. The co-generation of electric power, water and heat by the on-board fuel cell can lead to significant jet fuel savings.

### 5.3.7 Conclusions and References

Hydrogen will assume a key role in Europe's effort to adopt its energy dependent society to satisfy its needs without releasing vast amounts of Greenhouse Gases (GHG). The paradigm shift is so paramount that one speaks of the "Hydrogen Economy", as the energy in this new and ecological type of economy is to be distributed by hydrogen. However, $H_2$ is not a primary energy source like nuclear power but rather an energy carrier. As such it is a means of storing, transporting and distributing energy, which will be generated by other means, like solar, wind or nuclear power plants.

Various $H_2$ storage and distribution methods are possible, but as it stands right now the most favoured one in terms of energy density of storage and practicability is the storage of gaseous hydrogen in high pressure tanks. The biggest promoter of this storage methodology is the automotive industry that is already preparing the generation change from the fossil fuel internal combustion engines to hydrogen based fuel cells. Yet there are more applications, all adding to the synergy potential with the aerospace sector.
To provide the best scientific and technical support to the implementation of the Hydrogen Economy, the JRC-IE conducts its R&D activities along the whole hydrogen value chain, covering all aspects from the hydrogen production, up- and downstream storage and distribution, to the final utilisation. Test facilities allow for specific experiments and cover the high pressure gaseous hydrogen storage tanks and their piping and valves (GasTeF), hydrogen sensors (SenTeF), as well as the fuel cells (FCTEST).

All these test facilities show to a certain degree overlaps with the hydrogen applications in the aerospace sector. While the synergies are rather obvious for the fuel cells, which are to become the state-of-the-art power train for the next generation automobiles, there are somewhat smaller overlaps for the sensors and the tanks, because of the specific environmental constraints (e.g. absence of ambient pressure and oxygen) and operational requirements (e.g. very high hydrogen mass flow rates). Still there is a strong motivation to spin-in terrestrial hydrogen technologies into the aerospace sector as the costs of these systems is by orders of magnitude lower – mostly due to the larger customer base and the pronounced need to innovate in a shorter time scale, which ultimately leads to better system performances.

Especially ESA has built up a certain tradition to spin-in technologies from adjacent technological sectors or commercial spacecraft into its scientific space missions. Mars Express for example makes extensive use of hardware developed for other missions – 80% of its hardware stems from the Rosetta spacecraft, the ESA mission to 67P/Churyumov-Gerasimenko[12]. Future exploration missions are likely to take the next step by adapting terrestrial systems entirely into their technology portfolio, either to save on cost and/or to enable a mission that would otherwise not be feasible in terms of mission duration, fuel consumption, power constraints or requirements in consumables.

The aviation sector, which is much more driven by commercial considerations, is already taking these next steps, by installing a terrestrial fuel cell and gaseous high pressure hydrogen tank system on an Airbus A320, as part of the ATRA experiment by the German Aerospace Center DLR. Once accomplished successfully, the DLR's A320 ATRA fuel cell experiment will serve as a role model, how terrestrial hydrogen technologies can be transferred-in into the aviation sector to save on jet fuel and operational costs. With this activities in mind, it is not very bold to assume that sooner (than later) fuel cells, tanks and hydrogen sensors for spacecraft and rovers will be transferred-in entirely from terrestrial systems, just as it is happening right now in the aviation sector.

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[12] SPACE 2006, Eugen Reichl, Stefan Schiessel, ISBN 3-00-017760-4, „Eis, Methan und Fomaldehyd – Basis für Leben auf dem Mars?", page 19

# 6. Technology Transfer Examples: From Energy and ICT to Transportation – Spin-ins and Spin-offs

CERN, ESA, the JRC-IET and others, all these entities perform technology transfer - all at different levels. Given the specific constraints that these different players are confronted with, both the technologies transferred as well as the encompassing strategies will vary, as will the partners, which participate to this transfer. Consequently **every technology transfer example is unique, very much dependent on the involved technology, the partners and the specific constraints of the encompassed sectors**. Therefore the technology flow, hence the decision whether the technology transfer will be a spin-off or a spin-in depends very much on the involved R&D strategies and the possible applications. Naturally **terms like spin-in and spin-off are of relative nature; one entity's spin-in is the other one's spin-off.**

As pointed out in the sections before, space activities, and especially the commercial ones, are especially prone for technology transfer as the know-how generated within space projects may be used for other industrial sectors, which distinguish themselves by the need for high quality standards, the requirement to control harsh environments and/or the necessity to deal with potentially high energies.


Typical examples for such overlapping industrial sectors are the aviation and the automotive industry, the Information and Communication Technology (ICT) sector, as well as the Maritime, Energy, Software and Sensor/Instruments industry. All of these sectors are prone to utilise Technology Transfer (TT) and as such to provide for innovations both in the space and the terrestrial sector(s). Given the complexity of the endeavour however, not all sectors will perform TT strategies at all times – **traditionally TT has been utilised predominantly between space, aviation, automotive[39] as well as the ICT sector**. Figure 6-1 depicts the principal Technology Transfer axes between these traditional TT areas and lists EADS and Honeywell as two Multinational Organisations (MNO) that master technology transfer internally, especially between the aviation and the space sector. In doing so, both MNOs maximise profits and Intellectual Property Rights (IPR), for example by transferring know-how gained in the development of high performance alloys for aircraft turbines into rocket engines parts or vice-versa.

[39] One could also include maritime and rail, thereby enlarging aviation, automotive and maritime to 'transportation'

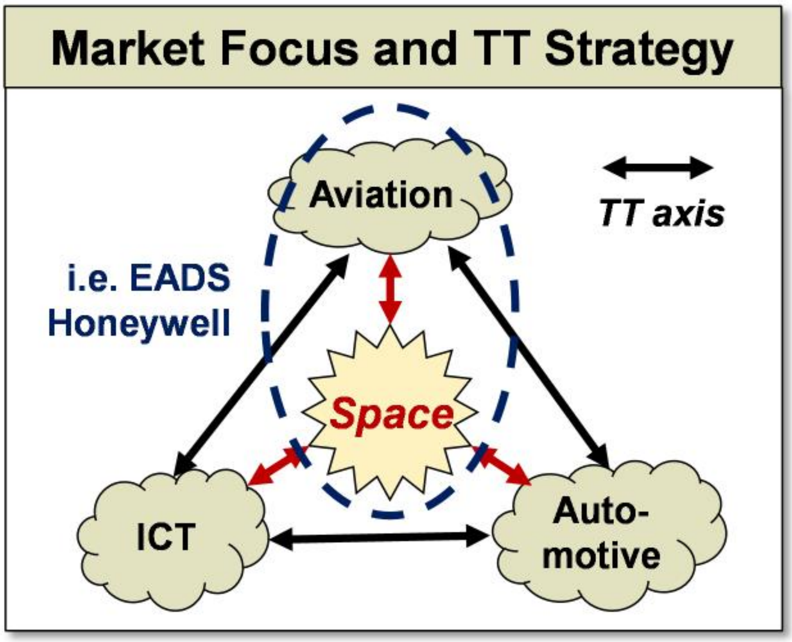


*Figure 6-1: Predominant Technology Transfer Areas with Aerospace*

As discussed before, Figure 6-1 outlines the principal TT axes between space and the three predominant industrial sectors aviation, automotive and ICT. The double sided arrows suggest that the technology flow will be bidirectional; hence that spin-ins and spin-offs will occur at a comparable level. This however is a generalisation and only true when looking at the long-term picture. **While the early stages of technology transfer favoured spin-offs, hence the knowledge transfer from space to the respective terrestrial sector, recent developments have shifted the pendulum towards the spin-in side, with the space sector employing more and more the strategy of 'importing and adopting' terrestrial technologies for its activities**. The drivers for this pendulum swing towards 'spin-in' are twofold and we will have a closer look at them on the following pages, before we dive deeper into specific Technology Transfer Examples.

## 6.1 Spin-in Driver No. 1: Technical Progress and Generation Cycles

Technical progress is clearly a key driver – one might also say the key paradigm - of our modern industrial society. Products and technologies become better with every generation – this 'better' may attribute to faster, smaller, lighter, cheaper, more robust, etc. In an ideal open market only the best products will survive – and similar to an evolutionary process, the competitiveness of these products will be challenged by new – and potentially better – products that emerge with the next technological generation cycle. Similar to history, which tends to repeat itself also from time to time, technical progress is both linear and cyclic as depicted in Figure 6-2. This graphic outlines the current technical progress paradigm, interconnecting scientific research, technological development, as well as application and transformation. Assuming that the whole chain starts with a specific technology/process, which is a result of fundamental and/or applied scientific research, this technology/process needs to see some further technological development to give it an innovative flavour and to allow for a commercial launch. Once introduced into the market, its further utilisation will soon trigger an application and a transformation of the orginal concept into a new – and better - technological generation, which will integrate further insights from scientific research and technological development, thereby starting a complete new Product Life Cycle (PLC).

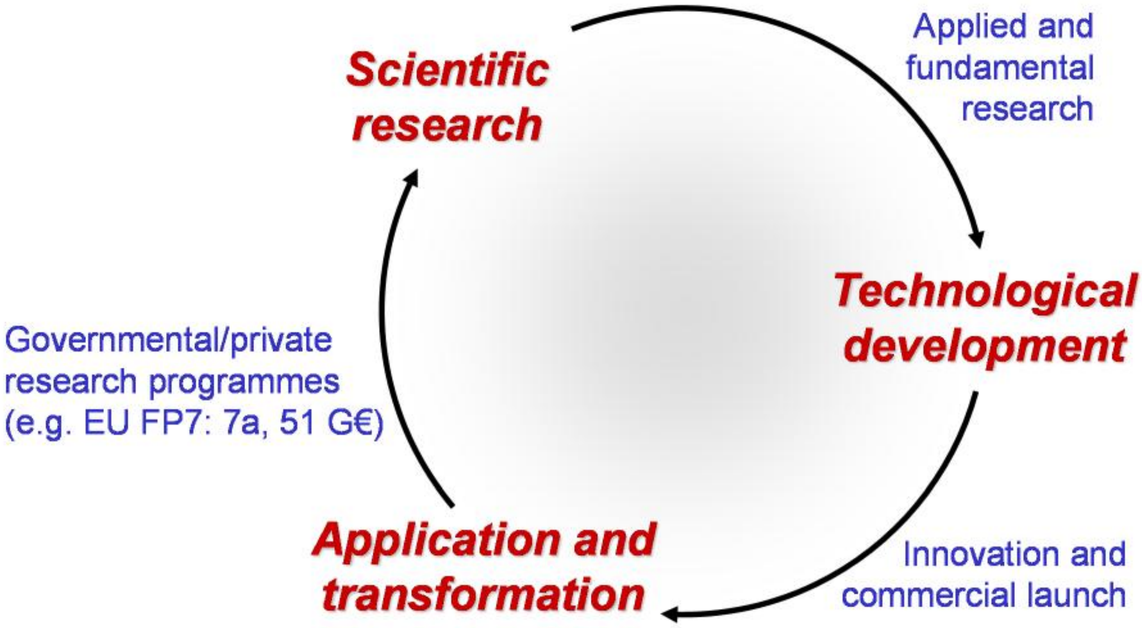


*Figure 6-2: Recent technical Progress Paradigm*

Most of the processes within the technical progress paradigm are out of the coontrol of governments besides the one when one product life cycle comes to an end and a new one is about to start- Then governmental as well as private research programmes kick in, aiming to provide an impetus for the next technological generations by carefully supporting research that points into specific pre-selected directions. The European Union performs such a strategic research funding by its Framework Programmes, i.e., the 7th Framework Programme (FP7), which features a budget of € 51 000 million, lasting for 7 years from 2007-2013.

While governments have a certain chance to influence the direction in which technological progress is likely to occur, their potential to exert influence on the generation cycle is rather limited, especially when the technology flow does not follow a spin-off but rather a spin-in pattern. Moore's law  is a classical example for such a process that is out of reach of the governments, although it had been started by a governmental programme in the 1960s – the Apollo Programme. **Contrary to public belief it is not the Teflon pan that is a spin-off from NASA's Apollo Programme, but the modern computer, which stems from NASA's requirement to minaturise computer technology to the highest level possible a that time – eventually leading to the integrated circuit (IC)-based computer using microchips based on silicon technology.**

Triggered by this start in the 1960s a whole new industry – the Information and Communication Technology (ICT) sector – started to emerge, triggering the *Digital Revolution*, which eventually cummulated in the *Information Age*[40] by introducing evermore powerful PCs, laptops, notebooks and mobile phones into every part of our professional and private lives. This constant progress is based on Very Large Scale Integration (VLSI) of µ-chips, Li-ion and Li-polymer batteries, MIMO (Multiple Input/ Multiple Output antennas), AMOLED displays, CODECs such as MPEG4 Part10, low cost CAT5 cables and WiFi standards, etc. Moore's law

[40] See also: http://en.wikipedia.org/wiki/Information_Age

- the observation that over the history of computing hardware, the number of transistors on integrated circuits has doubled approximately every 18 months - plays the decisive driver in this context. Even if the 2010 update to the 'International Technology Roadmap for Semiconductors'[41] has forecasted that the growth will be slowing at the end of 2013, calling for transistor counts and densities to double only every three years, this generation cycle is still much shorter than the one within the aerospace sector, which features a cycle in the order of 7-10 years. By introducing new technological generations at a pace which is three to five times faster, the ICT sector is prone to progress more rapidly than the space sector; therefore **one can assume that the technology flow between the ICT and the space sector will not only continue to remain in a spin-in pattern but also that the ICT sector will maintain and expand its role as a major technology contributor for the space arena in the years to come.**

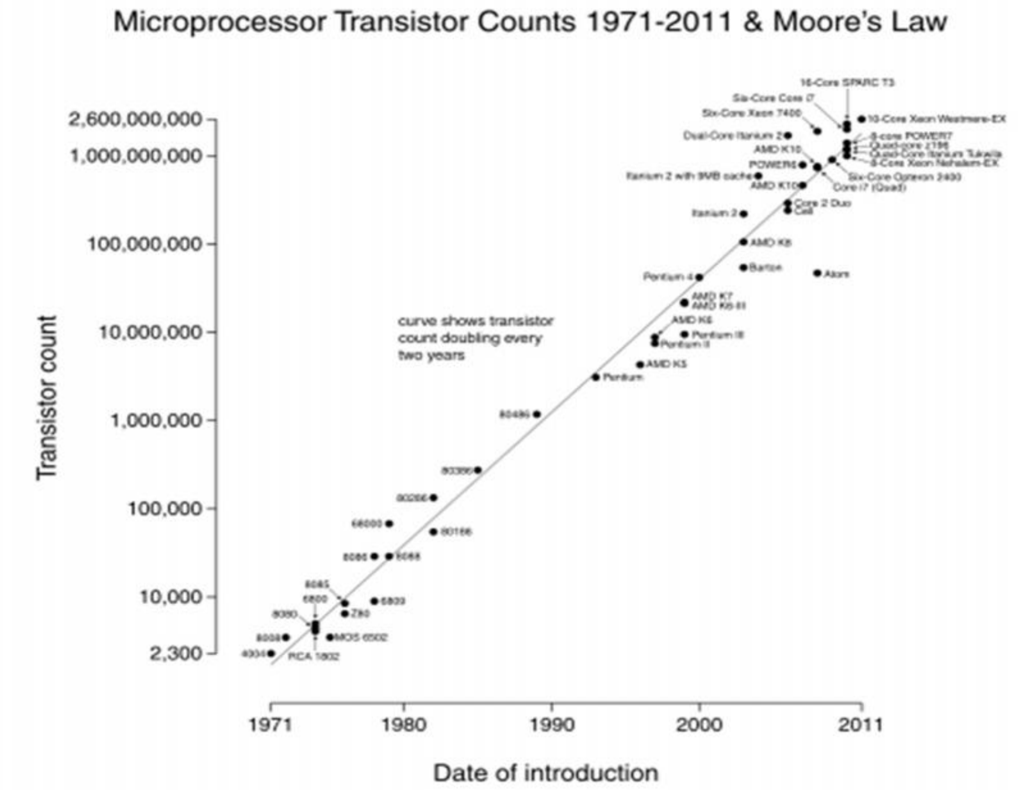


*Figure 6-3: Moore's Law (Source: Wikipedia)*

## 6.2 Spin-in Driver No. 2: R&D Budgets and technological Progress

While shorter generation cycles of specific terrestrial sectors are one key driver for the pendulum swing towards 'spin-in', the magnitude of the associated R&D expenditures are another key item, which amplifies the possibility of spin-ins vs. spin-offs. A recent study published in a JRC Technical Note has assessed the R&D expenditures of the automotive industry and the aerospace and defence sector, confirming that the automotive industry is the largest R&D investor in the EU-27, accounting for one quarter of total industrial R&D investments. And this observation is likely to remain valid in the years to come, as both car manufacturers and component suppliers show elevated R&D intensities with an increasing trend over the past years.

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[41] A set of documents produced by a group of semiconductor industry experts, who are representative of the sponsoring organisations, including the Semiconductor Industry Associations of the US, Europe, Japan, South Korea and Taiwan.

*Table 6-1: R&D investments, sales and total number of employees of companies included in the EU Scoreboard related to the 'automotive' sector (2008), 'aerospace and defence' and all industries (Source: JRC Technical Note JRC 58727)*

| | **R&D investment (€bn)** | | **Sales (€bn)** | | **Number of employees (million)** | |
|---|---|---|---|---|---|---|
| | World | EU27 | World | EU27 | World | EU27 |
| Automotive manufacturers | 53 | 20.9 | 1213 | 423 | 2.76 | 1.26 |
| Automotive suppliers | 19.6 | 9.5 | 437 | 156 | 2.33 | 0.98 |
| Commercial vehicles and trucks | 6.9 | 2.4 | 233 | 66 | 0.62 | 0.22 |
| **Automotive industry** | **79.5** | **32.8** | **1883** | **645** | **5.7** | **2.5** |
| *Aerospace & defence* | *15.6* | *7.5* | *379* | *129* | *1.75* | *0.55* |
| *All industries* | *431* | *130* | *13897* | *5712* | *45.1* | *21* |

*Source: derived from the EU Scoreboard 2009 (DG RTD-IPTS, 2009) (rounded numbers)*
*Note: The table shows the aggregated figures for 65 EU-based and 140 worldwide companies related to the automotive sector.*

As visible in Table 6-1, the worldwide R&D investment of the automotive sector outweighs the one of the aerospace and defence sector by a factor of 5.1 worldwide and by 4.4 in the EU-27. This leads to a clear conclusion in the discussion of spin-in vs. spin-off; the sheer difference in R&D expenditure in the aerospace and the automotive sector clearly favours a spin-in of terrestrial automotive technologies into the space sector.

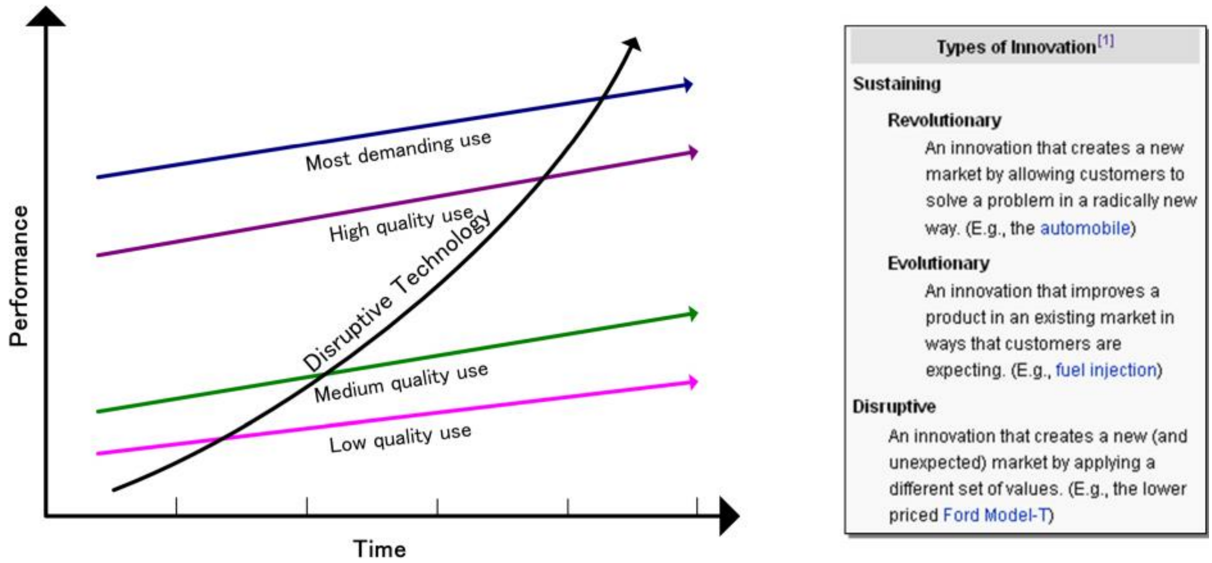


*Figure 6-4: Sustaining vs. disruptive Technologies (Source: Wikipedia)*

Another item to be taken into account – and which is depicted in Figure 6-4 - is that the progress in R&D does not always follow a steady pattern, but will sometimes embark on a disruptive route, thereby turning an already existing market and value network (over a few years or decades) upside down, eventually displacing an earlier technology. From what we have seen in space in the last years and decades, the likelihood for disruptive space innovations is rather small, while terrestrial sectors have experienced such events rather frequently throughout history, as outlined by some examples in the table below.

*Table 6-2: Examples of disruptive Innovations (Source. Wikipedia)*

| Innovation | Distrupted Market | Comments |
|---|---|---|
| **Plastic** | **Metal, wood, glass etc.** | Bakelite and other early plastics had very limited use - their main advantages were electric insulation and low cost. New forms had advantages such as transparency, elasticity and combustibility. In the early 21st century, plastics can be used for nearly all household items previously made of metal, wood and glass. |
| **Telephones** | **Telegraphy** | When Western Union infamously declined to purchase Alexander Graham Bell's telephone patents for $100,000, their highest-profit market was long-distance telegraphy. Telephones were only useful for very local calls. Short-distance telegraphy barely existed as a market segment, which explains Western Union's decision. |
| **Light-Emitting Diodes (LED)** | **Light bulbs** | A LED is significantly smaller and less power-consuming than a light bulb. The first optical LEDs were weak, and only useful as indicator lights. Later models could be used for indoor lighting, and now several cities are switching to LED street lights, while light bulbs are being phased out. |
| **LCD** | **CRT** | The first liquid crystal displays (LCD) were monochromatic and had low resolution. They were used in watches and other handheld devices, but during the early 2000s they largely replaced the dominant Cathode Ray Tube (CRT) technology for computer displays and television sets. |
| **Downloadable Digital media** | **CDs, DVDs** | In the 1990s, the music industry phased out the single, leaving consumers with no means to purchase individual songs. This market was initially filled by illegal peer-to-peer file sharing technologies, and then by online retailers such as the iTunes Store and Amazon.com. This low end disruption eventually undermined the sales of physical, high-cost CDs. |
| **Minicomputers** | **Mainframes** | Minicomputers were originally presented as an inexpensive alternative to mainframes and mainframe manufacturers did not consider them a serious threat in their market. Eventually, the market for minicomputers became much larger than the market for mainframes. |
| **Personal computers** | **Minicomputers, Workstations. Word processors, Lisp machines** | |
| **Smartphones** | **Personal computers** | Smartphones and tablets can be used everywhere. The computational power of high end smartphones is similar to the performance of PCs, but requires smaller footprint and power compared to a PC. |
| **Email** | **Postal mail** | E-mail has replaced postal mail because it can be sent from one place to another place in few milliseconds, without wasting paper and spending money for postage stamps. |
| **Wikipedia** | **Traditional encyclopedias** | Traditionally edited general encyclopedias have been displaced by Wikipedia, the free, non-profit, community-edited online encyclopedia. Former market leader *Encyclopædia Britannica* ended print production after 244 years in 2012. *Britannica*'s price of over $1000, its physical size of dozens of volumes, its weight of over 100 pounds, and its update cycles lasting a year or longer were all annulled by Wikipedia. |

No one can say, what the next disruptive innovation will be and where it will happen, however **chances are high that any disruptive innovation will not happen within the space but rather in the ICT (short generation cycles) or the transportation sector (high R&D budgets), further establishing the already existing spin-in trend.**

But how strong are the influences from the transportation and the ICT sector? How many technologies are still driven ‘in-house’ by the space sector, how many are being ‘imported and adopted'? In aiming to answer these questions we have assessed the technology flows along the technology domains of ESA's Technology Tree V3, summarising the result within Table 6-3.

*Table 6-3: Assessment of Technology Flows (Spin-in vs. Spin-off) between Space and the two predominant terrestrial TT Areas - ICT and Transportation*

| Information, Communication Technology (ICT) Sector - | Technology Flow | Space Application | | Technology Flow | Transportation (Aviation, Automotive, Rail, Maritime) Sector - |
|---|---|---|---|---|---|
| | | TD | Technology Domain (Space: ESA Technology Tree V3) | | |
| Computer and mobile phone industry drive CPU capabilities (FLOPS, power, etc.) | ⇨ | 1 | On-Board Data Systems (spacecraft data management and payload data processing) | ⇦ | Aviation and increasingly automotive, as aircraft and cars become more and more 'intelligent' |
| The commercial ICT sector drives S/W development (i.e., gaming industry) | ⇨ | 2 | Space System Software (basic techniques and technologies in the field of software and IT with respect to their application to space missions) | ⇦ | Aviation, especially as far as the safety aspect is concerned |
| CPUs and Ics become more and more powerful to control high power levels | ⇨ | 3 | Spacecraft Electrical Power (techniques and technologies related to power system architecture, to power generation, distribution and conditioning and to energy storage) | ⇦ | All, especially with the upcoming electrification of transportation (Hybrids, BEV and FCEV) |
| | | 4 | Spacecraft Environments and Effects (creation of environment models and the knowledge of effects) | ⇦ | Aviation and maritime (i.e., radiation, pressure changes, temperature cycles) |
| Mobile phones and tablets employ g-sensors driving R&D (esp. size, power) | ⇨ | 5 | Space System Control (design and implementation of control systems for space applications, i.e., AOCS for satellites, GNC for space vehicles and launchers, Pointing Acquisition and Tracking systems for antennas) | ⇦ | R&D of Inertial Measurement Units is pushed for UAVs and 'classical' aircraft |
| WiFi, 3G, LTE, MIMO, etc. are technologies driven by the PC/mobile phone industry | ⇨ | 6 | RF Systems, Payloads and Technologies (technologies and techniques related to satellite systems and networks, spacecraft payloads, instruments and specific ground equipments, TT&C, navigation, EO and space science) | ⇦ | Modern transportation systems employ telemetry systems; TT&C is a 'must' for UAVs |
| WiFi, 3G, LTE, MIMO, etc. are technologies driven by the PC/mobile phone industry | ⇨ | 7 | Electromagnetic Technologies and Techniques (antennas and related technologies, wave interaction and propagation and electromagnetic compatibility) | ⇦ | WiFi within planes, ships, trains and cars; 'SatCom on the move' for permanent internet access |
| Reprogrammeable ASICs introdcued into the ICT world; nowadays frequent 'patching' strategy (i.e., gaming, apps, etc.) | ⇔ | 8 | System Design & verification (technology, methods and tools to support the System Engineering processes (specification, design, and verification) of space systems during the complete lifecycle (phases 0 to F)) | ⇔ | Originally space systems engineering was a spin-off; today's cost pressure favours terrestrial methodologies |
| Modern CPUs allow for higher autonomy | ⇨ | 9 | Mission Operation and Ground Data systems (control and operations of space system elements (satellites, transfer vehicles, orbiters, landers, probes, rovers, etc.) and related ground segments) | ⇔ | Originally mission ops was a spin-off; today's cost pressure favours terrestrial methodologies |
| Powerful CPUs allow for computer aided/guided, nearly/fully autonomous flight manoeuvres | ⇨ | 10 | Flight Dynamics and GNSS (analysis and definition of trajectory aspects of space projects, known as mission analysis, includes all operational ground activities to measure and control the spacecraft orbit and attitude) | ⇔ | Modern military aircraft use flight regimes that can only be controlled by computers (i.e., F -16); space planes (i.e., SS1/2) still thrive on space R&D |
| | | 11 | Space Debris (meteoroid and debris environment including space surveillance, databases, assessment of debris risk levels, re-entry of space objects, hyper velocity impacts and protection, mitigation measures) | ⇦ | Modern naval warfare R&D deals with railguns, which fires kinetic bullets with Mach 7 at a 350 km distant target (through the atmosphere) |
| Although originally space, VSAT R&D is now driven by ICT (i.e., backhaul at mobile phone networks) | ⇨ | 12 | Ground Station System and Networks (engineering of facilities that connect the space segment with the control centers, i.e., high performance deep space stations to networks of small ground stations) | | |
| | | 13 | Automation, Telepresence & Robotics (specification, development, verification, operation and utilisation of space automation systems, i.e., space robot systems and Space laboratory automation and payload control systems in manned and unmanned missions) | ⇔ | Automation is by now a terrestrail domain; telepresence increasingly as well high performance robotics is still driven by space |
| CPUs and sensors developed for computers and tablets drive capabilities (i.e., bio-sensors) | ⇨ | 14 | Life & Physical Sciences (technological aspects related to the instrumentation in support of life and physical science, and for ensuring the delivery of a complete system (instrument) technology) | ⇔ | Human performance supervision (i.e., fatigue measurement) |
| | | 15 | Mechanisms (all devices whose operation involves a moving function of one or several parts (e.g. actuator, hold-down&release device, pointing mechanism, deployable boom, thrust vector control mechanism), and associated specific disciplines (such as tribology and pyrotechnics) and tools) | ⇦ | Military aviation is embarking on thrust vector control for increased maneouvrability (i.e., F-22) |
| Laser systems developed for fiber optics, optical memories, etc.; in future optical computers | ⇨ | 16 | Optics (technologies and techniques for systems, instruments and components, as well as design, engineering and verification methods, in the field of optics) | | |
| Optocouplers and in future optical computers | ⇨ | 17 | Optoelectronics (development and application of technologies combining photonics (i.e., circuits handling photons) with electronics to achieve given functions) | | |
| | | 18 | Aerothermodynamics (the dynamics of gases (physical processes & modelling) especially of atmospheric interactions with moving objects at high speed, i.e. take-off to landing, orbital ascent/descent, aero heating) | ⇔ | High performance aircraft (i.e., SR-71) as well as jet cumbustion engines |
| | | 19 | Propulsion | | |
| | | 20 | Structures (technologies and methodologies related to the design, analysis, manufacturing and testing of structures and mechanical systems for S/C, planetary infrastructures, habitats, launchers and re-entry vehicles) | ⇦ | Composite materials incrasingly employed in aviation, automotive, rail and maritime |
| Mobile phones are extemely demanding WRT to power and mass, volume constraints | ⇨ | 21 | Thermal (all technologies needed for the thermal control of space systems) | ⇦ | Modern systems are strongly driven by efficiency considerations (i.e., recuperation) |
| | | 22 | Environmental Control Life Support (ECLS) and In-Situ Resource Utilisation (ISRU) (all technologies for controlling, maintaining and supporting human presence in space and the utilisation of local resources) | ⇔ | Originally a spin-off sector; today's cost pressure favours terrestrial methodo-logies (aviation, submarines, etc.) |
| High quality demands for mobile phones and PCs drive the development | ⇨ | 23 | EEE Components and quality (design, production and testing of Electric, Electromechanical & Electronic (EEE) components meeting performance/reliability requirements for use in on-board electric/electronic systems) | ⇦ | Today's customers want the highest quality for their cars, ships and planes |
| Demanding operational requirements for mobile phones and notebooks (i.e., 'rugged computer') | ⇨ | 24 | Materials and Processes (incl. materials mechanics and processes, and their physical/chemical behavior and the interaction with the operational environment; involves all manufacturing processes) | ⇦ | Very demanding lifetime requirements for platforms (trains/ships: 40 years; aircraft: 30 years; cars: 15-20 years) |
| | | 25 | Quality, Dependability and Safety (quality, reliability, availability, maintainability and safety of space systems and their constituents (hardware, software and human element)) | ⇔ | KISS principle increasingly employed for automotive, esp. For upcoming electric vehicle |

A swift look at Table 6-3 provides already for some interesting insights:

- The **technology flow between space and the ICT sector** covers nearly two thirds of all technology domains and 94% of these technology flows are spin-ins
- The **technology flow between space and the transportation sector** covers 84% of all technology domains and 62% of these technology flows are spin-ins
- **Spin-ins from the ICT sector are mostly based on the progress of chipsets** (Moore's Law)
- **Technology flows between space and the transportation sector encompass predominantly the aviation sector**; with the advent of electric cars, the automotive sector is likely to become another spin-in contributor
- **Propulsion is the only technology domain without a noteworthy technology flow**; neither spin-ins nor spin-offs alleviate the cost pressure

The following paper takes a closer look on the promises and challenges, which come along with the electrification of the automotive sector, thereby providing for an analysis of the potential technology transfers that may emerge between space and the automotive industry.

## 6.3 A Technology Transfer from the automotive Industry to Space in the Making: "The Hydrogen Vaue Chain - Applying the automotive Role Model of the Hydrogen Economy in the Aerospace Sector to increase Performance and reduce Costs" ([G] Frischauf, et al., 2013)

Published in Frischauf, N. et al: The Hydrogen Value Chain: Applying the automotive Role Model of the Hydrogen Economy in the Aerospace Sector to increase Performance and reduce Costs, in *Acta Astronautica* (2013), pp. 8-24 [G]

### 6.3.1 Introduction

Hydrogen, the most abundant element in the universe, can be stored in many ways as metal hydride, compressed gas, cryo-liquified, in carbon nanotubes, gas micro spheres, as liquid carrier or chemically bonded. Which storage methodology is finally utilised is driven primarily by the application concerned.

In the aerospace sector, hydrogen is used as propellant and prime resource in large scale power systems and stored according to the application. For rockets, featuring for example cryogenic engines, which demand big amounts of hydrogen with very high flow rates, the storage of cryo-liquified hydrogen has established itself as state-of-the-art. Short duration space applications, where energy and power considerations become major drivers, are also in favour of cryogenic storage solutions, showcased as early as in the 1960s and 70s with NASA's Apollo Programme, which brought man to the Moon using cryo-liquified hydrogen and oxygen to supply a fuel cell, generating power and water for the spacecraft. An Apollo Mission lasted for a period of one week, relying on hydrogen/fuel cell technology for longer time periods than that - such as required when flying to Mars – would call for cryogenic storage methods with near zero boil off. Although possible, at this moment, these concepts lose out due to the technological issues of re-filling the associated high pressure tanks.

The automotive sector, which does not require the throughput of vast amounts of hydrogen in a short timeframe, is much more driven by mass market issues and particularly by safety and cost aspects. Obviously, safety is imperative for the aerospace sector as well, however a clear distinction between the two sectors is that it is very well trained personnel that fill the rocket with liquid hydrogen, while it is the man on the street that will refill his own car—hence the safety aspects for automotive tanks are of a completely different nature. With this in mind and the fact that the lots in the transport sector are much bigger and customers are much more price sensitive, the automotive sector, as the biggest driver of hydrogen technology, has settled on storing gaseoushydrogen in high pressure tanks. Therefore, for on-boardapplications, both compressed gas for automotive and liquid hydrogen for aerospace applications have established themselves as state of the art.

While the preferred storage methodology differs for the aerospace and the terrestrial sector, the technology employed to generate power out of the stored hydrogen is similar—by making use of fuel cells. Already invented in 1839 by Sir William Robert Grove [1], fuel cells saw their application in aerospace in the 1960s within NASA's Gemini and Apollo-Programme and were the main power generation means in the Space Shuttle. The terrestrial world did not employ fuel cell technology on grand scale until the 1990s, when the automotive sector discovered its benefits for the decarbonisation of the transport sector and started to implement it as the primary drive train system for the next generation cars. After an initial launch as prototype fuel-cell powered cars in 1997 by Daimler and Toyota [1], the next generation commercial fuel cell electric vehicles are now expected to see their market roll-out by 2015 [2]. In the years to come thereafter, through a gradual change over, cars will not burn gasoline or diesel but rather convert hydrogen into electricity to power a high performance electric motor, provided that the infrastructure to produce, store and distribute the hydrogen exits. Once it does, the world's energy infrastructure will change from its current oil-economy to a ''Hydrogen Economy'' Figure 5-36.

The shift from the current oil-based to the hydrogen economy requires careful planning and a sound technological base. Therefore, considerable R&D investments had been made in the recent years, not only by the public, but also by the industrial sector. As such, the automotive sector alone has invested 13 G€ in research focusing on technologies to reduce Greenhouse Gas (GHG) and air pollutant emissions in 2008. This corresponds to 43% of the total R&D investments [3].

These investments have turned the terrestrial fuel cell into a reliable, high performing system, sufficient to provide 25 kW of power (or more) for a car's drive train, with an anticipated duty cycle of 12,000 km per year and a life of at least 10 years [4,5]. Are these performance characteristics already sufficient to satisfy the requirements of future space missions? Would it therefore make sense to conduct a spin-in of terrestrial fuel cell technology into the aerospace sector? These are the questions that we are trying to answer with this paper.

### 6.3.2 The Hydrogen Value Chain

Figure 5-37 depicts the hydrogen value chain, which is valid for both the terrestrial and the space sector. Various $H_2$ production, storage and distribution methods exist, primarily driven by the final utilisation and specific environmental conditions.

Obviously space is primarily concerned by mass and volume considerations. Bearing in mind that the launch of 1 kg of mass into Low Earth Orbit (LEO) costs between €10,000 and €20,000, both factors play such an important role in the performance of the overall system that a somewhat higher cost of a high-performance fuel cell, carbon hydrogen piping and lightweight cryo-tanks can be readily traded-off against the mass/volume savings. Hydrogen production in space is not yet an issue, as launchers and spacecraft that rely on hydrogen take their supplies with them in specific cryogenic tanks for short duration missions. This item however might change in the future when a manned Lunar or Martian base is established. Such a base will require duty cycle numbers as well as power and energy levels of such magnitude (50 kW and more [6]) that battery technology will not be effective anymore; hydrogen based power systems will likely step in then and the hydrogen will have to be produced on site. Given the absence of natural gas and high temperature energy wells, the hydrogen production by means of electrolysis is likely to be the method of choice, if one does not rely on the utilisation of nuclear power.

In contrast to space, terrestrial applications focus primarily on safety aspects and on costs. Safety is of prime concern, as the number of systems is high, the likelihood of an accident is therefore higher as well and it is untrained persons that will handle the fuel dispenser, the hydrogen powered car or the Uninterrupted Power Supply (UPS). This is in strong contrast to the space sector, where all systems concerned are under constant supervision and all hydrogen related activities are performed by well trained experts, thus significantly reducing the likelihood of major incidents. The second major driver in the terrestrial sector is costs—on unit, subsystem and system level. In a competing mass market, which is governed by innovation pressure, limiting the time that a system can excel in the market, cost is a major item. According to Moore’s law , electronic systems feature a generation change every two to three years (refer to Figure 6-3).

Due to the high importance of electronics technology for most of nowadays systems, this leads to a trend of swifter generation changes in all areas. A car model is obsolescent after six years (10–20 years ago, car models lasted for nine years or more) and so are its major components—the fuel cell and its associated hydrogen storage and distribution system are no exception.

### 6.3.3 Hydrogen Storage and Distribution

With current technologies, hydrogen storage in space is most efficiently achieved on total system level by employing high pressure (100 bar) electrolysers for reactant regeneration from the water produced by fuel cells during eclipses. This is a significant advantage in terms of complexity and reliability compared with very high pressure (700 bar) tanks as proposed for FC cars, which would require compressors not lasting very long without maintenance. Additionally the reliability aspects of peripherals like pressure transducers and flow controllers is a significant problem.

Given the current shortfalls of cryo-systems, cryo-storage is not yet the method of choice for long term space missions. With the advent of high performance cryo-coolers however, this is likely to change. In contrast, short space missions, lasting no longer than a few weeks may be based on primary (non-regenerative) fuel cells. Liquefying the reactants in space in a regenerative system is not a technical option.

Slush is a possible advanced option to cryogenic storage, offering another 10% higher storage density. It is however at a very early stage and might be used for rocket fuel storage primarily.

Today’s state of the art for terrestrial hydrogen storage, such as in the automotive industry, comprises 35 MPa (350 bar) and 70 MPa (700 bar) compressed gas tanks. Carbon fibre fully wrapped-reinforced tanks are already in use in prototype hydrogen-powered vehicles. Two types of inner liners are typically used: metal (aluminium, Cr-alloys) ones in ‘‘Type 3’’ storage pressure vessels and high molecular weight polymer in ‘‘Type 4’’ tanks, as described in ISO 15869 [7]. The application of such materials comes from the need of guaranteeing impermeability of the inner liner to the hydrogen molecules whilst having the tank being as lightweight as possible.

Both SAE 2579 and draft ISO 15869 propose the following tests for compressed hydrogen storage tanks:

- Sequential exposure to impact, chemicals and cyclic stresses.
- Sequential exposure to static high pressures (simulates vehicle parking) and fuelling stresses.
- Exposure to hydrogen fuelling under extreme ambient temperatures.
- Simulated fuelling failure (i.e., overpressures) at the end of vehicle service.

It is up to specific research institutes and the industry to perform and further develop these test regimes as scientific knowledge progresses. And it is imperative to do this on global level so that the ‘‘Hydrogen Economy’’ vision can be realised. A major actor on European level, contributing to science, R&D and engineering, is the JRC-IET.

The Institute for Energy and Transport (IET) is part of the Directorate General Joint Research Centre (JRC) of the European Commission. Its mission is to provide scientific and technical support for the conception, development, implementation and monitoring of community policies related to energy.

The JRC-IET performs research in solar and nuclear power, power management, as well as hydrogen generation and storage, detection and usage, hence covering the whole hydrogen value chain (refer to Figure 5-37). To carry out ‘‘expected-service performance verification tests’’ on fullscale high pressure vehicle tanks for hydrogen or natural gas, the JRC-IET has set up a facility, dubbed GasTeF (for Gas Testing Facility, refer to Figure 5-38). In addition, the testing of any other high-pressure components, such as valves and pipes, is also possible Figure 6-5-Figure 6-9.

### 6.3.4 Terrestrial $H_2$ Utilisation: Applications, Technologies and Regulations

As depicted in Figure 5-37, hydrogen can be utilised in numerous ways, such as feedstock within chemical facilities, as fuel within combustion engines or as reactant in fuel cells. Of these three application areas the usage in combustion engines and fuel cells has not yet materialised in large numbers. This however is likely to change, as soon as the hydrogen economy will start to increasingly replace Internal Combustion Engines (ICE) by fuel cells.

A major driver for this replacement is $CO_2$ reduction, imperative for humanities world climate protection activities. When hydrogen serves as energy carrier, $CO_2$ production will not happen anymore in our cars but–if at all–during $H_2$ production, for example when steam reforming is utilised.

In comparison to battery based systems, Hydrogen based energy systems excel when higher power and/or energy levels are required. This is due to the better scalability of the system, traded-off for higher complexity. Compared to a fairly simple battery system, comprised of the battery, a battery charge and discharge regulator and a shunt, a fuel cell system is much more complex. It has however the distinctive advantage that the hydrogen storage is a separate element, such as a high pressure hydrogen tank. When one tailors the system therefore to a certain power/energy level only the hydrogen storage element is concerned, while the fuel cell and its accessories are mostly untouched. In short it means that if one wants to double the energy level of a battery system, the complete mass of this system will double. For a hydrogen based system, only the hydrogen tank volume will double—but not the total mass of the complete system.

During the last two decades, fuel cells regained great attention both in academia and industry as they are more energy efficient (direct conversion to electricity) and far more versatile than conventional electrical energy conversion systems. In the near term, their application in automotive propulsion (on-road and off-road) and onboard power as well as in auxiliary power units (APU) including uninterrupted power supply systems (UPS) and distributed power generation (DG) is expected to make drastic changes to the automotive and power generation sectors also driven by the ever increasing need for cleaner and more sustainable fuels and of power demands. Given the large scale build-up of refuelling infrastructures, low cost production and the availability of safe storage capacities hydrogen is one suitable future energy carrier to harvest the great potential of fuel cells in these terrestrial applications.

#### 6.3.4.1 Mobile Applications

Polymer electrolyte or Proton Exchange membrane Fuel Cells (PEFC) rapidly developed during the last two decades especially in mobile applications and particularly in the automotive sector. PEFC are relatively compact, have high power densities, high efficiencies at partial load, fairly rapid start-up capabilities and are ideally suited for mobile applications, operating at low temperatures (50–120 °C). Although low temperature PEFC use noble metals especially platinum, a scarce and hugely expensive resource and have a water management issue as the electrolyte membrane (e.g., nafion) needs humidification at all times to exhibit high proton conductivity, the other attractive characteristics as mentioned suggest PEFC as possible power sources in vehicles for both propulsion and as APU. The latter helps to run electric steering and brakes, A/C compressors, and even entertainment devices.

Nevertheless, more than a few technological challenges are to be tackled before mass production and commercialisation of fuel cell passenger cars and buses becomes an everyday experience. Apart from drastic cost reductions for the fuel cell system including balance-of-plant components (US$ 50 kW system target) and drive train, these challenges are mainly fuel quality tolerances, durability (> 5,000 h operation target equivalent to 250,000 km driven), diverse environments (climate zones and road surface conditions, e.g. cold start at - 40 °C), and volume and weight reductions (2,000 W/l and 2,000 W/kg targets) especially for on-road vehicles. The development of new materials with improved properties and structures for the MEA (Membrane Electrolyte and Electrodes Assembly), GDL (Gas Diffusion Layer) bipolar gas separator plates, gaskets and sealants, of new processing routes and production methods capable of mass manufacture, new designs and optimised operation strategies are the focus in present R&D efforts.

The optimum choice of a hybridisation consisting of adding a supplementary battery and/or capacitor to the fuel cell system to meet complex operation modes (driving cycles, starts–stops, high power loads and idling condition) is another technology challenge for fuel cell vehicles to equate on the ride energy consumption to generation.

#### 6.3.4.2 Stationary Applications

In stationary power generation, fuel cells perform advantageously for modularity, reduced space demand, higher electrical efficiencies (> 50% at stack level), massively reduced emissions to air and great versatility from low to high capacity power systems (few kilowatts to megawatts).

PEFC operation is most often continuous in such application, for example, for residential use (μ–CHP or combined heat and power) to supply electricity and heat (hot water) and is far less complex in discontinuous operation, for example, in APU and UPS in strong contrast to vehicular PEFC, which are much more stressed and thus degrade far more rapidly. Although the demand on durability is greater for stationary PEFC (> 40,000 h of operation with maximum 1% degradation per 1000 operation hours), fewer constraints regarding design, dimension, fuel quality and operational performance make them more cost effective than in mobile applications. Also, stationary PEFC can play a major role in future power generation especially in DG markets due to their ability to utilise in conjunction with reforming and gasification a variety of fuels whether of fossil (diesel, natural gas, LPG) or renewable origin (e.g., biogas) and to readily and intermittently supply power for grid load levelling (load shaving and balancing of renewable energy sources) especially when embedded into intelligent energy grids.

Current R&D efforts for stationary PEFC focus largely on materials developments mainly at cell (membranes) and stack level (bipolar plates), new system designs including optimisation and integration of balance-ofplant components, improvements in operational performance and reducing stack degradation as well as on system cost reduction and wider demonstration.

#### 6.3.4.3 Safety Standards and Regulations

Hydrogen technologies, as well as all other new energy technologies, have to comply with a set of safety standards and regulations. Common sense approach is that the new technology has to guarantee the same as or better safety level than the already widely adopted technologies. Due to the specific and unique aspects of the hydrogen technologies, in the past years standardisation and regulatory bodies have been intensely busy in adapting existing, and in many case developing completely new regulations, codes and standards concerning the performance assessment and safety testing of hydrogen components for transport, stationary and mobile applications.

A thorough overview of all existing standards does not fit in the scope of this paper. It will be enough to mention, in relation to international standards, the work of the Technical Committee on Hydrogen technologies of the International Standard organisation, which has produced, among many others, standards for gaseous and liquid hydrogen storage devices and hydrogen blends [8,9]. These two documents specify the requirements for refillable fuel tanks intended for on-board storage of respectively high-pressure compressed gaseous and liquid hydrogen on land vehicles. Similarly, the International Electrochemical Committee has focussed with its Technical Committee 105 on standards regarding fuel cells technologies for all commercial land-based applications. Among its many publications it is worth to mention the IEC safety and performance testing standards for stationary fuel cells [10,11] and the correspondent safety standard for portable fuel cells system [12]. Important and pioneering work has been performed by SAE International for example with the Technical Information Report on vehicular hydrogen systems [13], which first among the standardisation bodies adopted a full performance-based standard to guarantee safety operation during the whole life of hydrogen pressurised components. The standard consists mainly of an Expected-Service Performance Verification test and a Durability Performance Verification test.

In parallel to these standardisation activities, and often building upon them, a similar effort has been invested at national and international levels for the development of legally binding regulations. The European Commission has prepared a regulation for type approval of hydrogen-powered motor vehicles [14] which has been approved by the European Parliament and the Council in 2009 and, in 2010 [15], an additional, more technical document containing the implementing measures such as the individual tests required for the type approval. In this document all the tests and performance requirements needed to ensure safe and reliable function of all the components of a hydrogen-propelled vehicle are described in detail. Typical tests for high pressure components such as tanks are: burst test, bonfire test (resistance to fire), chemical exposure test, ambient temperature and extreme temperature pressure cycle tests, accelerated stress rupture test, impact damage test, leakage test hydrogen gas cycling test. According to the hydrogen gas cycling test, for example, the high pressure tank must be subjected without deterioration to 1000 hydrogen filling and emptying cycles which simulates the refilling at the refuelling station, followed by the fuel consumption during travel.

More recently, the United Nations Economic Commission for Europe (UN-ECE) has also concluded the drafting work for a Global Technical Regulation for Hydrogen Fuelled Vehicle [16], containing compliance tests for fuel system integrity, test procedures for compressed hydrogen storage and for electrical safety.

### 6.3.5 Aerospace $H_2$ Utilisation: Applications and Technologies

Ten years ago, storage and distribution of hydrogen resembled a huge issue – both for the upstream (from the production to the fuel station) as well as for the downstream part (fuel station to the automobile). Today, the issue has been partly closed, with the automotive industry agreeing among its members to use the storage of gaseous hydrogen in high pressure tanks as the technical baseline for the automobiles of the future. With the downstream storage and distribution issue being closed, focus is now put on the upstream part and the question, how the hydrogen will be best transported from the production facilities (e.g., nuclear power plants, wind parks, etc.) to the dispensers of the refuelling stations. It is not a matter of technology per se – but rather a question of cost effectiveness. Only time and continued R&D will tell whether this role is to be fulfilled by hydrogen pipelines, hydrogen trailers and/or localised hydrogen production facilities.

As far as aerospace is concerned, one can foresee that hydrogen will gradually move into energy and propulsion related applications. This is due to the fact that hydrogen energy systems scale better then solar cells or batteries when bigger power levels are needed – which means that their mass increases at a lower rate per power increment, leading to a lower mass at a certain power level - and that hydrogen constitutes the best propulsive medium that can be used. No other medium is lighter in mass and can therefore provide readily for high specific impulse ($I_{SP}$) levels, which are paramount to save on fuel consumption.

#### 6.3.5.1 $H_2$ based Propulsion Systems

Let us take the example of a Telecom satellite, such as the ASTRA 1K, with a mass of 5250 kg and an anticipated lifetime of 15 years. As a typical telecom satellite, ASTRA 1K will be parked in the geostationary belt, 35,786 km above the Earth's equator. It will be brought to a Geostationary Transfer Orbit (GTO) by a Heavy Lift Launch Vehicle (HLLV) like an Ariane 5 or a Proton, and once it has been released there it will fire its main engines to arrive at its designated slot in the Geostationary Orbit (GEO). This manoeuvre has already taken some fuel, but although the satellite is now in its final parking position, there is more to be spent. The Sun and the Moon, the Earth's gravity field, all sorts of disturbances act on the Telecom satellite, trying to move it out of its slot. To maintain in the designated position and out of any collision courses with the adjacent Telecom satellites, roughly 50 m/s velocity increment have to be invested every year. This surmounts to 750 m/s in 15 years and dependent on the chosen propulsion system, the required fuel mass ranges from 1181.40 kg for a classical bi-propellant system with an $I_{SP}$ of 300 s, to 245.04 kg for a plasma engine with an $I_{SP}$ of 1600 s and 99.42 kg for an advanced pulsed plasma thruster with an $I_{SP}$ of 4000 s [17]. The dependency of the required fuel ($m_{propellant}$) is described by equation (1), whereby $m_{S/C\_Initial}$ resembles the initial spacecraft mass before the manoeuvre, ΔV is the velocity increment (in our case 15 x 50 m/s) and g is the standard acceleration of gravity, hence 9.81 m/s².

$$m_{propellant} = m_{S/C\_Initial}(1 - e^{-(\frac{\Delta V}{g \cdot I_{SP}})}) \qquad (1)$$

*Equation 6-1: Propellant Mass as Function of Spacecraft Mass and ΔV*

Hydrogen would clearly be the best propulsive medium, were it not for the fact that it features a mediocre storage performance due to its low density. At the moment the fuel savings are more than offset by the mass penalty of the hydrogen tanks, making it impractical to use $H_2$ as propellant, besides of HLLVs where matters of thrust-to-weight ratio come into play as well. Once high performance engines become available – such as high performance plasma, fission and/or fusion engines - then things might change and then it will make sense to copy the terrestrial upstream $H_2$ distribution and storage solutions for space. Consequently, hydrogen tanker spaceships might then be utilised to supply remote outposts, as envisaged in the Aurora programme of the European Space Agency ESA (here as feedstock hydrogen for an In-Situ Resource Utilisation (ISRU) plant on Mars, utilising the Sabatier-reaction to produce methane as rocket fuel) [18].

#### 6.3.5.2 $H_2$ based Energy Systems: Human Spaceflight

Fuel cells have been used in NASA's human space missions like Gemini, Apollo and the Space Shuttle providing primarily high power levels and as added benefit potable water. These applications were all non-regenerative and demand the availability of enough fuel and oxidiser to support the entire mission.

Current human exploration architecture and system studies as well as technology developments in the area of regenerative fuel cell systems - a combination of fuel cell and electrolyser - show that this technology is critical for larger human space exploration missions of the future. Typical examples of system studies are lunar habitats/bases and Lunar Pressurised Rovers. But what also has been shown is the overall synergy within a manned architecture between the Life Support systems, the Power Management systems (regenerative FC) and the In Situ Resource Utilisation systems which all share the use of $O_2$ and $H_2$. Future systems will need to be designed from the start utilising these synergies allowing sharing of resources and reduced system mass.

Under a study being performed by CGS for ESA on Energy Provision and Management an architecture for energy provision for a lunar base has been defined utilising solar arrays for the power generation, regenerative fuel cells for power conversion and some batteries for auxiliary power. The design relies on many smaller Lunar Power Plant Elements each compatible with a possible lunar lander sized according to the Ariane 5 capabilities. Depending on the power needs and the gradual build-up of a station, additional power plants could be introduced into the system. The solar arrays would provide the power under daylight conditions to electrolyse water into $H_2/O_2$ which would then be stored for future use. The $O_2/H_2$ can then either be used at the base during night conditions or transferred to e.g., a Lunar Rover for use on a specific expedition away from the base.

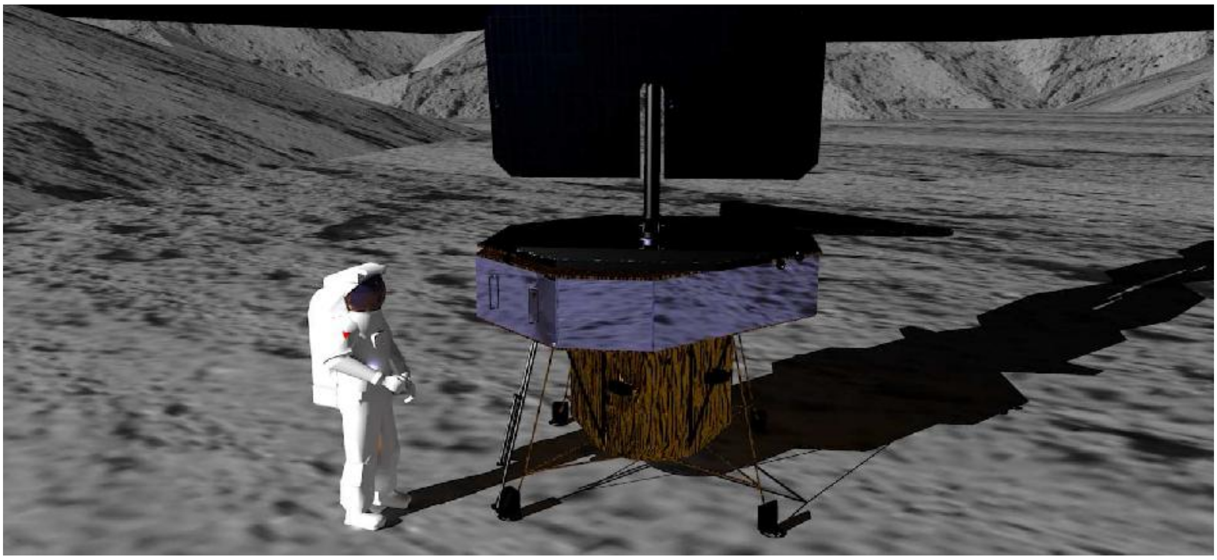

*Figure 6-5: Lunar Power Plant Element (Source: CGS/ESA)*

Similar to an automobile on Earth, the combination of high pressure hydrogen gas tanks, buffer batteries, hydrogen leakage detectors and fuel cells could provide critical technology for a manned pressurised rover, allowing 2-4 astronauts to explore planetary bodies like the Moon during a cruise of several weeks, thereby covering a range of 1000 km or more. As part of an ESA contract with Thales Alenia Space, the Liquifer Systems Group (LSG) has designed a Rover for Advanced Mission Applications (RAMA).

RAMA has been designed for surface missions with a crew of two or three lasting up to approximately 40 days, its source of energy, a fuel cell fed with hydrogen and oxygen coming from cryogenic tanks, allowing it to be driven and operated during the day as well as the night. RAMA may be operated and replenished from a fixed site base or co-operate with other rovers of the same type to provide a mobile base. The rover in all cases will be refuelled using the products supplied by an in-situ resources facility.

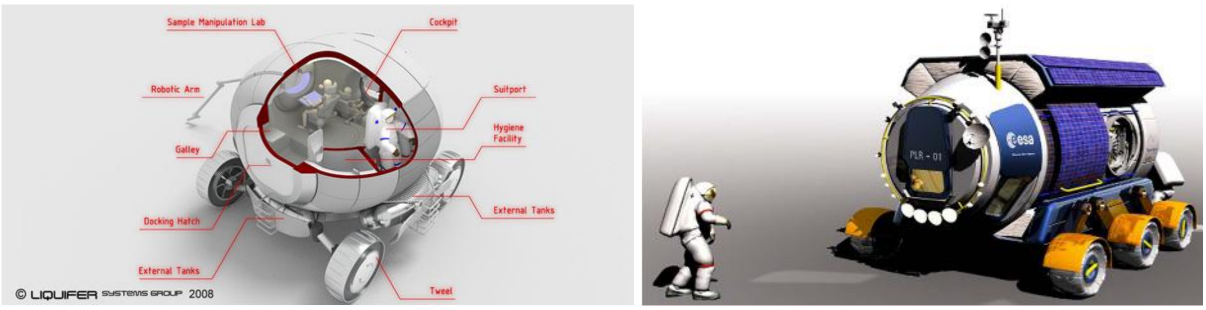


*Figure 6-6: Illustration of LSG’s RAMA Concept [left] (Source: Liquifer website) and of the Lunar Pressurised Rover (Source: TAS-I/ESA) [right]*

A later design by TAS-I with different requirements provided the Pressurised Lunar Rover (PLR) concept, which similar to RAMA relied on regenerative fuel cells for its main power generator. The PLR would start its mission with full tanks of $O_2$/$H_2$ which would be depleted during the mission. Sizing of the tanks is done including operational and system contingencies. Batteries would be used for auxiliary power and for redundancy. During all passive operation, i.e., not roving, the PLR would deploy small solar arrays to augment the available power. As with the Lunar Power Elements mentioned above, this power would be used to electrolyse water into $O_2/H_2$ for storage. After the mission the PLR would be able to connect to the Lunar Base and transfer the water for processing while taking on board $O_2/H_2$ for the next mission.

Lunar ISRU plants would be possible which would extract $O_2$ from the Lunar Regolith and produce water or $O_2$ directly. Bread boarding activities performed by CGS for ESA have shown that this is feasible using carbo-thermal reduction of Regolith with Methane. The investigated process would use Methane and Hydrogen in a cyclic manner needing replenishment only to overcome leakage and waste due to inefficient processes.

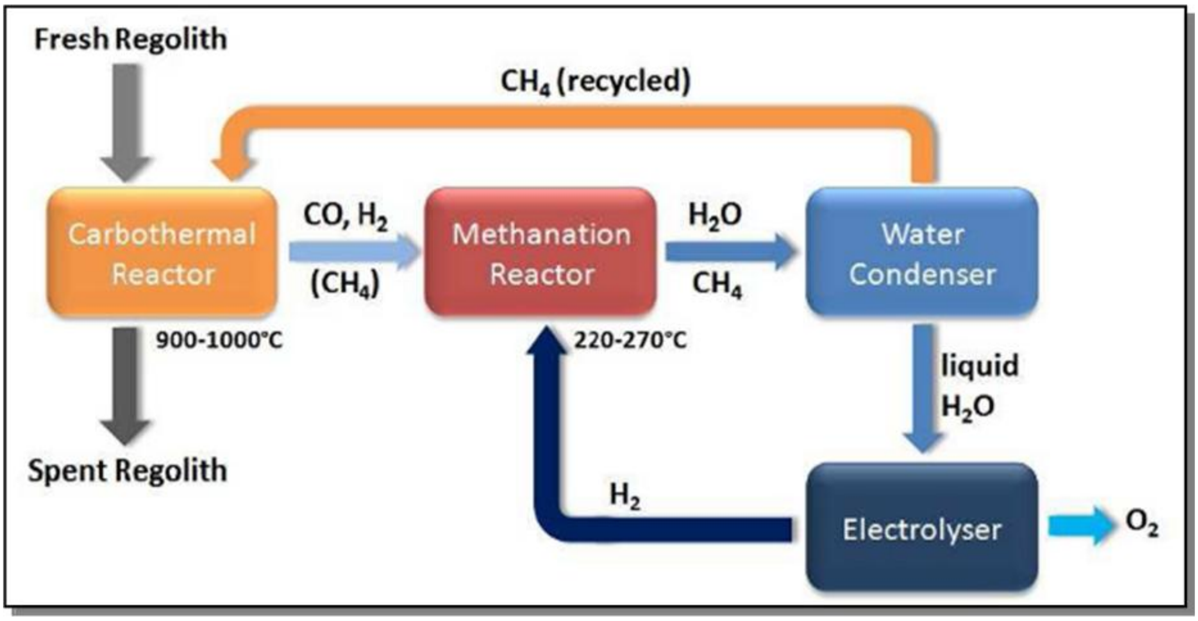


*Figure 6-7: Oxygen Process Ideal Process (Source: CGS/ESA)*

Obviously there is a significant synergy with the fuel cells in the automotive sector, but with a few major differences. While the terrestrial applications have chosen high pressure tanks for $H_2$ storage, space applications vary between cryogenic storage for short duration missions without reactant regeneration and medium pressure tanks avoiding compressors.

#### 6.3.5.3 $H_2$ based Energy Systems: Telecomm Satellites

The commercial part of space technology is satellite communication and there in particular it is the TV broadcast branch generating globally more than 120 G$ annual revenues. The value chain starts at satellite manufacturing worth about 4 G$ annual. A 30 times multiplication of downstream value is enabled by a sophisticated technology. The work horse in TV broadcast is operating in the Ku-band. The available spectrum there allows 110 transponder to be transmitted from one orbital position. Each transponder has a usable bandwidth of 36 MHz. An angular separation is needed to limit the interference generated by neighbouring satellites.

The basic task of a TV broadcast satellite is to serve a large number of customers. Therefore coverage area is the most relevant parameter of a communications satellite. Another important parameter of a TV broadcast satellite is its EIRP which is the product of transmit power and transmit antenna gain. An EIRP of 54 dBW is one commonly used value. The transmit power for this ranges between 110 and 150 W. The coverage area is determined by the beamwidth of the antenna. A beamwidth of 3° creates a spot of about 2100 km radius on Earth. The antenna diameter required is about 50 cm. The antenna gain is 33 dB. The difference between an EIRP of 54 dBW and an antenna gain of 33 dB is 21 dBW or 125 W. That is the transmit power required per transponder. A state-of-the-art TV broadcast satellite can carry about 50 transponders. Its launch mass is about 5,800 kg. The geostationary mass at begin of live is 3,400 kg, the difference of 2,400 kg is required to inject the satellite into the geostationary orbit once released from the launcher. The DC power generated is 16 kW, resulting in e.g., an EIRP of 54 dBW per transponder. Due to the orbital configuration there is a shadowing of the satellites solar arrays if the satellite the Earth and the Sun are aligned on one line. This is happening during two periods per year, around 21st March and 21st September. This effect is known as equinox and requires buffering of the DC power by on-board batteries. A power black-out is not acceptable for satellite operators, since a single transponders is leased for about 1 M$ to 4 M$ per year to broadcasters. The maximal eclipse duration is just below 80 minutes and is happening during so-called prime time. A single power black-out would destroy the business of a satellite operator immediately because customers would re-point their antennas to another satellite. The satellite battery is absolutely needed and their availability without noticeable degradation during the typical lifetime of 15 years of the satellite needs to be guaranteed by the satellite manufacturer. Due to their charge and discharge cycles batteries may degrade. Particular attention needs to be paid to ensure their specified performance.

State-of-the-art battery technology is $NiH_2$ with a tendency of using Li-Ion batteries in new spacecrafts. The figure of merit is Energy per mass. For $NiH_2$ batteries we have about 50 Wh/kg and for Li-Ion batteries about 90 Wh/kg. In the previous case of a 48 transponder satellite with 16 kW power the mass of the Li-Ion battery pack is about 333 kg.

If we replace the Li-Ion battery with regenerative fuel cells having a specific energy of 145 Wh/kg for the same DC power the FC mass would drop to 210 kg. This would result in a lower dry mass of the satellite of about 2,050 kg, a GEO BOL mass of about 3,100 kg and a launch mass of about 5,300 kg. The spacecraft would be lighter and therefore cheaper, the launch would also be cheaper. An overall cost reduction of about 6-7 % is estimated.

In the year 2008 Thales Alenia Space has performed a “Fuel Cells for Telecom Satellite System Study” [19], with the objective to determine the overall performances of a selected total RFCS, chosen among the ‘available’ ones, in a closed loop system compared to an advanced Li-Ion battery system (G5 technology 180 Wh/cell). The work was focused on the implementation of a Regenerative Fuel Cell System (RFCS) on a large telecom platform (15 kW total satellite power requirement).

The RFCS was subject to the following requirements:

- The FC shall be qualified for > 2250 hours.
- Efficiency allocation: Fuel Cell mode > 50%, Electrolysis mode > 90%
- A reliability figure of 0.99 at 15 years is a target. Double isolation shall be implemented
- The equipment shall be designed to meet space environmental conditions.
- Protections shall be implemented in the RFCS or on board the satellite to avoid any degradation of the mission.
- The RFCS shall respect Electromagnetic Compatibility for itself and with respect to the rest of the spacecraft. Safety rules shall be respected.
- The supplier shall identify in the user’s manual and justify the constraints associated to the powering ON/OFF of the RFCS.
- Maximum voltage range: 0-100 Volts.

Trends were derived for power levels from 15 kW up to 30 kW and a system study was carried out for a payload with a power level of 11.3 kW. The following graphics outline the volume and mass trends for the assessed energy storage systems:

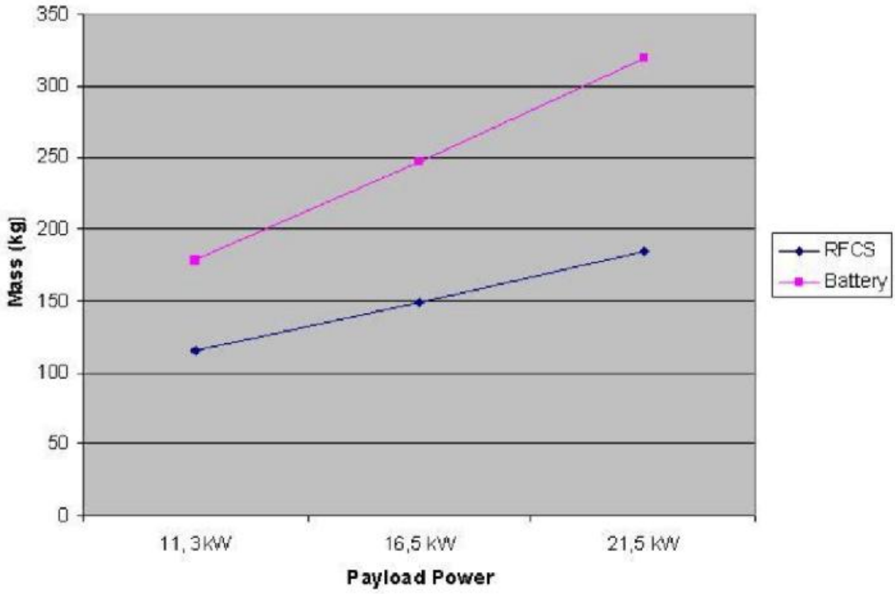


*Figure 6-8: Mass trend for the energy storage systems (Source: ESA Fuel Cells for Telecom Satellite Systems Study)*

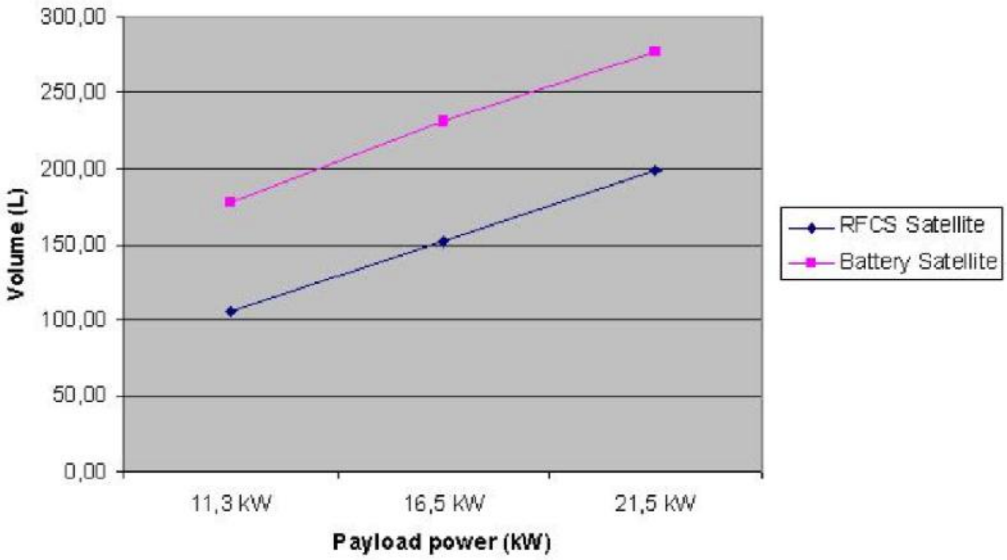


*Figure 6-9: Volume trend for the energy storage systems (Source: ESA Fuel Cells for Telecom Satellite Systems Study)*

If now we keep the same launch mass as previously and install regenerative fuel cells instead of Li-Ion batteries we could increase the generated DC power to about 20 kW. The ratio of 20 kW over 16 kW is equivalent to 1 dB. That means that such a TV broadcast satellite could transmit in each transponder an EIRP of 1 dB higher. That seems not a big improvement; it is only 25 % more. However, looking at the coverage, depicted in Figure 6-10, we can see a wider geographical coverage with a 1 dB higher EIRP. This can be seen either as an increase of the coverage area, thereby accessing a bigger number of potential customers or a greater amount of more satisfied customers in that region, as this 1 dB offers higher resilience vs. bad weather conditions etc.; in any case, this 1 dB surplus finally results in higher revenues, as the satellite broadcaster can charge higher transponder lease rates to his customer, the broadcaster.

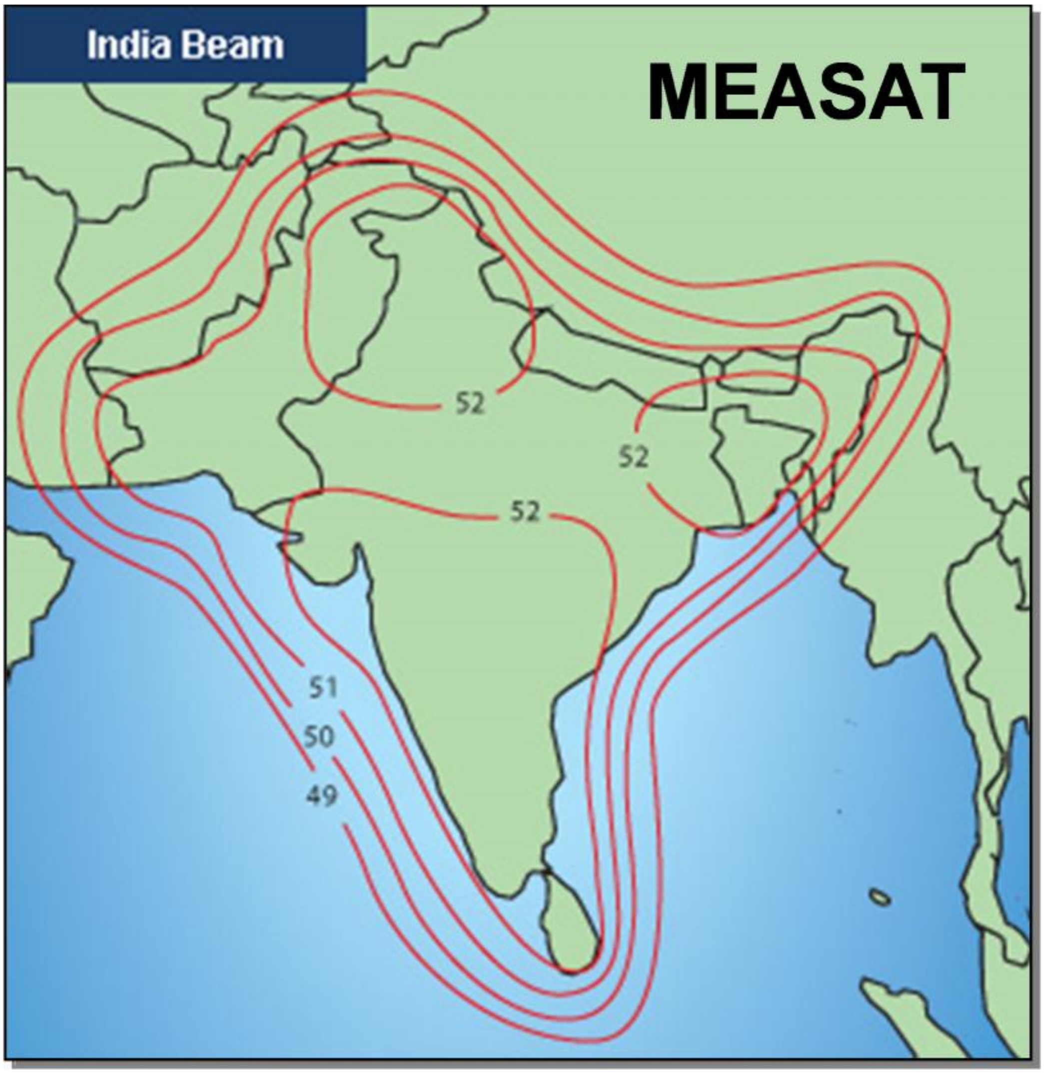


*Figure 6-10: Indian beam coverage by Measat (Source: www.measat.com)*

Since the entrance of new technologies into commercial communication satellites is relative slow compared with e.g., terrestrial communication technologies the necessary research needs to start early enough to have the product available right in time. The Boeing Company is developing under DARPA contract a new generation solar array. The goal is a scalable design of a 30 kW electrical power solar array with a specific mass of 130 W/kg. That is about twice better than today's solar arrays. The 30 kW array can be launched together with a LEO satellite on a FALCON 1E launcher having a fairing of 1.7 m. For launchers with 5 m fairing, such as Ariane V, Atlas V and Delta IV about 180 kW electrical power arrays can be launched. Such high power satellites can have another attractive feature; to use electric propulsion for orbit raising from perigee to apogee. The 30 kW array could achieve an orbit-raising time of about 60 days. The additional positive effect is that a huge saving in apogee propellant will be made at the cost of orbit raising duration. This mass saving can be used to increase the payload mass and together with the achieved high power a total increase of payload performance is made. It is obvious from this future trend that the application of regenerative fuel cells in commercial communication satellites replacing batteries will be needed to finally increase the business case of the satellite operators.

#### 6.3.5.4 $H_2$ based Energy Systems: Earth Observation Satellites

Earth observation (EO) satellite missions serve a very broad range of applications This has a direct impact on platform size, instrument choice and number, orbit selection and, as a result, on power requirements.

From a purpose-focussed approach, one can distinguish three types of (Earth) remote sensing missions: (a) multi-purpose missions; (b) specialised missions; (c) operational missions. Whereas (a) and (b), in the typology used for simplification purposes, are science-driven missions, (c) missions are feeding practical applications. Class (c) missions generally use robust technologies and build on heritage of precursor missions; data collected with such missions are translated into services. The European Sentinel satellites, in the frame of GMES (see below), are examples of operational missions.

In a first approach to examine power requirements of current and future EO missions, it can be stated that mission requirements – as primary influencing factor of the power budget – are in general more restricting in terms of resolution, coverage, revisit time, accuracy and stability than for space exploration missions [20]. Another factor is the question whether a platform carries an active instrument (radar, lidar) or passive instruments only; and the number of instruments. Instrument sizes and masses are linked to the required repetition rate and observation accuracy, on top of the technical characteristics of the observation technology employed.

A basic advantage compared to interplanetary spacecraft missions is the relative proximity to the Sun at 1 Astronomical Unit (not taking into account concepts with Lagrange positioning). This allows practically all EO missions to gain energy from the Sun through solar arrays. The type and required size of the solar array in return is a mass factor.

EO mission cover today a vast array of scientific and operational applications, ranging from climate monitoring to weather monitoring, from land surface to ocean surface monitoring; from ground-penetrating radars to atmospheric chemical constituency monitoring; from global, medium-resolution data sets to very high resolution optical imagery. The ‘standard orbit’ for most optical and radar missions is a low Earth orbit between 600 and 900 km, usually sun-synchronous (SSO). Swath and GSD vary from mission to mission. The geostationary orbit is a primary high ground for many meteorological missions, although new concepts think of an enlarged use of this orbit for other types of EO satellites.

The pioneering ERS missions of ESA provided continuous data collection from 1991 to 2011 (ERS-2 was passivated in September 2011). ERS constituted the first civil Synthetic Aperture Radar (SAR) ever flown. The satellites had a launch mass of about 2.5 tons (2384 kg for ERS-1 and 2516 kg for ERS-2). ERS-1 was powered by two 5.8 m x 2.4 m solar array wings with 22,260 silicon solar cells supplying more than 2000 W [21].

The successor mission Envisat is until today the largest EO satellite ever built. It is a multi-purpose mission with ten instruments on the tailor-made platform. Envisat was launched in 2002. It has an overall mass of 8211 kg [21], more than tripling the mass of ERS-2, and flies in SSO at about 800 km with a 35 day repeat cycle. This mission has a high power demand. Its power budget accounts for 3560 W total load in sunlight (at 3847 W system capability), out of which 1841 W for the payload [21].

Earth Explorers (EE) form a smaller satellite class. Their existence is linked to the development of Earth system science and the need to answer specific scientific questions related to various elements of the planet's interior, surface, water body, cryosphere and atmosphere. Each EE has a precise scientific task; the EE are medium-size EO research missions.

CryoSat-2, launched in 2010, measures the variation of ice volumes on Earth. Two GaAs body-mounted solar arrays deliver 850 W each. The SMOS (Soil Moisture and Ocean Salinity) mission, launched in 2009, uses an interferometric radiometer to measure microwave radiation emitted from Earth's surface within the L-band (1.4 GHz) [21]. The power budget accounts for up to 1065 W, out of which 511 W are available for the payload. The GOCE mission is perhaps the lowest-orbiting EO science mission. It weighs about 1t and is tasked to measure the Earth's gravity field with the highest accuracy so far obtained. A fixed Gallium Arsenide (GaAs) cell solar array provides 1300 W [21].

The EarthCARE satellite (under development) is an example of a rather complex and big EE (mass with fuel app. 2 t) with two active instruments. The mission shall help a better understanding of atmospheric cloud–aerosol interactions and of the radiative balance of Earth; nominal lifetime is 3 years. EarthCARE features a deployable solar array (GaAs triple junction cells) with an end-of-life average power of 1710 W (1670 W required in nominal mode).

Another important class of EO missions are meteorological satellites. In Europe, industry develops the Meteosat series (now: in third generation; MTG) under ESA management. Once in orbit, the satellites are operated by a dedicated international organisation, EUMETSAT. The currently operational system – Meteosat Second Generation (MSG) – consists of spin-stabilised satellites in geostationary orbit with a power requirement of 600W at end of life (after seven years in orbit). The MSG solar array is built from eight curved panels (2.4 m high and 1.25 m wide) linked in a drum skirt around the satellite body. One of the panels has a cut-out for the instrument aperture [21]. The array delivers app. 720 W of power at equinox. Two Nickel-Cadmium batteries serve for eclipse periods.

As example of a meteorological mission of significant size in LEO, the MetOp mission has 1812 W power consumption at end of life; it builds on the heritage of Envisat.

Since the suite of European missions serves as exemplary 'cross-section' of modern EO mission families here, it is imperative to take a look at the successors of the ERS and Envisat 'workhorses': the Sentinels. The Sentinel missions cover a broad range of operational requirements and are being developed for the European Global Monitoring for Environment and Security (GMES) programme. Sentinel-4 and Sentinel-5 are instruments to be embarked on the MTG and MetOp Second Generation. Sentinel-1, -2 and -3 units are satellites of their own, currently under development for launches as of 2013.

The Sentinel-1 mission is designed for a nominal lifetime of seven years, to fly in a SSO in a 12-day repeat cycle at 693 km altitude (mean LST 18:00 at Ascending Node), with almost 100 h operative autonomy and a maximum eclipse duration of about 19 min. Launch mass is 2300 kg. The Sentinel-1 power budget is impressive: 5900 W at end-of-life.

Sentinel-2 (7.25 years nominal lifetime; SSO at 786 km; 5 days global revisit with two satellites; 15 days of operative autonomy) will obtain high resolution land imagery. Launch mass is 1150 kg. It features a multispectral instrument payload (13 channels with a resolution of 10, 20 and 60 m). Power is provided by a 7.2 $m^2$ solar array providing 1700W at end-of-life.

The Sentinel-3 mission will serve land applications on a global scale as well as operational oceanography, providing 2 day global coverage (with two satellites) and aiming at a real-time product delivery in less than 3 hours. Two satellites shall operate simultaneously. Mission duration per satellite is about 7 years, and the launch mass is 1250 kg. In order to fulfil the requirements, Sentinel-3 will fly in a frozen SSO with a 27 day repeat cycle at 814.5 km altitude and 10:00 at descending node. The power budget is 2100 W (10 $m^2$ triple junction solar cells), powering an ocean and land colour instrument, a SAR radar altimeter and a microwave radiometer.

*Table 6-4: ESA's EO Satellites: Mass and power levels*

| ESA Earth Observation Satellites | | | | |
|---|---|---|---|---|
| **Name** | **Operational Period** | **Mass** | **Power** | **Comment** |
| ERS | 1991 - 2001 | ca. 2500 kg | 2000 W | SAR |
| Envisat | 2002 - now | 8211 kg | 3560 W | SAR |
| MSG | 2002 - now | 2036 kg | 720 W | |
| MetOp | 2006 - now | 4093 kg | 1812 W | |
| GOCE | 2009 - now | ca. 1000 kg | 1300 W | |
| SMOS | 2009 - now | 658 kg | 1065 W | |
| CryoSat-2 | 2010 - now | 750 kg | 1700 W | |
| EarthCARE | TBD | ca. 2000 kg | 1710 W | |
| Sentinel-1 | TBD | 2300 kg | 5900 W | SAR |
| Sentinel-2 | TBD | 1150 kg | 1700 W | |
| Sentinel-3 | TBD | 1250 kg | 2100 W | |

The power budget of the examined missions ranges between 600 W and 6000 W. The highest power budgets are related to large multi-instrument satellites with active sensors (such as missions with SAR). They will remain a pillar of the portfolio (Table 6-4).

The future EO mission landscape is scattered in terms of size, mass and power requirements, due to the multitude of observational needs in scientific and operational EO. Certainly describable as a trend, small spacecraft (like the off-the-shelf missions from SSTL (UK)) are increasingly successful. A European example of a small satellite (constellation) is the German Rapideye: three GaAs solar panels provide about 100 W of power generation capability when in the sun [21]. Many concepts are under review or study; they explore innovative observation concepts; the use of new or seldom used frequencies like P-band; increased synergy with other instruments and missions; convoy or formation flying; data continuation for sustainable observation series; new orbits (e.g., high resolution from the geostationary orbit).

It can be assumed that power requirements of civil EO satellites will stay within the margins exemplarily described above.

An area of Earth Observation satellites not discussed so far are the exclusively military EO satellites, of which the RADAR satellites form again the class with the highest power levels. Naturally information on these satellites is difficult to obtain, but albeit scarce, available data suggest that there is clear leader in this sector: the US LACROSSE/VEGA/ONYX satellites (Figure 6-11). Built to overcome the shortcomings of classical optical intelligence satellites - the inability to see through clouds - the Lacrosse satellites use a powerful SAR to provide intelligence data. Already started in 1976 by the CIA, the first satellite was launched in 1988 by the Space Shuttle from Vandenberg [22]. Assumed to feature a resolution of less than 1 m and a total mass of 14,500-26,000 kg, the satellites are reported to utilise a solar array with a wingspan of nearly 50 m, "which suggests that the power available to the radar could be in the range of 10 to 20 kilowatts, as much as ten times greater than that of any previously flown space-based radar" [22].

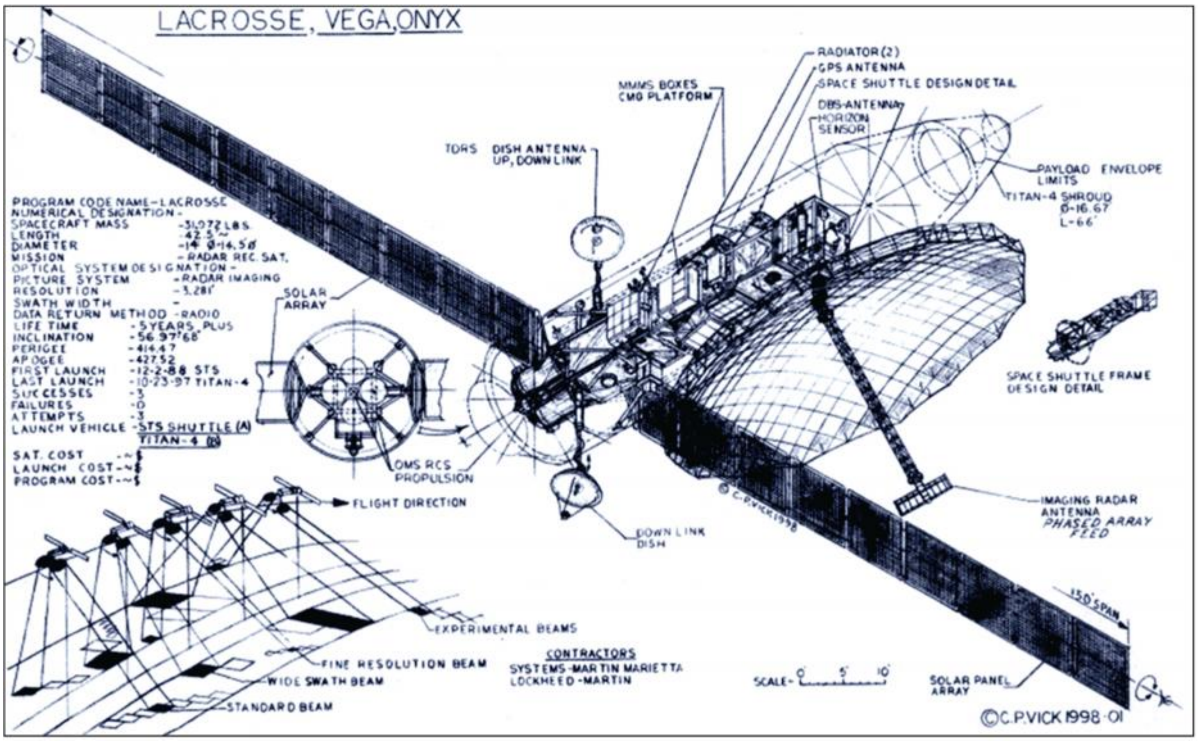


*Figure 6-11: Artistic concept of LACROSSE/VEGA/ONYX (Source: Spacefacts.de)*

10-20 kW of electric power is a power level that is well within the power regimes of today's telecom satellites. If RADAR satellites will continue to play a role in modern and future reconnaissance efforts - and there is strong credence in the belief that this will be case - then we are likely to see even more powerful SAR satellites, reaching and exceeding the 20 kW threshold in the years to come. The main driver for this power level increase are military requirements, such as the demand for better resolutions and greater penetration depths of the signal, to track down bunkers and submarines for example.

### 6.3.6 Batteries and Fuel Cells

#### 6.3.6.1 Aerospace

The retired US Orbiter clearly has written fuel cell history for fuel cells in space, batteries could not do the job, even with nowadays most advanced lithium-ion technology fuel cells perform better. It has been simply a question of mass. Batteries at the time of the shuttle design offered not more than 50 Wh/kg if they were depleted to 100%, not realistic for reliability and life time, whereas the now almost 40 year old fuel cell provided by IFC, a subsidiary of United Technology, offered more than 1000 Wh/kg including all reactant storage inclusive tanks.

Given the mission profile of the Space Shuttle, which spent 14 days in space at most, the final design choice was an easy one; the energy system was designed as a primary system, a system where the reactants were not regenerated, hence an electrolyser was not part of the system (refer to Figure 6-12). An additional advantage of this concept, still holding through today, is that a fuel cell based on hydrogen and oxygen will produce drinkable water - water that was used by the astronauts on board.

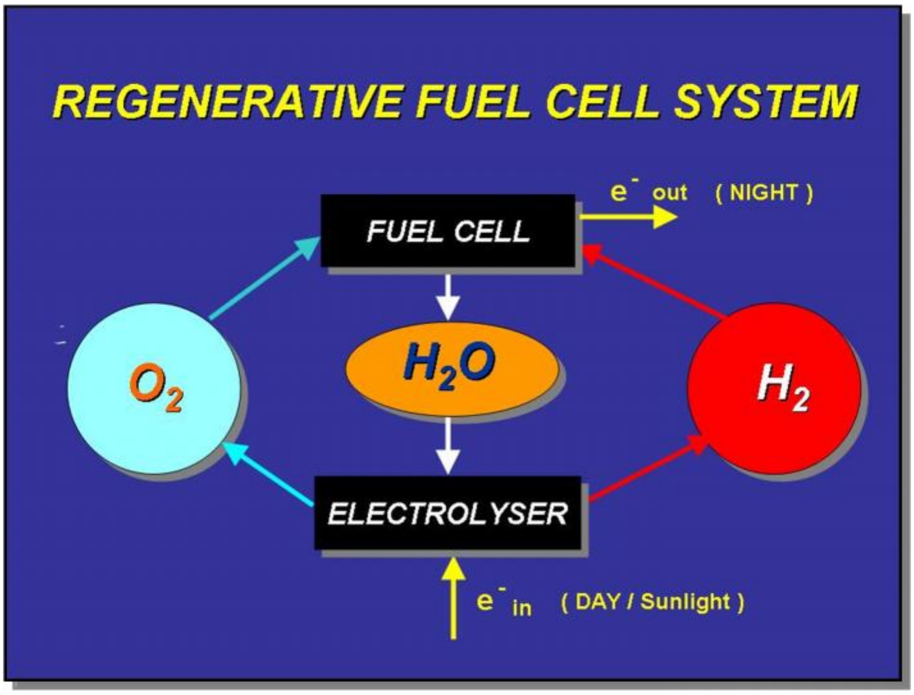


*Figure 6-12: A regenerative fuel cell (Source: ESA)*

Longer space missions, however, clearly require regenerative energy storage, if one wants to avoid bringing along vast amounts of consumables; batteries are recharged by solar arrays directly, in fuel cells the reactants hydrogen and oxygen are recharged by electrolysing the product water from the fuel cell operation whenever solar array power is available. This adds a lot of complexity. Nevertheless the significantly higher energy density provided by regenerative fuel cells (fuel cell + electrolyser) compared to batteries would be technically speaking a clear choice. A mass saving of two to three in power system weight vs. the most advanced space battery system is achievable and looks also in terms of launch cost very promising. Additionally a fuel cell can clearly separate power requirements from energy requirements, the power is sized by the electrode stack (the reactor), the energy is defined by the size of the reactant storage. In batteries this option is not available, the reactants are contained in the electrodes – it has to be sized for the worst case. The ESA Pressurised Lunar Rover study performed a detailed trade between different technologies for energy storage and delivery. Regenerative fuel cell systems were compared to different battery configurations, super-capacitors as well as nuclear. For the case of the Rover the trade clearly showed that the regenerative fuel cell system provided the lowest system mass by a large margin. This mass saving also justified the choice even with the higher complexity.

Therefore some future exploration missions, specifically human or robotic missions having high energy demands, will clearly benefit from fuel cell technology. These missions need many new technologies and have technology development programmes in place to address cost and risk.

But we should not overlook some facts like development risk and cost, complexity, reliability, and especially industrial considerations and conservatism in commercially sensitive areas like telecom satellites. A change within that sector from batteries to fuel cells will require significant modifications of the whole spacecraft with enormous impact on extra design cost and uncertainties, only a move to significantly bigger platforms than those being built now will not leave another choice than moving to fuel cells.

With all these aspects, one can therefore assume that future high power/energy space power systems will be based on regenerative fuel cells (especially PEM fuel cells)[42].

#### 6.3.6.2 Automotive

In the effort of replacing the current Internal Combustion Engines (ICE), like gasoline and diesel, by systems, which perform better in terms of Greenhouse Gas (GHG) emissions, the automotive sector has started to assess batteries and fuel cells.

As discussed in section 6.3.4.1 Mobile Applications, Polymer electrolyte or Proton Exchange membrane Fuel Cells (PEFC) are the system of choice as far as fuel cells are concerned. The choice is based on specific advantages like compactness, high power density, high efficiency at partial load, fairly rapid start-up capabilities and the suitability for mobile applications, operating at low temperatures (50–120°C).

Still, fuel cells are more complex than batteries and hence more costly, so one has to careful assess when to use them and when not. In this particular case, costs can be traded off against performance, based upon the fuel cells' better scaling characteristics with respect to specific power and energy density. This scaling effect is laid out in Figure 6-13.

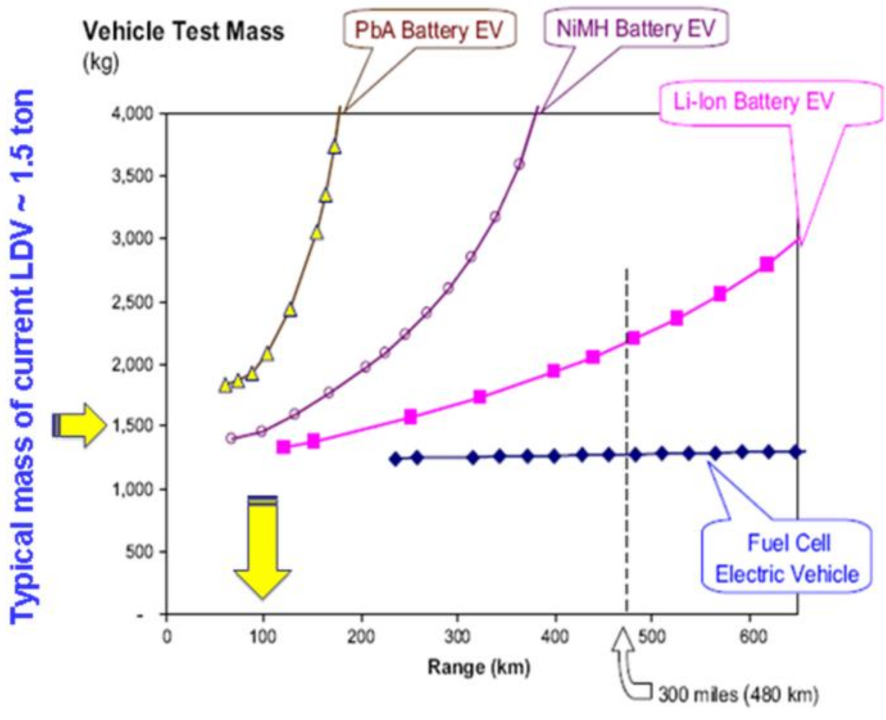


*Figure 6-13: Analysis of vehicle test mass and achievable range for different energy storage technologies (Source: IJHE 2009, Thomas [23])*

[42] It shall be noted that all these considerations are purely focusing on non-nuclear power system trade-offs – simply because the automotive role model, whose applicability is examined within this paper, does not consider any nuclear power and /or drive trains.

Depending on the employed energy storage system, mass and range of the test vehicle change accordingly. For a typical Low Duty cycle Vehicle (LDV) with a mass of 1.5 tons, batteries can provide for a range of 100-200 km, without an exceedingly high mass penalty. If one wants to achieve a range of at least 400 km however, only fuel cells remain as system of choice as even a Li-ion battery will face a mass penalty of 650 kg. For heavier cars and/or greater ranges this mass penalty becomes worse.

Another discriminating factor to decide when it makes sense to use fuel cells or batteries is the produced greenhouse gas emissions, depicted in Figure 6-14.

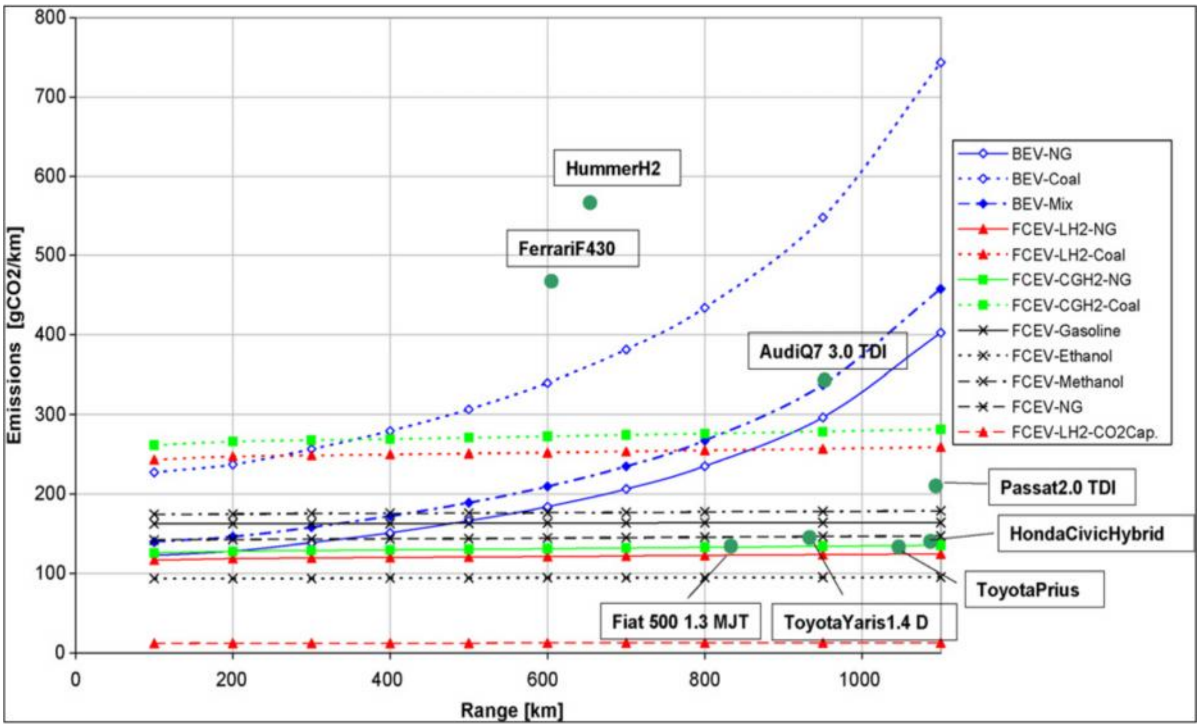


*Figure 6-14: Analysis of greenhouse gas emissions vs. range for Battery Electric Vehicles (BEV), Fuel Cell Electric Vehicle (FCEV) and today's cars utilising Internal Combustion Engines (ICE) (Source: IJHE 2009, Campanari [23])*

Here the produced GHG vs. achievable range are plotted for BEVs, FCEVs and state-of-the-art ICEs, taking into account the underlying primary energy source to produce the electric current or the hydrogen. Again, the same trend, which is visible in Figure 6-13 is reaffirmed. If one wants to achieve a range of at least 400 km, fuel cells outperform battery based energy systems in terms of greenhouse emissions, non-respective whether the hydrogen has been produced by solar, wind, ethanol or natural gas.

### 6.3.7 Discussion

When one asks the question, whether a spin-in or spin-off is likely to occur, the associated R&D expenditures play a role, as do potential barriers between the concerned sectors. A recent study published in a JRC Technical Note has assessed the R&D expenditures of the automotive industry and the aerospace and defence sector, confirming that the automotive industry is the largest R&D investor in the EU-27, accounting for one quarter of total industrial R&D investments. And this observation is likely to remain valid in the years to come, as both car manufacturers and component suppliers show elevated R&D intensities with an increasing trend over the past years.

| | R&D investment (€bn) | | Sales (€bn) | | Number of employees (million) | |
|---|---|---|---|---|---|---|
| | World | EU27 | World | EU27 | World | EU27 |
| Automotive manufacturers | 53 | 20.9 | 1213 | 423 | 2.76 | 1.26 |
| Automotive suppliers | 19.6 | 9.5 | 437 | 156 | 2.33 | 0.98 |
| Commercial vehicles and trucks | 6.9 | 2.4 | 233 | 66 | 0.62 | 0.22 |
| **Automotive industry** | **79.5** | **32.8** | **1883** | **645** | **5.7** | **2.5** |
| *Aerospace & defence* | *15.6* | *7.5* | *379* | *129* | *1.75* | *0.55* |
| *All industries* | *431* | *130* | *13897* | *5712* | *45.1* | *21* |

*Source: derived from the EU Scoreboard 2009 (DG RTD-IPTS, 2009) (rounded numbers)*
*Note: The table shows the aggregated figures for 65 EU-based and 140 worldwide companies related to the automotive sector,*

*Figure 6-15: R&D investments, sales and total number of employees of companies included in the EU Scoreboard related to the 'automotive' sector (2008), 'aerospace and defence' and all industries (Source: JRC Technical Note JRC 58727 [24])*

As visible in Figure 6-15, the worldwide R&D investment of the automotive sector outweighs the one of the aerospace and defence sector by a factor of 5.1 worldwide and by 4.4 in the EU-27. This leads to a clear conclusion in the discussion of spin-in vs. spin-off; the sheer difference in R&D expenditure in the aerospace and the automotive sector clearly favours a spin-in of terrestrial fuel cell technology into the space sector.

From the financial aspects it is clear that the space agencies around the world cannot afford anymore a dedicated fuel cell development for a dedicated space programme, a spin-in is the preferred - if not the only - option. There are however two major technical issues. In space we do not use air as oxidant, but pure oxygen, which of course leads to corrosion problems or worse at higher temperatures and pressures when using cheap commercially available products. The second issue is the need for closed loop reactant operation; in space we do not have the luxury to have “free of charge” abundant air available with 80% of inert gas in it, which is just perfect to remove the product water out of the fuel cell through exhaust pipes. In space both reactants are supplied, circulated and managed in closed loops including sophisticated water removal, complicating the thermal management as well. Finally – if the reactants are stored in their liquefied form – another major factor is the boil off during long duration cryo storage, which is actually another issue calling for a significant technology development.

### 6.3.8 Conclusions

Albeit complex, compared to battery based energy systems, fuel cells excel when high energy and/or high power demands become immanent. Given their higher specific energy density, which leads to a mass saving of at least 2-3 in power system weight compared to today's most advanced space battery system, fuel cells based space power systems are an option to be considered for space mission with power levels of 15 kW or more. Today's telecommunication satellites utilise already such power levels, certain military reconnaissance satellites using Synthetic Aperture RADAR might do as well and future exploration missions, going to the

Lagrange points, the Moon or Mass will see even higher power levels, especially when humans are on board of these spacecraft.

In contrast to the space shuttle mission, which lasted at maximum 14 days and could therefore employ a primary fuel cell, the fuel cell systems utilised in long term exploration missions and high power/energy Earth observation and telecom satellites, will be of the regenerative type, featuring a fuel cell and an electrolyser. In times of excessive power consumption, the fuel cell will use the on-board hydrogen and oxygen supplies to generate power; the water produced (out of the hydrogen and oxygen) will be stored on board. As soon as the power balance is positive again (e.g., when the satellite has left the eclipse and is generating power with its solar arrays again), the electrolyser starts up and converts the water into $H_2$ and $O_2$ again, which is then stored on board for the next discharge cycle. Although this system is more complex than a battery it offers the great advantage that one can separate power requirements from energy requirements, as the power is sized by the electrode stack (the reactor), while the energy is defined by the size of the reactant storage. In batteries this option is not available, the reactants are contained in the electrodes – it has to be sized for the worst case.

From the financial perspective, the higher complexity of fuel cells vs. any battery system, will lead to higher initial costs, costs that need to be offset by their better performance. This better performance is achieved by the better scaling characteristic of the respective specific power and energy density. While a fuel system can achieve energy densities in excess of 1000 Wh/kg for primary systems and up to 500 Wh/kg for long term regenerative systems, Li-ion based battery systems for satellites can achieve around 150 Wh/kg on battery level in near future. The quintessence is therefore that it does not make any sense to use a fuel cell system for a satellite with limited power requirements, like SGEO, the Small Geostationary satellite, which features a mass of 1500-2500 kg and maximum payload power of 3000 W [25] - the cost penalty would be too high. In this case it is better to stick to the classical battery system.

These cost driven considerations are similar to the ones in the automotive industry, which foresees to employ fuel cells in bigger cars, requiring more power and/or cars that travel longer distances, therefore requiring more energy. As outlined in Figure 6-14, this is driven primarily by the different scaling features of the two systems. If one wants to achieve a range of at least 400 km, fuel cells outperform battery based energy systems in terms of greenhouse emissions, non-respective whether the hydrogen has been produced by solar, wind, ethanol or natural gas.

As far as the discussion spin-in or spin-off is concerned, we have shown that the worldwide R&D investment of the automotive sector outweighs the one of the aerospace and defence sector by a factor of 5.1 worldwide and by 4.4 in the EU-27. This - and the observation that the space agencies around the world cannot afford anymore a dedicated fuel cell development for a dedicated space programme - leads to the conclusion that a spin-in of terrestrial fuel cell technology into the space sector is much more likely to occur.

The automotive sector alone has invested 13 G€ in research focusing on technologies to reduce Greenhouse Gas (GHG) and air pollutant emissions in 2008. This corresponds to 43% of the total R&D investments. These investments have turned the terrestrial fuel cell into a reliable, high performing system, sufficient to provide 25 kW of power (or more) for a car's drive train, with an anticipated duty cycle of 12,000 km per year and a life of at least 10 years.

It seems that the circle might be coming to a full closure after all; first employed in space missions, fuel cells have recently found their mass market application in the automotive sector. Starting with prototype tests in the 1990s, fuel cells form now an integral part of the hydrogen economy and are expected to see their market roll-out by 2015, with the next generation commercial fuel cell electric vehicles. Space in contrary has retired its fuel cells in the summer of 2011, when the last Space Shuttle mission came to a successful end. The high power/energy requirements remain however and so we are likely to see a spin-in of terrestrial fuel cell technology into space in the years to come.

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# 7. A Technology Transfer Paradigm Shift: Intruducing a Spin-in with the Propulsion Technology Domain with MOA$^2$, a pulsed Plasma Accelerator, which serves both space and terrestrial Applications

One of the key messages of chapter 6 “Technology Transfer Examples: From Energy and ICT to Transportation – Spin-ins and Spin-offs” was that “**Propulsion is the only technology domain without a noteworthy technology flow**; neither spin-in nor spin-off”, a statement that was clearly visible within “Table 6-3: Assessment of Technology Flows (Spin-in vs. Spin-off) between Space and the two predominant terrestrial TT Areas - ICT and Transportation” on page 110, with propulsion being the only technology domain without any technology flow arrows being attached to it.


*Figure 7-1: A Photo Montage of Saturn V Launches (Source: NASA)*

While it may sound a bit captious at first, that propulsion is still a “puristic space undertaking”, the fact that propulsion does not yet allow for spin-ins, is one of the reasons, why space transportation is so expensive. As stated within chapter “6.3.2 The Hydrogen Value Chain” on page 112, the launch of 1 kg of mass into Low Earth Orbit (LEO) costs between €10,000 and €20,000, which surmounts to an impressive monetary value when one considers to launch a satellite with a mass of 5250 kg like ASTRA 1K.

A non-neglectable part of the underlying cost equation is the rocket engines, which are needed to propel the rocket and its payload into space. If we take one of the most powerful rocket engines ever built, Rocketdyne’s F-1 (refer to Figure 7-2), used within the first stage of the famous Saturn V rocket (refer to Figure 7-1), a 2006 ‘Space Review’ article by Dwayne A. Day[43] states that, “Rocketdyne estimated that the cost of each engine would be $15 million, assuming an order of 40 or more engines at a rate of 10–12 a year.” As Rocketdyne conducted

[43] “Thunder in a bottle: the non-use of the mighty F-1 engine”, http://www.thespacereview.com/article/588/1, accessed in August 2013

this assessment in 1992, the cost of an F-1 engine in 2013 economic terms would surmount to US$28 million[44]. Although nearly 50 years old, the F-1 remains an impressive rocket engine up today, as can be seen in the Space.Com infographic[45] depicted in Figure 7-3.

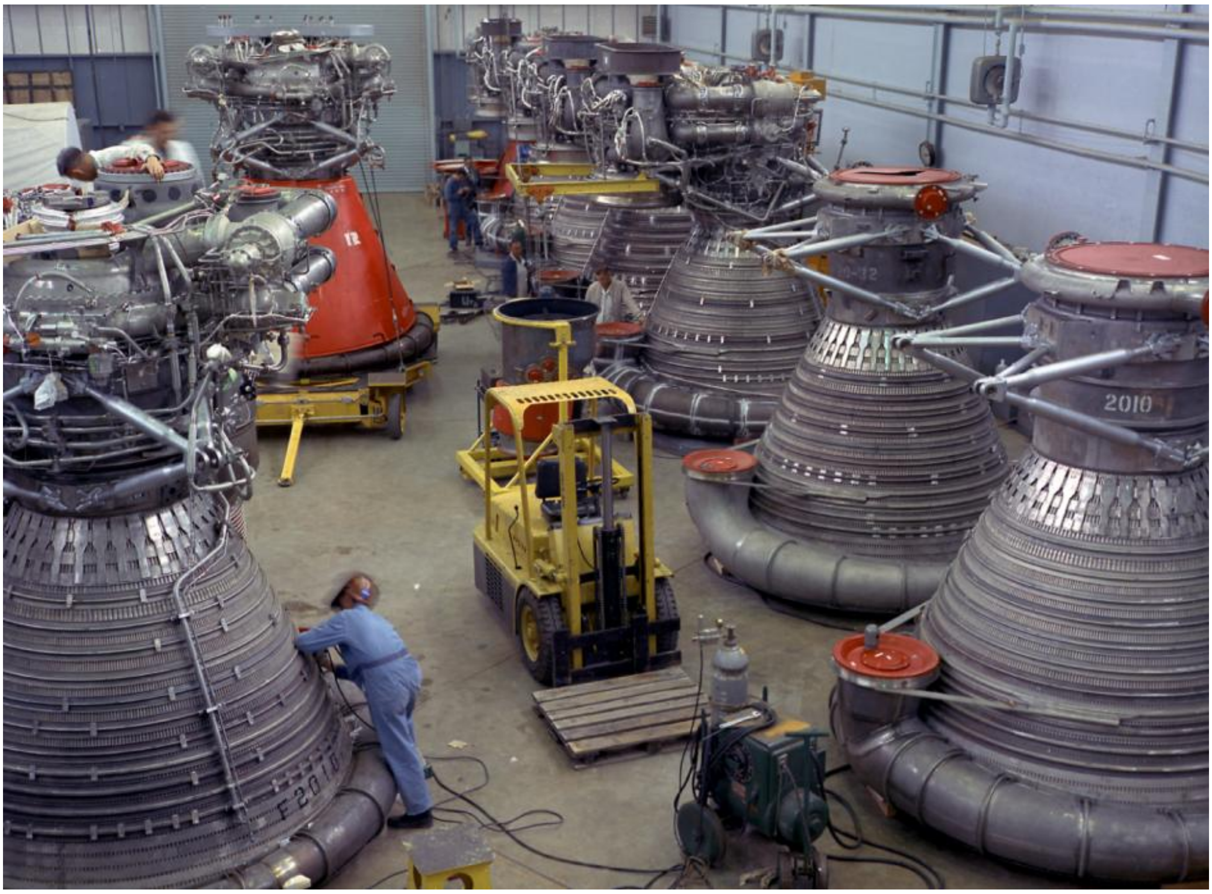


*Figure 7-2: F-1 Engines being stored in the F-1 Engine Preparation Shop (Source: NASA)*

[44] Assuming an inflation rate of 2.8%
[45] http://www.space.com/15099-apollo-moon-rocket-engine-recovery-infographic.html, accessed in August 2013

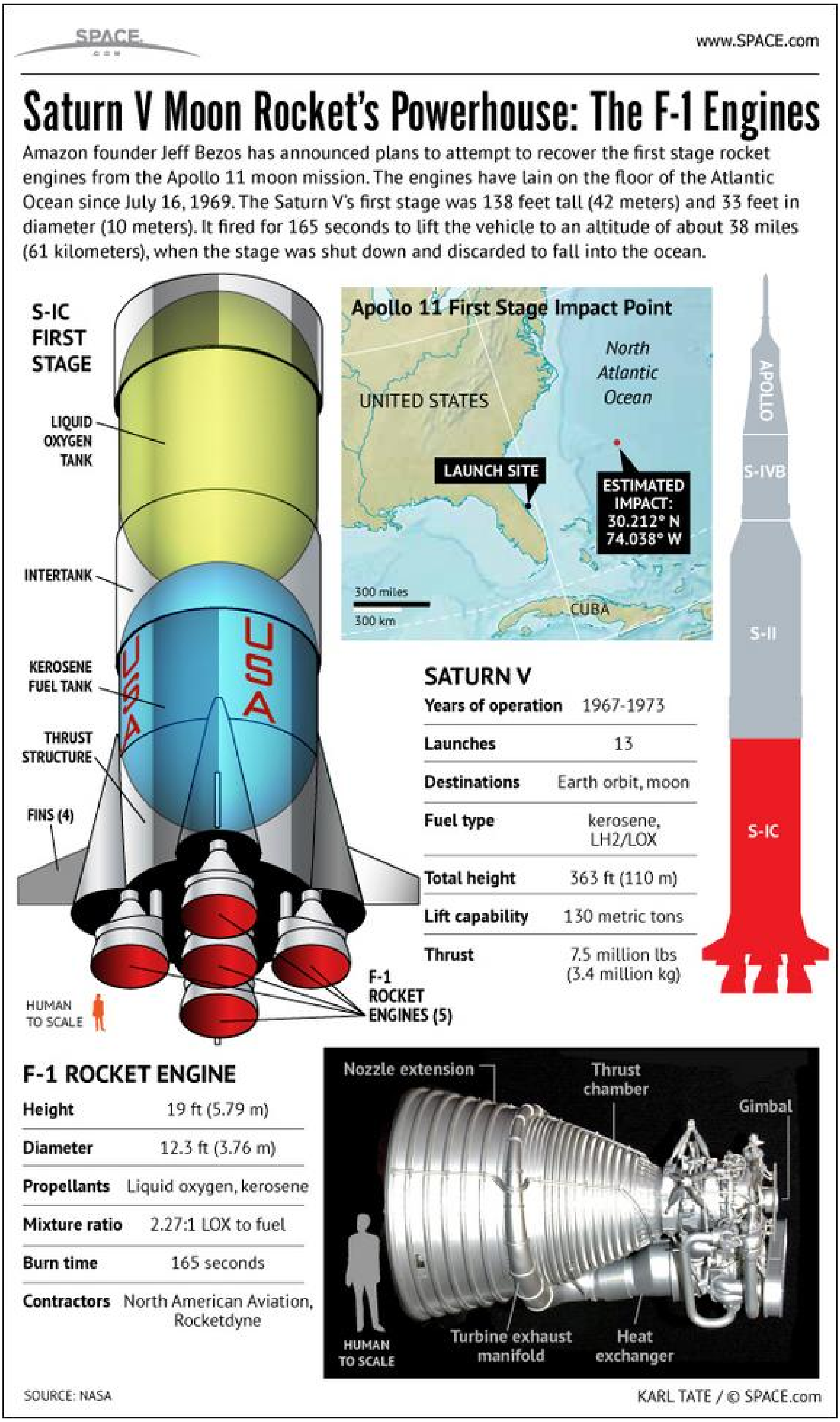


*Figure 7-3: Infographic on the Saturn V F-1 Engine (Source: Space.Com)*

As impressive as this engine is, US$28 million per piece are an enormous cost factor; even more so if one considers that the S-IC stage of the Saturn V utilised five of these engines. While other rocket engines may be cheaper; the engines as such still remain to be a major cost factor in the space transportation equation. This paradigm has held through until today, irrespective of the engine type (chemical, electric, nuclear or advanced) as all engines have one thing in common – they are all complex machines.

Every rocket engine is made up of hundreds of individual components, which are built and assembled by many suppliers; therefore rocket engines follow immediately on the "complexity trail" after the launcher itself. To put this in perspective, the Space Shuttle is - according to NASA - the most complex machine ever built[46], with:

- more than 2.5 million parts, including almost 370 kilometers of wire;
- more than 1,060 plumbing valves and connections;
- over 1,440 circuit breakers; and
- more than 27,000 insulating tiles and thermal blankets.

Bearing in mind that the Space Shuttle is a design of the 1960s it is no surprise that the Airbus A380 topped this complexity number, being made up of approximately 4 million parts, 530 km of wires and more than 100,000 connectors[47]. According to Flugrevue 03/2012, one can buy an A380-800 for the price of US$390 million, also a very impressive cost figure, which shows that complexity goes hand in hand with cost. In trying to minimise costs, it is therefore imperative to simplify the design of propulsion systems – such as it has been shown with a novel pulsed plasma thruster dubbed MOA, the Magnetic field Oscillating Amplified thruster, which is described in the following paper.

## 7.1 Reducing Complexity to make up a cost-effective Space Propulsion System: "Recent Activities in the Development of the MOA Thruster" ([H] Frischauf, Hettmer, Grassauer, Bartusch, & Koudelka, 2008)

Published in Frischauf, N., Hettmer, M., Grassauer, A., Bartusch, T., Koudelka, O.: Recent Activities in the Development of the MOA Thruster, in *Acta Astronautica* (2008), pp. 389-399 [H]

### 7.1.1 Introduction

It was in 1942, when the later Nobel laureate Hannes Alfvén published a letter, stating, that oscillating magnetic fields can accelerate ionised matter via magneto-hydrodynamic interactions in a wave like fashion [1]. These waves were later called "Alfvén waves", in honour of their discoverer. Although the evidence for Alfvén's hypothesis came already rather early with the observation of certain plasma phenomena, such as being connected with high solar wind Wolf-Rayet stars, more than 60 years had to pass by before a technical implementation of Alfvén waves for propulsive purposes was proposed for the first time.

The name of this concept, utilising Alfvén waves to accelerate ionised matter for propulsive purposes, is MOA – Magnetic field Oscillating Amplified thruster. It is a highly flexible

[46] http://www.spaceflight.nasa.gov/shuttle/upgrades/upgrades5.html, accessed in August 2013
[47] http://www.airliners.net/aviation-forums/tech_ops/read.main/259188/, accessed in August 2013

propulsion system, whose performance parameters are easily adapted in real-time, by changing the mass flow and/or the power level.

Its working principle is based on Alfvén waves that are utilised to accelerate ionised matter for propulsive purposes. Alfvén waves or magneto-hydrodynamic waves are transverse waves, which move parallel to the magnetic field with the Alfvén velocity $v_A$ and depend only on the magnetic field density **B** and the mass density $\rho_m$ of the Plasma. The following equation shows the exact relation [2]:

$$v_A = \frac{B}{\sqrt{\mu_0 \rho_m}} \qquad (1)$$

*Equation 7-1: Calculation of the Alfvén velocity*

Typical Alfvén velocity values are in the order of 34.7 km/s for Argon plasmas ($Ar^+$) used in illumination applications and 7700 km/s for Deuterium plasmas ($D^+$) as being used in fusion applications [2].

The Alfvén waves of the MOA concept are generated by making use of two coils, one being permanently powered and serving also as magnetic nozzle, the other one being switched on and off in a cyclic way, deforming the field lines of the overall system. This deformation is at the very heart of the MOA concept, as it generates the Alfvén waves, which are in the next step used to transport and compress the propulsive medium, in theory leading to a propulsion system with a much higher performance than any other electric propulsion system. Mathematic models suggest that the MOA concept is capable to deliver a maximum specific impulse of 13 116 s (12.87 mN) at a power level of 11.16 kW, using Xe as propellant, but can also be attuned to provide a thrust of 236.5 mN (2411 s) at 6.15 kW of power.

One of the biggest strength of the MOA concept is that it is in principle capable of using all sorts of propellants, as long as they can be ionised. Gases that we have used in our tests so far include Nitrogen and Argon, in the future Hydrogen, Helium and Xenon are to be tested as well. The following picture shows the MOA prototype in its test rig within the vacuum chamber (Figure 7-4).

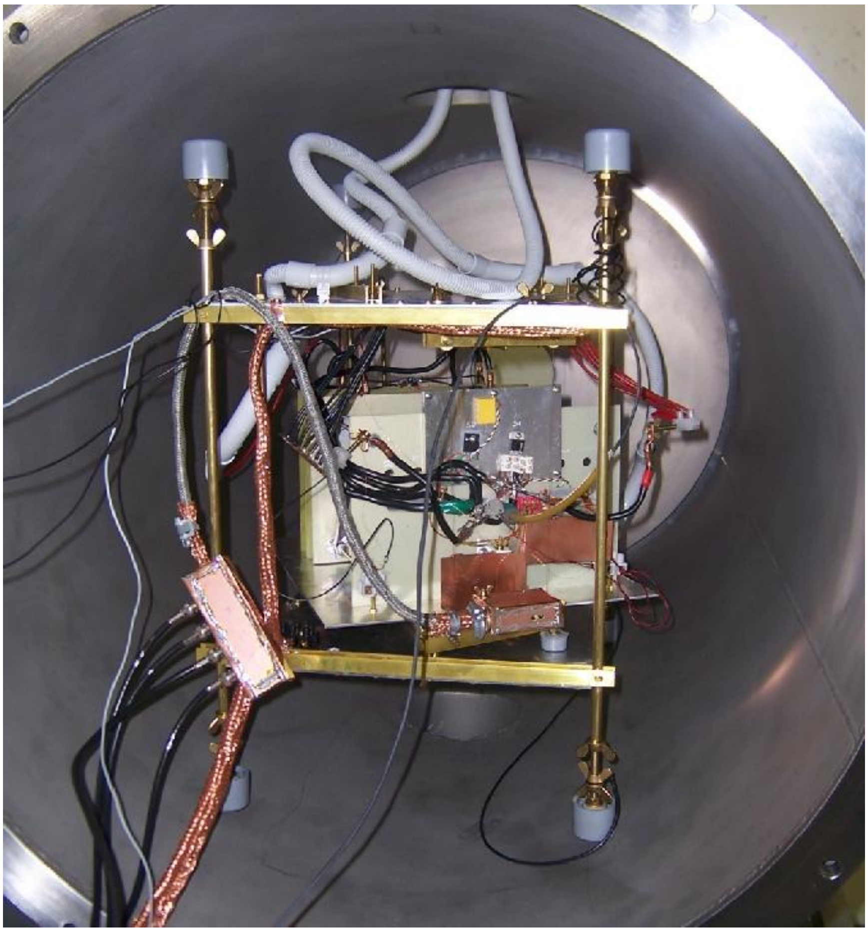

*Figure 7-4: The MOA Prototype inside the vacuum chamber*

Expert opinions on the MOA concept, such as the one of Prof. Horst Löb, one of the fathers of electric propulsion, which were commissioned by the inventors, have validated the inventors' model and stated the feasibility of the overall concept. When checking the MOA concept against his own plasma dynamic models, Prof. Horst Löb derived the following parameters for MOA, which suggest that MOA has an excellent potential as a North-South Station Keeping (NSSK) propulsion system, outperforming all other systems currently available (Table 7-1):

*Table 7-1: Assumed Parameters of a MOA NSSK-System (Simulation Prof. Löb)*

| MOA Thruster with $H_2$ propellant: | |
|---|---|
| Thrust: | 80 mN |
| Beam Power: | 1.6 kW |
| Specific Impulse: | 4000 s |
| Specific Power Consumption: | 20 W/mN |

Due to its high flexibility, the MOA developing consortium considers the application of MOA not only as a NSSK thruster for geostationary satellites, but also as an Attitude Control and Kick-Booster system.

MOA has been filed for patent at the European Patent Office on 15th of September 2003 and has been published with patent number WO2005/027142 as of 24th of March 2005.

### 7.1.2 MOA – Characterisation and Principle of Work

A basic characterisation of the MOA thruster quickly leads to one result: MOA falls in the class of electric propulsion systems as it requires an external energy source, which afterwards accelerates the propellant by electromagnetic means. In trying to characterise the MOA system further by comparing it with:

- electrothermal systems (e.g. arcjet, resistojet);
- electromagnetic, electrodynamic systems or plasma engines (e.g. MPD, PPT, VASIMR); and
- electrostatic systems or ion engines (e.g. FEEP, colloid engine, HET);

it becomes evident that MOA is best described by a pulsed plasma thruster (PPT), however with the difference that the thermal heating and the acceleration of the propulsive plasma are due to a periodic variation of a magnetic field, as outlined in the following graphic, showing typical scenes of operation (Figure 7-5).

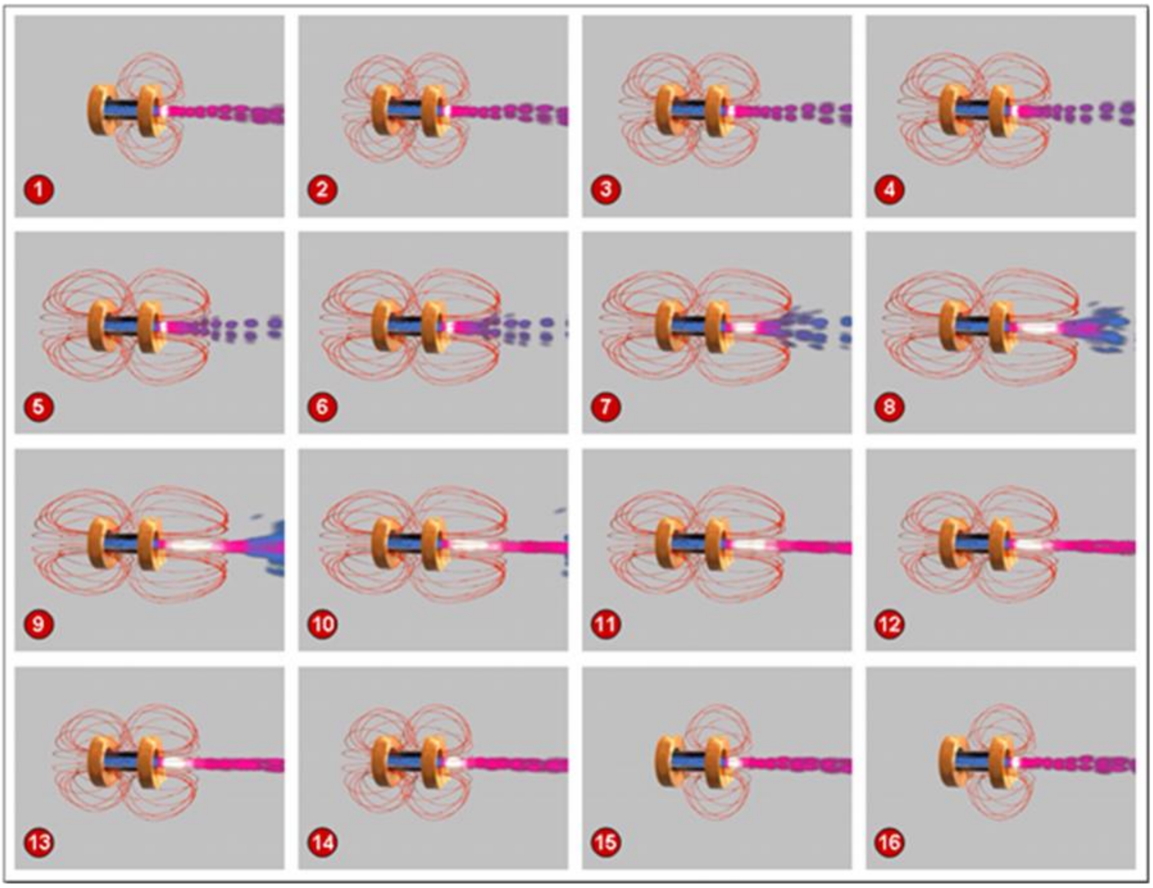


*Figure 7-5: Scenes of operation of the MOA thruster*

This special heating and acceleration process has its origins in the unique 2-coil-assembly, which leads to an adiabatic compression, a plasma confinement and finally to the acceleration of the emitted propellant mass due to magnetic pressure waves propagating with the Alfvén velocity. Obviously the thermodynamic expansion plays a significant role as well, therefore the MOA system needs ultimately to be characterised as a combination of a thermo- and electrodynamic propulsion system. The following graphic shows the new thruster, called MOA P3 Multifunctional Prototype (MOA P3-MFP) in its cross section:

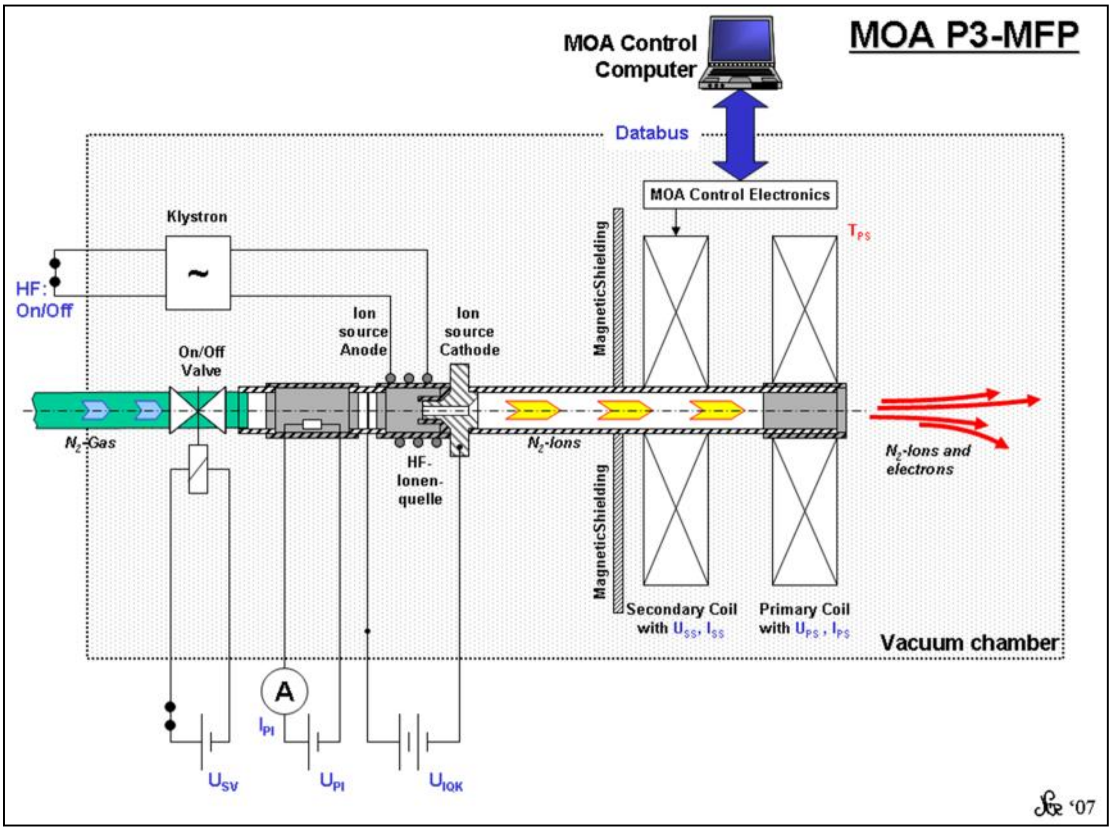


*Figure 7-6: Cross section of the MOA thruster (P3-MFP)*

As one can easily depict from the figure above, the system features a rather straightforward assembly with no specific complexities, which enables a modular set-up to adapt MOA best to its various applications. Because of its intrinsic behaviour as a thermo- and electrodynamic propulsion system, MOA is highly adaptable in terms of power, thrust and specific impulse, by trading-off one feature against the other. If one emphasises the thermodynamic features, power consumption and thrust will decrease, while thrust will increase accordingly. Accentuation of the electrodynamic features however, will lead to the opposite effect, namely a decreased thrust on the expense of higher power consumption and better if not superior specific impulse values.

Of particular interest of the MOA system is the fact that the beforehand mentioned attune ability in terms of power consumption, thrust and $I_{SP}$ can readily be utilised in real-time during flight, making MOA the most flexible of all advanced propulsion systems.

All in all, the MOA thruster is comprised of five subsystems, as being depicted in Figure 7-6: Cross section of the MOA thruster (P3-MFP):

- the *plasma generator* (in this case the High-Frequency Ion Source);
- the *central tube*, with the magnetic nozzle at the exit;
- the *primary coil*, which generates a timely constant but spatial inhomogeneous magnetic field that also defines the magnetic nozzle;
- the *secondary coil*, which is powered by current pulses, generating a periodic varying magnetic field that counteracts the primary field; and
- the *supply and control units* for the gas flow, the plasma generator and the two coils (e.g. the on/off valve, the MOA control computer, etc.).

### 7.1.3 MOA in the Context of advanced Propulsion

Due to the sheer remoteness and limited accessibility of space, the spacecraft's on-board resources are the most valuable asset and should therefore be utilised as efficiently as possible. This requirement is inherent in every space mission but becomes absolutely imperative if one wants to overcome the "space-time gap", that is flying either far away and/or staying in space for a long time.

Whilst the first objective is typical at the very heart of scientific space missions, which reach out for interplanetary and even interstellar space, the latter one is of general importance to all space missions. Increasing the life time of a satellite in general will enable an increased mission flexibility, a better scientific output and/or a higher profit margin.

The most limited resource onboard of any spacecraft is typically the propellant as it is a real consumable - at least as long as we have to rely on Newton's third law "action = reaction" to generate thrust by expelling mass in one form or the other. Power should be considered critical as well, however to a lower extent because one can make use of systems that are either regenerative (solar cells with secondary batteries) and/or have a high energy density (especially nuclear power reactors).

When trying to tackle the propellant problem it turns out that the most effective approach is to use advanced propulsion systems, with a high exhaust velocity/specific impulse ($I_{SP}$) and therefore a low fuel consumption. The importance becomes obvious, when looking at the interdependence of propellant mass $m_{\text{propellant}}$, velocity change $\Delta V$ and the specific impulse $I_{SP}$ [3]:

$$m_{propellant} = m_{S/C\_Initial}(1 - e^{-(\frac{\Delta V}{g \cdot I_{SP}})}),$$

*and with*

$$m_{S/C\_Initial} = m_{propellant} + m_{S/C\_Dry}$$

*follows*

$$\frac{m_{propellant}}{m_{S/C\_Dry}} = e^{(\frac{\Delta V}{g \cdot I_{SP}})} - 1$$

*Equation 7-2: Calculation of the propellant mass to the dry spacecraft ratio*

In the search for the most suitable propulsion system, numerous sorts of systems have been studied, ranging from "classical" chemical to the various electric and finally the nuclear systems in all their different facets. The following table compares the fuel consumption of four exemplary systems (Space Shuttle Main Engine (SSME) as a chemical system, NERVA as a nuclear fission Nuclear Thermal Propulsion (NTP) system, MOA as an advanced electric and the Gas Dynamic Mirror (GDM) as a nuclear fusion NTP system) for different planet destinations [4]:

*Table 7-2: Fuel mass to spacecraft mass ratio for different destinations and propulsion system concepts*

| Destination Planet | Total Velocity Increment [km/s] | Ratio of Fuel Mass to S/C Mass ($m_{Propellant}/m_{S/C\_Dry}$) | | | |
|---|---|---|---|---|---|
| | | Chemical Engine (SSME) | Nuclear Fission (NERVA) | MOA Concept | Nuclear Fusion (GDM) |
| | | $I_{SP}$ = 455 s | $I_{SP}$ = 825 s | $I_{SP}$ = 10000 s | $I_{SP}$ = 126800 s |
| Moon | 6,00 | 2,837E+00 | 1,099E+00 | 0,0631 | 0,0048 |
| Mars | 25,00 | 2,702E+02 | 2,098E+01 | 0,2904 | 0,0203 |
| Saturn | 70,00 | 6,504E+06 | 5,721E+03 | 1,0417 | 0,0579 |
| Pluto | 180,00 | 3,308E+17 | 4,596E+09 | 5,2682 | 0,1558 |

As it can be seen from Table 7-2 the specific impulse is of utmost importance when one aims for low fuel consumption. Still thrust is not to be neglected, as lots of loss mechanisms like gravitational loss exist, which can lead to an increased fuel consumption that decreases the gains of using high $I_{SP}$ systems. Similar considerations are true for the power consumption. One has to carefully trade-off the extra mass of the power system to the gain in lower fuel consumption for a given mission, before deciding which propulsion system is to be taken onboard.

Because of all these trade-offs, plenty of propulsion concepts exist, all differing in their characteristics ($I_{SP}$, thrust, power consumption, physical characteristics, cost, etc.), level of complexity and the state of technical maturity. The following graphic tries to compare the different systems and concepts in terms of specific impulse, complexity and maturity [1], [5] - [14] (Figure 7-7).

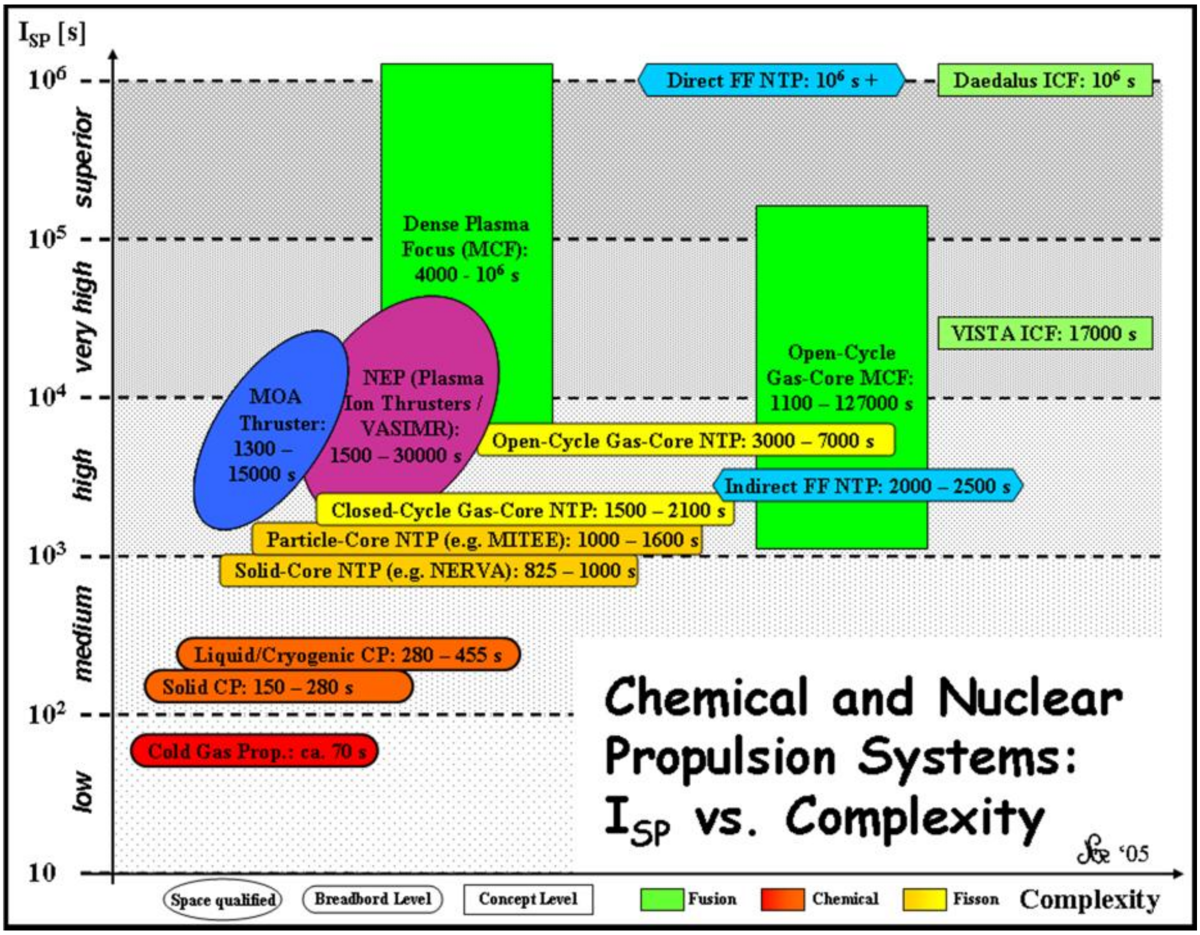


*Figure 7-7: Comparison of different propulsion systems in terms of specific impulse, complexity and maturity*

As can be easily depicted in the table above, the low $I_{SP}$ Systems, cold gas and chemical propulsion, are the ones with the highest maturity. This has mostly historical reasons, as these systems have seen the longest period of development, because of their applications in missile systems. Superior to the chemical systems in terms of $I_{SP}$ are the different fission based Nuclear Thermal Propulsion (NTP) systems. Some of these have nearly made it to space qualification, like the US NERVA programme in the early 1970s. Nowadays they are again under discussion for being used as propulsion systems for human exploration missions in the Solar System. Even better than these systems are the fission fragment and fusion based NTP systems. While the first ones are only at study level, some of the fusion systems have already been realised as breadboards for deeper studies (e.g. the Gas Dynamic Mirror (GDM) Fusion concept at NASA MSFC [13] and the Dense Plasma Concept (DPF) at the University of Illinois) [4].

A class on their own are the electric propulsion systems. Featuring high to very high specific impulse values, these systems are usually hampered by relatively low thrust values, because of their power dependability. A likely word-around solution would be the use of a powerful nuclear power reactor, generating the required high power values. Such a system is in general called a Nuclear Electric Propulsion (NEP), whereby the electric thruster can be any sort of system, such as an arcjet, ion, hall, magnetoplasmadynamic, pulsed plasma thruster, the VASIMR [8] or the MOA concept. The following table shows how the MOA concept compares to some of the other electric propulsion systems:

*Table 7-3: Different electric thrusters in comparison to possible MOA modi*

| Name | Type | Propellant | P [kW] | F [mN] | $I_{SP}$ [s] | Comments |
|---|---|---|---|---|---|---|
| Melco ETS-VI | Ion | Xe | 0.62 | 25.00 | 3140 | Japanese Technology Demonstrator |
| SNECMA-SEP PPS-1350 | Plasma | Xe | 1.35 | 70.00 | 1500 | SMART-1 Engine, ESA |
| NSTAR | Ion | Xe | 2.33 | 90.00 | 3100 | Deep Space 1 Engine, NASA |
| NAL / NASDA / Toshiba BBM-2 | Ion | Xe | 3.30 | 150.00 | 3518 | Japanese Prototype |
| RIT-XT | Ion | Xe | 6.10 | 200.00 | 5500 | German Ion Engine, RIT-10 @ ARTEMIS, ESA |
| Fakel SPT-200 | Plasma | Xe | 8.00 | 300.00 | 3200 | Russian Prototype |
| | | | | 700.00 | 1500 | |
| ESA-XX | Ion | Xe | 8.45 | 240.00 | 3500 | European Prototype |
| | | | 10.50 | 250.00 | 6000 | |
| MOA, Xe-Dataset 13 | Plasma | Xe | 0.61 | 53.31 | 1359 | MOA in low power mode |
| MOA, Xe-Dataset 190 | Plasma | Xe | 6.15 | 236.48 | 2411 | MOA in high thrust mode |
| MOA, Xe-Dataset 172 | Plasma | Xe | 11.16 | 12.87 | 13116 | MOA in high $I_{SP}$ mode |

As it is clearly visible form Table 7-3, MOA is comparable in most of its characteristics to all other electric propulsion systems, but features three particular advantages:

a) the highest achievable $I_{SP}$ value,
b) its real-time attune ability in terms of power consumption, thrust and $I_{SP}$[48] and
c) a corrosion-free behaviour.

While point a) definitely qualifies MOA as an advanced propulsion system that matches performances of the yet to be developed fusion propulsion systems, point b) is not to be underestimated as well, as it makes the MOA concept the most flexible of the advanced propulsion systems, and the only one to allow for a high flexibility with respect to in-flight mission planning.

### 7.1.4 Design and Testing of the MOA Thruster

As outlined in Figure 7-6: Cross section of the MOA thruster (P3-MFP) on page 142, the MOA concept features a modular set-up for the sake of simplicity, high versatility and limited prototype cost. Since the MOA concept is designed to be corrosion free, low cost commercial off the shelf (COTS) materials can readily be used as well.

Before the MOA developing consortium started to test the prototype(s) outside and inside the vacuum chamber, several simulation runs with the software model were undertaken to define target values, which were afterwards aimed for to validate the software model and better define its limits.

#### 7.1.4.1 Software Model

##### *7.1.4.1.1 Description and Set-up*

The numeric simulation software is designed to be a worst case model. All parameters not directly dependent on the Alfvén-wave-effect are chosen in low level standards, the form of the magnetic nozzle and the cusp for example are approximated in a non-optimised average standard.

Therefore the simulation results represent only minimum values in terms of comparing them to ones that one would expect coming out of the experiments. The actual test results that were obtained confirmed these expectations.

The simulation of several configurations does result in characteristic behaviours of the mechanism with the propellant, the initial temperature, mass density and the magnetic flux acting as key parameters. If for example the propellant is comprised of molecules with a high particle mass, the compression period becomes the dominant factor, while for propellants comprised of lower mass ions the decompression period is the important mechanism assuming an identical propellant mass flow. This has important consequences on the operation of the whole system.

One of the most important parameters is the relation between the initial compressibility of the plasma and the Alfvén velocity. When using the MOA system as an afterburner – for example with an arcjet - the compression of the pre-heated plasma needs to be taken into account in the adjustment of the magnetic forces.

[48] Note: all three MOA data sets are different operating modi of only one propulsion system

In general the simulation model outlines the high flexibility of the MOA concept based on the easiness of adjusting certain key parameters like initial temperature, mass density and the magnetic flux.

#### *7.1.4.1.2 Highlights*

One of the targets of the numeric simulation is to define the maximum specific impulse and thrust values within certain boundary conditions, like the propellant type, maximum input power (e.g. 10 kW) and frequency (e.g. 10 MHz).

When using Hydrogen as propellant, the MOA system is estimated to reach an $I_{SP}$ of 15 057 s and a thrust of 14.77 mN at a power consumption of 11.23 kW, an oscillation frequency of 10 MHz and a mass flow of 0.0001 g/s.

If the mass flow is increased to 0.01 g/s in the same configuration, then the $I_{SP}$ drops to 3386 s, while the thrust rises to a value of 332.09 mN at an input power of 13.94 kW at 10 MHz.

With the same magnetic flux, but at a frequency of 6 MHz the $I_{SP}$ ends up with 8463 s and the thrust with 58.06 mN, given a mass flow of 0.0007 g/s at an power consumption of 3.81 kW.

In the same basic configuration, but with Xenon as propellant, the maximum $I_{SP}$ ends up with 13 116 s, at a thrust of 12.87 mN and an input power of 11.16 kW.
The most power effective record features an $I_{SP}$ of 1359 s and a thrust of 53.31 mN with a power level of 0.61 kW.

The relation between power and magnetic flux depends strongly on the inductive resistance of the magnetic coils; when fixing the flux the power consumption is increased accordingly with the frequency. On the other hand an optimised setup is obtainable either for high $I_{SP}$, high thrust or low power consumption values.

### 7.1.4.2 Design of the MOA Thruster Prototype

To ensure simplicity, high versatility and limited prototype cost, the MOA concept features a modular set-up. Being designed to be corrosion-free, low cost commercial off the shelf (COTS) materials were used for both the mechanics and the electronics of the prototypes.

#### *7.1.4.2.1 Mechanics*

The mechanics of the MOA thruster are rather simple. Inside a frame are two magnetic coils with a central tube. The central tube contains an optional plasma source. The electric and magnetic shielding components are mounted on the frame, additional electronic components may be mounted there as well.

#### *7.1.4.2.2 Electronics*

During the initial development period of the MOA thruster, two electronics concepts had been tested, both differing in the signal form for the field oscillation.

The constant signal part is generated outside of the MOA engine, the thruster only supports the power FETs and a driver box.

The periodic signal part is generated by an electronic box, which is mounted on the prototype’s frame.

### 7.1.4.3 Testing the MOA Thruster Prototypes

In terms of testing its prototypes, the MOA developing consortium followed a two-step strategy. First the subcomponents were vigorously tested in the lab, afterwards the certified subcomponents were integrated into the final prototype. This prototype was again tested in the lab and only after it had passed successfully the foreseen testing steps, the performance tests were started in the vacuum chamber.

#### *7.1.4.3.1 Tests outside the Vacuum Chamber*

The P1 prototype was designed for tests outside a vacuum chamber to observe the three-dimensional interactions of the magnetic fields. After confirming this fundamental principle, the next target was to design and build a prototype for tests in the vacuum chamber.

Before doing so however, the follow-up prototype P3 was also tested outside the vacuum chamber to certify the electronic components and to check for the behaviour of the coils and the associated magnetic fields. P3 is designed such as to enable early thrust measurements with a maximum frequency of 5 kHz, operating with a rectangular signal.

#### *7.1.4.3.2 Tests inside the Vacuum Chamber*

After the prototype had passed the functional tests in the vacuum chamber, which was still opened at that time, the vacuum chamber was closed to check out the prototype’s thrust performance values.

Thrust measurements were conducted with a laser triangulation sensor. This laser was directed onto a dedicated reflector on the prototype that was rigidly mounted to the structure. The laser triangulation sensor translated the minimal movements of the prototype into a voltage signal that was afterwards put on display on a digital oscilloscope. Using the VAVG (Averaging) function of the HP54502A Oscilloscope, averaging over four measurements and limiting the bandwidth, minimum, maximum and average voltage levels were obtained. By this approach spikes could be filtered out, leaving therefore only the constant part of the signal, which resembled the average movement of the prototype inside the vacuum chamber. The following graphic provides an overview of the test set-up inside the vacuum chamber for the 400 W prototype (Figure 7-8).

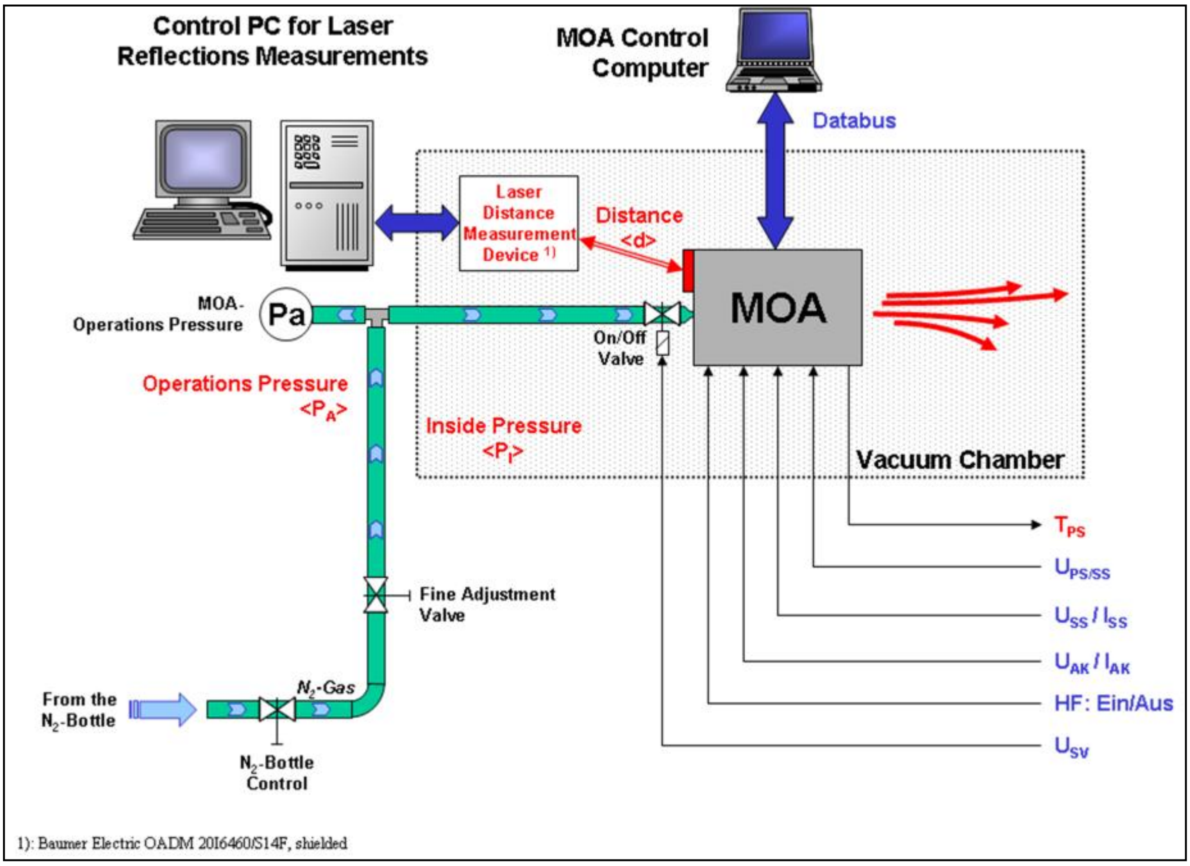


*Figure 7-8: Set-up for the MOA vacuum chamber tests*

For the sake of simplicity all tests were conducted with Nitrogen, as it is often used for industrial applications and readily available. With a fine adjustment valve the mass flow of the propellant (Nitrogen) feed line was regulated to an amount, where the turbo pump of the vacuum chamber could still operate satisfactory, which was the case when the maximum inside pressure of the vacuum chamber did not exceed $5 \cdot 10^{-3}$ mbar. In idle mode (no propellant feed) the turbo pump was able to reduce the vacuum chamber pressure to $1 \cdot 10^{-5}$ mbar.

To distinguish between the cold gas, ion wind, and Alfvén effects, we decided to conduct the tests in a "ramp" style, carefully switching on one subsystem after each other, measuring the thrust at each of the steps. The movement of the prototype due to the thrust vector is reflected in the different voltage values of the Laser sensor. Each measurement was integrated over 10 seconds to take into account average values only and to neglect short-time deviations due to spikes.

Once these different voltage values had been measured, a rather simple formula, taken into account the calibration set-up of the laser sensor (*X* mm of deviation per *Y* V of voltage output) and the trigonometric set-up of the whole experiment was used to obtain the thrust.

A magnetic deviation measurement was also conducted to correct for any errors that might arise because of a possible magnetic attraction between the primary coil and the power cables. The obtained value was subtracted entirely (worst case approach!) from the MOA related measurement, minimising therefore the final thrust vector. All the thrust values presented and discussed hereafter take this magnetic deviation correction into account.

### 7.1.5 Obtained Results

The developing consortium conducted more than a dozen testing campaigns at research institutes in Germany and Austria with several prototypes. In the cause of these tests several issues, like corona and multipaction, as well as electromagnetic problems, could be better understood and mitigated. At the end the consortium had improved the P3 prototype to a level where reliable measurements were possible. The results that were obtained are promising: with an overall power consumption of 400 W, 6-11 mN of thrust could be obtained, leading on the average to a specific power of approx. 50 W/mN for this yet un-optimised prototype in terms of power consumption. Table 7-4 presents average values and standard deviations for six comparable measurements.

*Table 7-4: MOA thrust measurement statistics of the 400 W prototype*

| Measurement | Thrust | $I_{SP}$ | Power | Ion Source | | Spec. Power |
|---|---|---|---|---|---|---|
| Number 1; 18:32 | 7,19 mN | 1114,5 s | 393,1 W | 96,0 W | 1160 V | 54,6 W/mN |
| Number 2; 20:15 | 10,89 mN | 738,4 s | 394,1 W | 97,0 W | 1150 V | 36,2 W/mN |
| Number 3; 21:05 | 9,65 mN | 833,0 s | 394,1 W | 98,0 W | 1200 V | 40,8 W/mN |
| Number 4; 15:32 | 7,53 mN | 1075,8 s | 397,1 W | 100,0 W | 1194 V | 52,8 W/mN |
| Number 5; 17:00 | 6,22 mN | 1306,2 s | 398,2 W | 100,0 W | 1200 V | 64,0 W/mN |
| Number 6; 20:30 | 7,05 mN | 1187,3 s | 410,5 W | 106,0 W | 920 V | 58,2 W/mN |
| Average value: | 8,09 mN | 1042,5 s | 397,9 W | 99,5 W | 1137,3 V | 51,1 W/mN |
| Standard Dev.: | 1,79 mN | 215,94 s | 6,50 W | 3,56 W | 108,60 V | 10,59 W/mN |

It has to be noted at this point that the specific impulse has been obtained indirectly only. Because mass flow measurements were not possible at this stage of the development, we decided to measure the power consumption of the whole MOA system (main bus and ion source) and to estimate the beam power thereafter, by accounting for it with a factor of 10% of the total power consumption.

A statistical check-up of the 2± calculations (95% confidence level) leads to the following results:

- Thrust: 8.09 ± 3.57 mN;
- $I_{SP}$: 1042.5 ± 431.9 s;
- Power: 397.9 ± 13.0 W;
- Specific Power: 51.1 ± 21.2 W/mN.

The developing consortium considers these results an excellent vector for future R&D activities.

### 7.1.6 Current and Future Activities

The next important steps in the continued development of the MOA concept is centred on the testing of improved coils, which are right at the moment integrated in the MOA P3-MFP (Multi-Functional Prototype). By using these new type of coils higher oscillation frequencies will become obtainable, leading to further performance improvements of the MOA thruster.

In addition QASAR has upgraded the MOA electronics to improve the efficiency and has already developed and successfully tested a new high frequency (HF) ion source instead of the currently used high voltage ion source. The following photo was taken at a recent test (Figure 7-9).

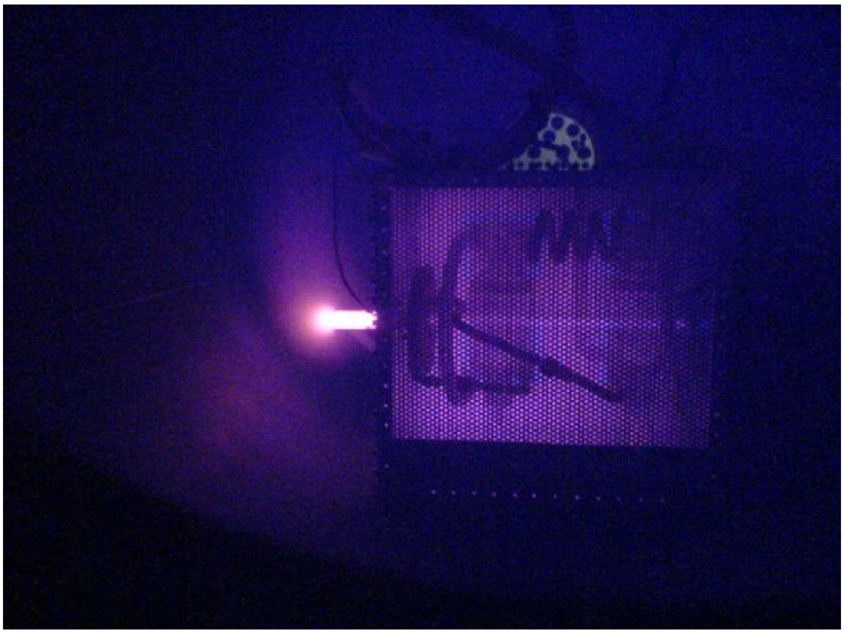

*Figure 7-9: HF Ion Source test in the vacuum chamber*

The first tests with the new HF ion source were so successful that Prof. Horst Löb, who was a witness at one of the tests, has provided a positive expert opinion on the feasibility of this important subsystem. With the upgraded electronics and the new HF ion source, we expect to fully utilise MOA's potential in operating with different ion and/or plasma sources, while we push up the power level of the thruster to 2.5 $kW_e$.

If these steps turn out to be as successful as anticipated, the MOA P3-MFP will become the nucleus for further breadboard models. Currently foreseen are models for a further study of Attitude Control System Thrusters (ACST) and NSSK thrusters.

Especially for the latter application, the developing consortium is very optimistic, because of the expert opinion of Prof. H. Löb, in which he states that a MOA derived NSSK thruster can be expected to feature a thrust value of 80 mN at a specific impulse of 4000 s, with a beam power of 1.6 kW (see also Table 7-1: Assumed Parameters of a MOA NSSK-System (Simulation Prof. Löb), on page 140 of this paper). Further optimisations in the area of power consumption are expected to improve the specific power to values of 20 – 30 W/mN for the P4 prototype and the associated breadboards [15].

While the so far described activities lead clearly into the NEP direction, we have recently started to explore another R&D area that has strong synergies with the NTP sector. Based on a request from commercial industry to develop a MOA thruster for metallurgic applications that can operate outside of a vacuum chamber, we are currently working on a derivative that can operate at ambient pressure. Model calculations predict that this is feasible, even at inlet gas pressures up to 10 bars. A first ambient pressure prototype is envisaged for the first half of 2008. If the follow-on tests are successful, this derivative of the MOA thruster could well serve as an "afterburner system" for NTP concepts.

By taking a certain fraction of the exhaust gases and accelerating it to high velocities by MOA's unique Alfvén wave concept, the $I_{SP}$ of the overall NTP concept could be increased. Naturally, this afterburner acceleration will be even more effective if a certain part of the NTP engine's exhaust gases are already ionised. Our estimates lend credence to the belief that a MOA augmented NTP could feature $I_{SP}$ values well above the "magical" 1000 s borderline.

### 7.1.7 Conclusions

More than 60 years after the later Nobel laureate Hannes Alfvén had published a letter stating that oscillating magnetic fields can accelerate ionised matter via magneto-hydrodynamic interactions in a wave like fashion, the technical implementation of Alfvén waves for propulsive purposes – the MOA concept - has been proposed, patented (patent number WO2005/027142) and examined for the first time by a group of inventors.

Different studies, expert opinions and practical tests have shown the technical feasibility of MOA, the magnetic field oscillating amplified thruster, a fact attributable to the simple modular set-up, the corrosion free behaviour and the possibility to use COTS components.

In terms of potential application areas, space propulsion is expected to be the prime application for MOA. Different terrestrial applications however, can be imagined as well, making the system highly suited for a common space-terrestrial application research and utilisation strategy.

One of the earliest targets for the further R&D roadmap of MOA will be the application as Attitude Control System Thruster (ACST) and/or North-South Station Keeping (NSSK) thruster. Especially the latter application looks very promising when taking into account the expert opinion of Prof. H. Löb, in which he states that a MOA derived NSSK thruster can be expected to feature a thrust value of 80 mN at a specific impulse of 4000 s, with a beam power of 1.6 kW.

Maybe the biggest strength of the MOA concept is its high flexibility. Most of its performance parameters are easily adapted in real-time, by changing the mass flow and/or the power level. Numerical simulations suggest that MOA is capable to deliver a maximum specific impulse of 13 116 s (12.87 mN, 11.16 kW), but can also be attuned to provide a thrust of 236.5 mN (2411 s, 6.15 kW) using Xe as propellant. In addition, MOA is capable of using all different sorts of propellants, as long as they can be ionised.

The hardware experiments conducted with the P3 prototype have been very promising, with an overall power consumption of only 400 W, 6- 11 mN of thrust could be obtained, leading on the average to a specific power of approx. 50 W/mN for this yet un-optimised prototype in terms of power consumption. Further optimisations in the area of power consumption are expected to improve the specific power to values of 20 – 30 W/mN for the follow-up prototype MOA P3-MFP and the associated breadboards.

While the application of MOA for solar and/or nuclear electric propulsion purposes is obvious, one can also think of using as the system as an “afterburner system” for nuclear thermal propulsion systems. Here, a certain fraction of the exhaust gases would be accelerated to high velocities by MOA’s unique Alfvén wave concept, thereby increasing the $I_{SP}$ of the overall NTP system. Our preliminary estimates suggest that a MOA augmented NTP could feature $I_{SP}$ values well above the “magical” 1000 s borderline.

### 7.1.8 Acknowledgements

The authors of this paper would like to express their thanks to the following individuals and organisations for providing their valuable support in the development activities of the MOA concept (names are in alphabetical order):

- Prof. P. Kramer, Immenstaat, Germany
- Prof. H. Löb,1. Physikalisches Institut Giessen, Germany
- F. Kuttner, W. Porges and E. Svoboda, Vienna, Austria
- N. Valavanoglou, Graz University of Technology, Austria

… and finally all the individuals, who contributed little but invaluable work when support was quickly needed.

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*Figure 7-10: A Launch of the non-commercial Space Shuttle "Atlantis" as seen from a commercial Airliner Window (Source: The Huffington Post)*

Whether it is space, aviation, automotive, software or any other sort of industry, according to Stephen Wilson and Andrei Perumal, "**Complexity costs are the single biggest determinant of your company's cost competitiveness**" ([J] Wilson & Perumal, 2009)[49]. As stated within their book, and depicted in Figure 7-11, complexity costs are different than any others as they follow a geometric growth; complexity costs do not just rise in proportion to the amount of complexity in the business, whether product, process, or organizational complexity; they rise exponentially with greater levels of complexity. This geometric nature of complexity cost growth separates it from other forms of cost.

[49] http://www.complexitycosts.com/, accessed in August 2013

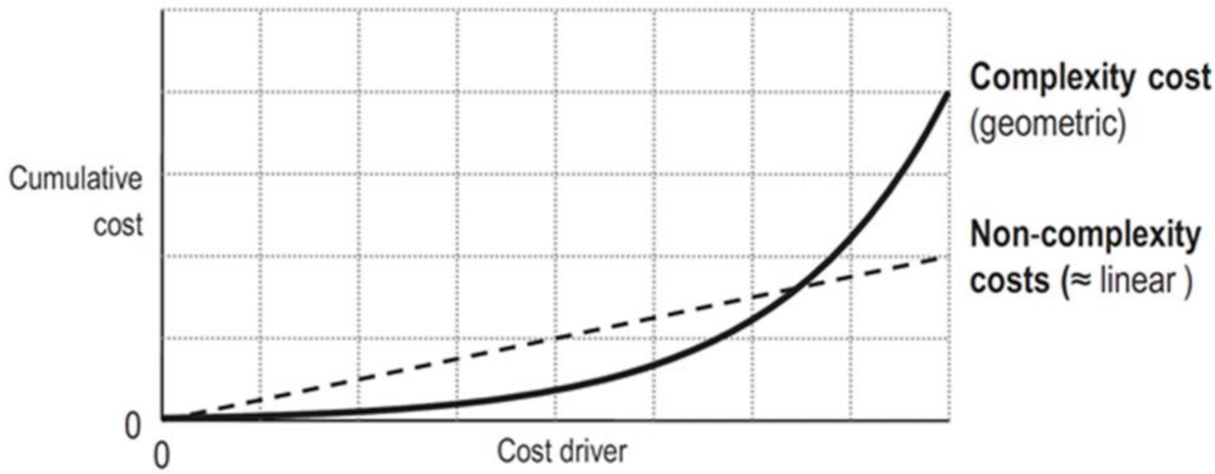


*Figure 7-11: Compexity Costs rise exponentially (Source: Waging War on Complexity Costs, p. 34, ISBN 9780071639132)*

Complexity costs, being all non-value-add, are driven by the overall number of items - the overall level of complexity. So, while complexity is simply the number of things, complexity costs are the non-value-add costs associated with having a number of things. Consequently, **reducing the complexity of a product (Space Shuttle, A380, but also a rocket engine like the SSME or the F-1, etc.) is key to reduce its cost. In addition, this strategy will also increase the reliability and maintainability of the product.** All these items are of great importance for any system and even more so for systems that need to be commercially competitive. Space propulsion should not be any exception, especially in a world with increasing cost pressure on projects and programmes.

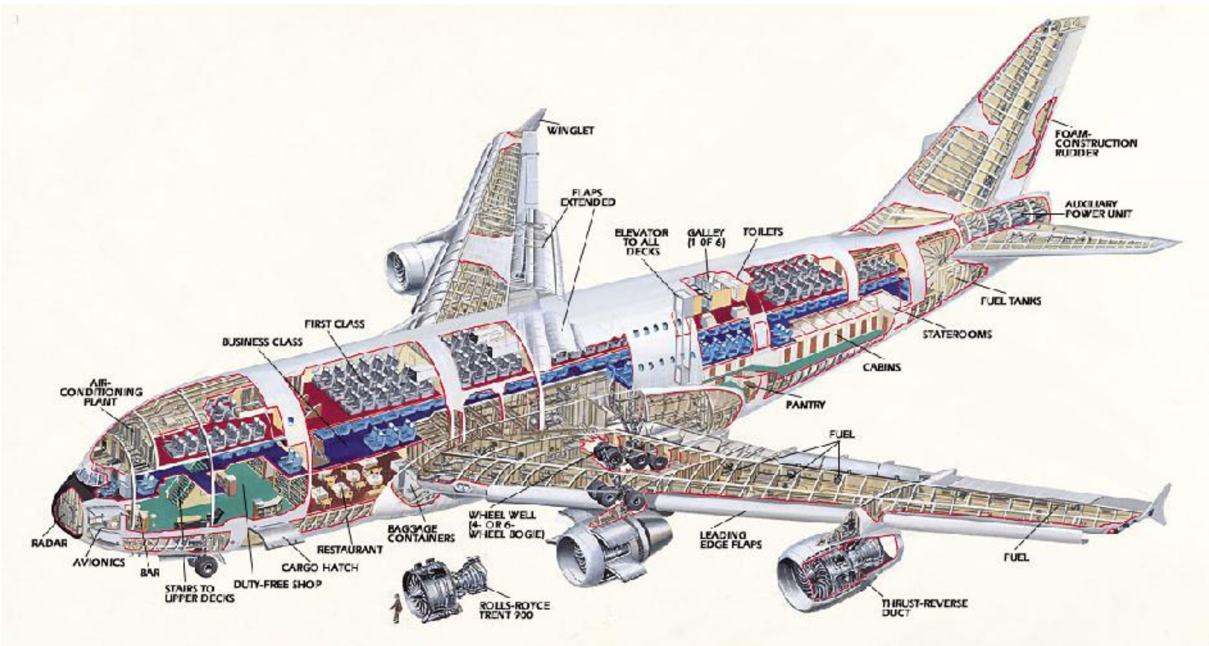


*Figure 7-12: Cut-away View of the A380 – a truly complex Airplane, though fully commercial (Source: www.airliners.net)*

Still the commercial competitiveness separates that space sector from any terrestrial industry. **While an A380 is as - or even more – complex than the Space Shuttle, it is still a commercial competitive system, albeit very expensive**[50] (refer to Figure 7-10 and Figure 7-12).

How is it possible that such a complex airplane is commercially viable?

Obviously airplanes can rely on a fully established market, which provides for the 'plus' on the balance side. On the 'minus' side – hence the cost – airlines thrive on another item that makes airplanes affordable and that is – again(!) – technology transfer. While an A380 can only fly because it uses a multi-suite of the latest technologies, comprising composite materials, avionics, control systems, metallurgy, etc., 99% of these technologies are not developed for this one airplane only, but rather for several systems within and beyond the aviation sector. Consequently **airplanes like the A380 are "spin-in machines", incorporating outside technologies and adapting them for their specific requirements**. What separates space from aviation in this respect is that space has not yet managed to transform itself into a sector using spin-ins as much as possible. Still there are a few technology domains where spin-ins are not yet fully realised – propulsion is the most outshining of these.

While it may not be possible – at least in the short/medium run - to spin-in a full-fledged chemical rocket engine like the SSME or the F-1, smaller, less complex concepts might stand a chance to feature spin-ins at a certain portion. Electric propulsion systems such as

- electrothermal systems (e.g. arcjet, resistojet);
- electromagnetic, electrodynamic systems or plasma engines (e.g. MPD, PPT, VASIMR); and
- electrostatic systems or ion engines (e.g. FEEP, colloid engine, HET);

offer the best chances for such technology flows, as their limited size and complexity allows for certain applications in the terrestrial domain, such as coating, surface treatments, etc.

When it comes to the utilisation of propulsion concepts in the terrestrial sector, classical space requirements like thrust to weight ratio, specific impulse ($I_{SP}$) and reliability are of less importance, while cost (= lowest complexity), versatility and durability become dominant factors. Naturally a jack of all trades device does not exist per se, there is however one concept that answers to most of the beforehand mentioned needs – $MOA^2$, the Magnetic field Oscillating Amplified Accelerator.

$MOA^2$ is a derivative of MOA, which has been introduced and discussed in chapter 7.1 on page 138 of this thesis. As stated therein, space propulsion was originally expected to be the prime application for MOA. Although different terrestrial applications were assumed as well at that time, no one of the investors (including myself) expected these to become so dominant whitn the R&D process, which followed after the paper had been presented at the International Astronautical Conference (IAC) in 2007.

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[50] As stated before, one can buy an A380-800 for the price of US$390 million (refer to chapter 0)

Although we knew of the great versatily of the pulsed plasma accelerator, we were still fully surprised that MOA² would be able to support a multi-suite of applications such as:

- coating (i.e., nitriding);
- surface treatment (activation, modification and cleaning);
- implantation and etching;
- plasma cutting; as well as
- somatic cell treatment

In the end we started to realise that MOA² was probably the first "space propulsion system", which was highly suited for a common space-terrestrial application research and utilisation strategy. With the ability to enable technology flows into both directions, MOA² is to be the first "space propulsion system", whose R&D could make extensive use of spin-ins, which is nothing else than a *Paradigm Shift* for this particular technology domain. Given its strong terrestrial character, we consequently renamed MOA to MOA², deliberately adding "accelerator" to its name. The following paper, presented at the International Astronautical Conference (IAC) in 2010, presents the development from MOA into MOA² and provides for some insights into the possible terrestrial applications that were encountered.

## 7.2 The premiere Technology Spin-in into Propulsion: "MOA²—an R&D Paradigm Buster enabling Space Propulsion by commercial Applications" ([I] Frischauf, Hettmer, Koudelka, & Löb, 2011)

Published in Frischauf, N., Hettmer, M., Koudelka, O., Löb, H.,: MOA² - An R&D Paradigm Buster enabling Space Propulsion by commercial Applications, in *Acta Astronautica* (2011), pp. 173-182 [I]

### 7.2.1 Introduction

It was in 1942, when the later Nobel laureate Hannes Alfvén published a letter, stating, that oscillating magnetic fields can accelerate ionised matter via magneto-hydrodynamic interactions in a wave like fashion [1]. These waves were later called "Alfvén waves", in honour of their discoverer. Although the evidence for Alfvén's hypothesis came already rather early with the observation of certain plasma phenomena, such as being connected with high solar wind Wolf-Rayet stars, more than 60 years had to pass by before a technical implementation of Alfvén waves for propulsive purposes was proposed for the first time.

The name of this concept, utilising Alfvén waves to accelerate ionised matter for propulsive purposes, is MOA² – Magnetic field Oscillating Amplified Accelerator. It is a highly flexible propulsion system, whose performance parameters are easily adapted in real-time, by changing the mass flow and/or the power level.

Its working principle is based on specific magento-acoustic waves that are utilised to accelerate ionised matter for propulsive purposes. Alfvén waves or magneto-hydrodynamic waves are transverse waves, which move parallel to the magnetic field with the Alfvén velocity $v_A$ and depend only on the magnetic field density **B** and the mass density $°_m$ of the Plasma. Equation 7-1 shows the exact relation for calculation of the Alfvén velocity [2].

Typical Alfvén velocity values are in the order of 34.7 km/s for Argon plasmas ($Ar^+$) used in illumination applications and 7700 km/s for Deuterium plasmas ($D^+$) as being used in fusion applications [2].

The Alfvén waves of the MOA² concept are generated by making use of two coils, one being permanently powered and serving also as magnetic nozzle, the other one being switched on and off in a cyclic way, deforming the field lines of the overall system. This deformation is at the very heart of the MOA² concept, as it generates the Alfvén waves, which are in the next step used to transport and compress the propulsive medium, in theory leading to a propulsion system with a much higher performance than any other electric propulsion system. Mathematic models suggest that MOA² is capable to deliver a maximum specific impulse of 13116 s (12.87 mN) at a power level of 11.16 kW, using Xe as propellant, but can also be attuned to provide a thrust of 236.5 mN (2411 s) at 6.15 kW of power.

One of the biggest strength of MOA² is that it is in principle capable of using all sorts of propellants, as long as they can be ionised. Gases that we have used in our tests so far include Nitrogen and Argon, in the future Hydrogen, Helium and Xenon are to be tested as well. Figure 7-13 shows an early MOA² prototype in its test rig within the vacuum chamber.

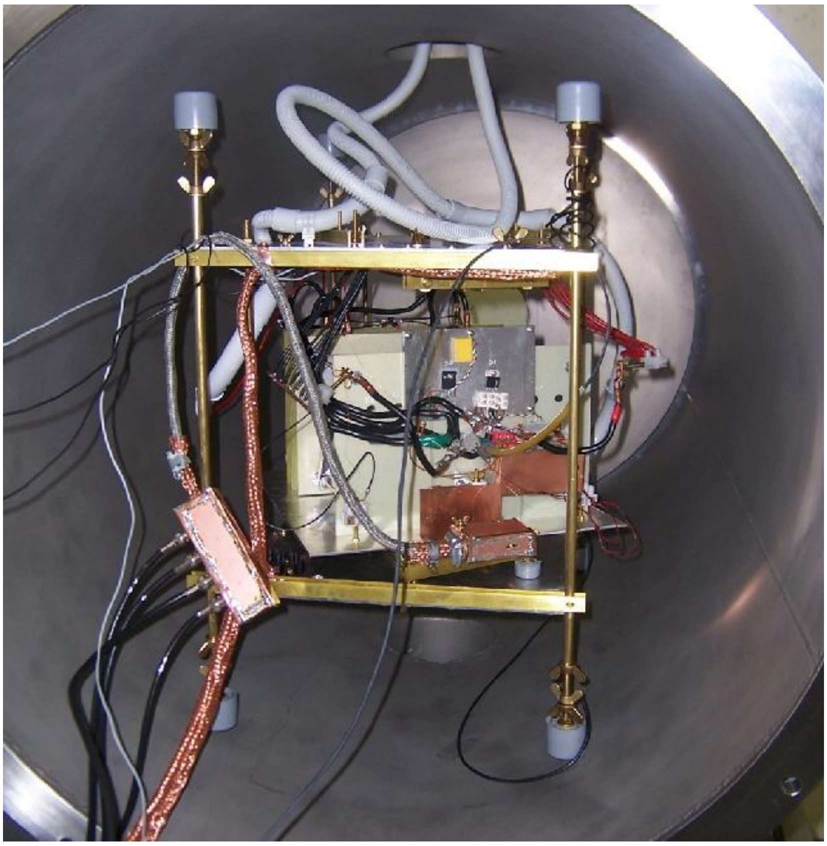

*Figure 7-13: MOA² Prototype inside the vacuum chamber*

Expert opinions on the MOA² concept, such as the one of Prof. Horst Löb, one of the fathers of electric propulsion, which were commissioned by the inventors, have validated the inventors' model and stated the feasibility of the overall concept. When checking the MOA² concept against his own plasma dynamic models, Prof. Horst Löb derived the following parameters for MOA², which suggest that MOA² has an excellent potential as a North-South Station Keeping (NSSK) propulsion system, outperforming all other systems currently available (Table 7-5):

*Table 7-5: Assumed Parameters of a MOA² NSSK-System (Simulation Prof. Löb)*

| MOA Thruster with $H_2$ propellant: | |
|---|---|
| Thrust: | 80 mN |
| Beam Power: | 1.6 kW |
| Specific Impulse: | 4000 s |
| Specific Power Consumption: | 20 W/mN |

Due to its high flexibility, the MOA² developing consortium considers the application of MOA² not only as a NSSK thruster for geostationary satellites, but also as an Attitude Control and Kick-Booster system. At higher power levels in the MW-regime, such as provided by a nuclear space reactor, higher thrust values can be achieved as well, thereby allowing for exploration missions. It has to be noted however that MOA$^2$ is not expected to deliver a thrust to weight ratio bigger than 1, so if MOA² is to be ever used for a manned exploration mission, this will then be only for the interplanetary travel, but not for operations deep inside a planetary gravity field.

### 7.2.2 MOA² – Characterisation and Principle of Work

A basic characterisation of the MOA² thruster quickly leads to one result: MOA falls in the class of electric propulsion systems as it requires an external energy source, which afterwards accelerates the propellant by electromagnetic means. In trying to characterise the MOA system further by comparing it with:

- Electrothermal systems (e.g. arcjet, resistojet);
- Electromagnetic, electrodynamic systems or plasma engines (e.g. MPD, PPT, VASIMR); and
- Electrostatic systems or ion engines (e.g. FEEP, colloid engine, RIT, HET);

it becomes evident that MOA² is best described by a pulsed plasma thruster (PPT). Contrary to other PPT such as the Pulsed Inductive Thruster (PIT) however, MOA$^2$ does not rely on capacitor banks to generate a power pulse. Instead it utilises a rather simple high frequency circuit, which switches the secondary coil on and off, thereby causing a displacement of the primary coil's magnetic field and ultimately an magnetic pressure wave (refer to Figure 7-5 for further details on the working principle).

Even though the principle acceleration mechanism works in pulsed mode, energies of the ejected particles can be very high.

Figure 7-14 shows a Quantitative Depth Profile Analysis of a steel sample, revealing the high plasma particle energies provided by MOA².

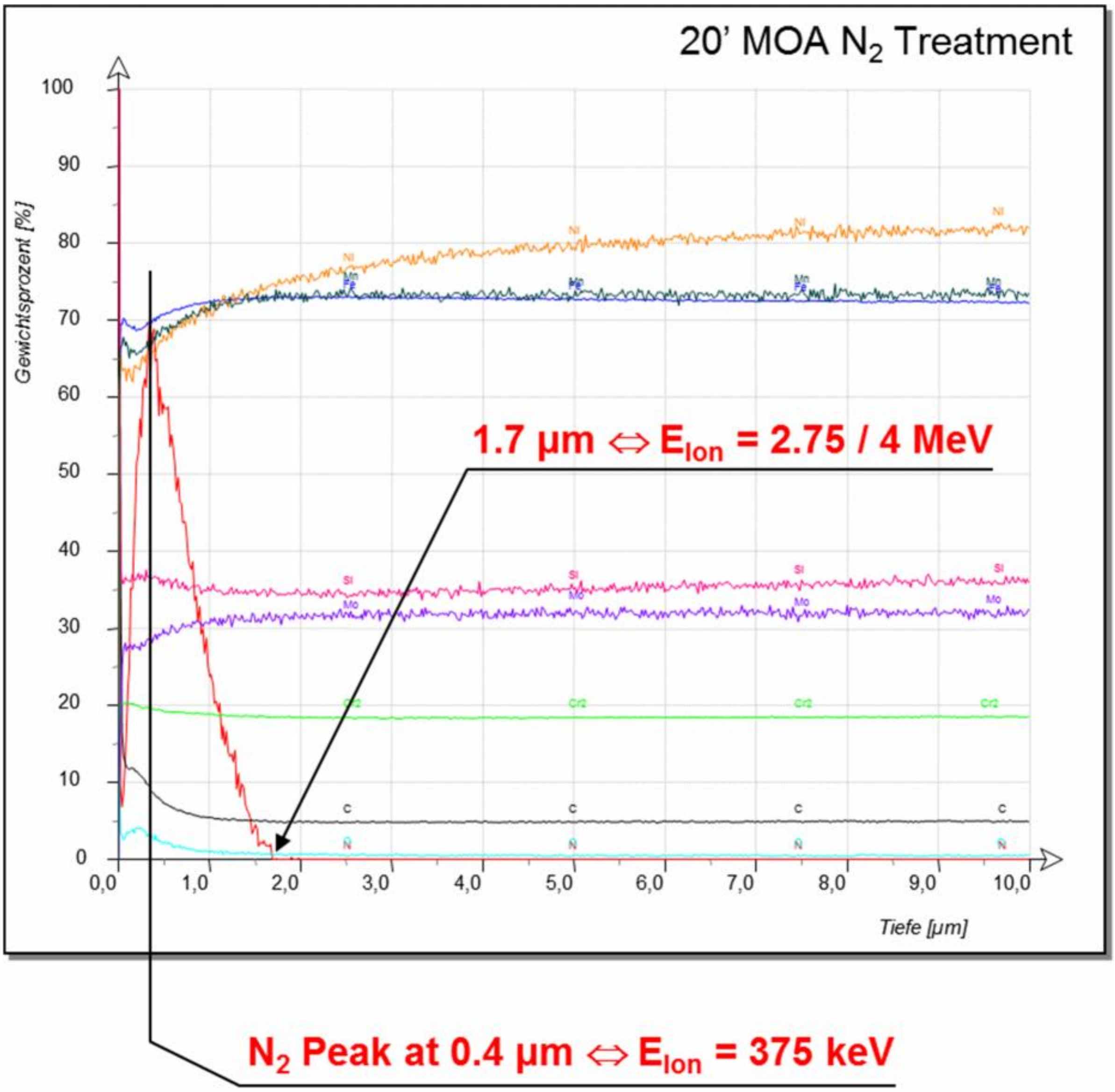


*Figure 7-14: Quantitative Depth Profile Analysis of a steel sample treated by a MOA Nitrogen beam*

Though MOA² is best described as a pulsed plasma thruster, one has to acknowledge the difference that the thermal heating and the acceleration of the propulsive plasma are due to a periodic variation of a magnetic field, as outlined in Figure 7-5.

This special heating and acceleration process has its origins in the unique 2-coil-assembly, which leads to an adiabatic compression, a plasma confinement and finally to the acceleration of the emitted propellant mass due to magnetic pressure waves propagating with the Alfvén velocity. The magnetic pressure waves have their origin in special arrangement of the two magnetic coils. As soon as the secondary coil is switched on (images 2-14 in Figure 7-5), the magnetic field of the secondary coil (left coil in Figure 7-5) displaces the one of the primary coil (right coil in Figure 7-5). This displacement manifests itself in a magnetic pressure wave (best described by an Alfvén wave) and as the magnetic field lines are coupled to the injected plasma, the pressure wave leads to an acceleration of the plasma. Obviously not only the magnetic pressure but also thermodynamic expansion plays a significant role in the acceleration process, therefore the MOA$^2$ system needs ultimately to be characterised as a combination of a thermo- and electrodynamic propulsion system. Figure 7-15 shows the latest accelerator prototype, called MOA P3 Multifunctional Prototype (MOA P3-MFP) in its cross section.

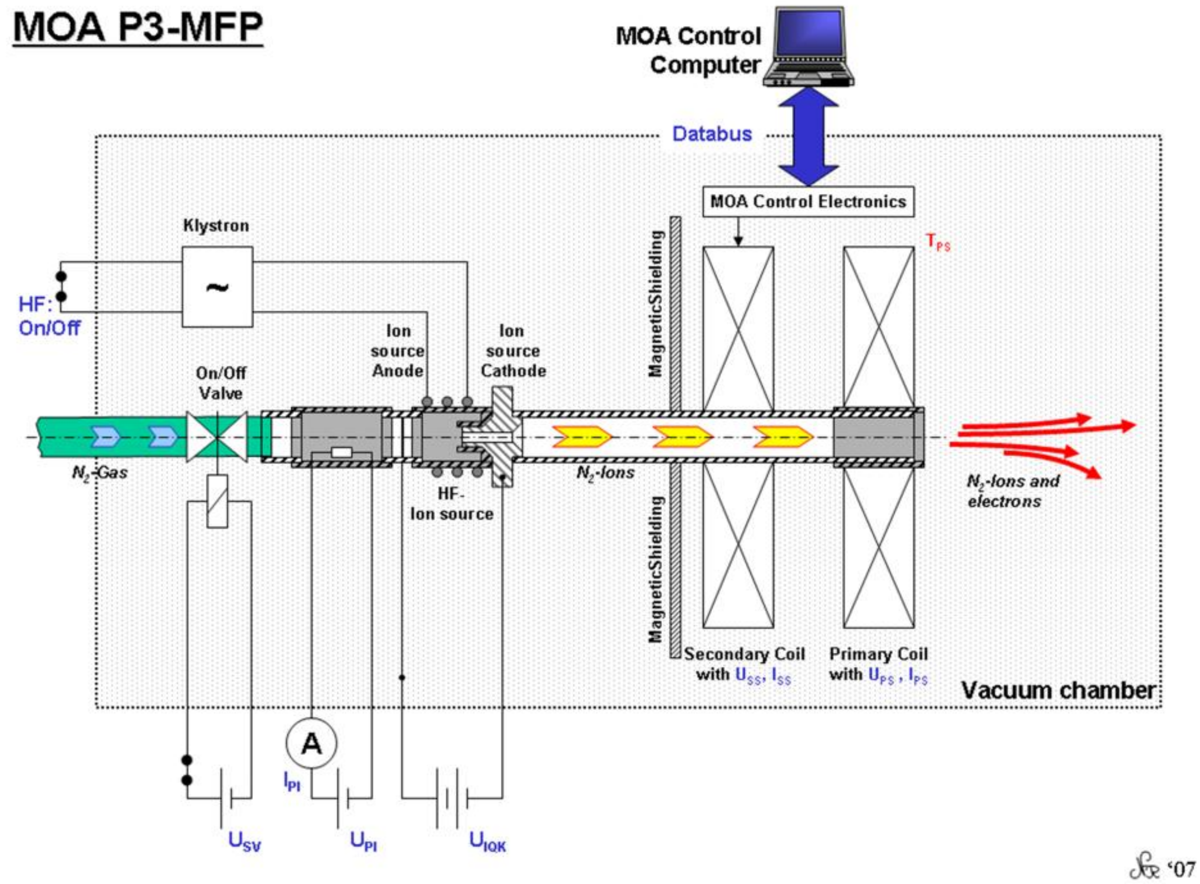


*Figure 7-15: Cross section of the MOA Accelerator in the P3-MFP configuration*

As one can easily depict Figure 7-15, the system features a rather straightforward assembly with no specific complexities, which enables a modular set-up to adapt MOA$^2$ best to its various applications. Because of its intrinsic behaviour as a thermo- and electrodynamic propulsion system, MOA$^2$ is highly adaptable in terms of power, thrust and specific impulse, by trading-off one feature against the other. If one emphasises the thermodynamic features, power consumption and specific impulse will decrease, while thrust will increase accordingly. Accentuation of the electrodynamic features however, will lead to the opposite effect, namely a decreased thrust on the expense of higher power consumption and better if not superior specific impulse values.

Of particular interest of the MOA$^2$ system is the fact that the beforehand mentioned attune ability in terms of power consumption, thrust and $I_{SP}$ can readily be utilised in real-time during flight, making MOA$^2$ the most flexible of all advanced propulsion systems.

All in all MOA² is comprised of five subsystems, as being depicted in Figure 7-15: Cross section of the MOA Accelerator in the P3-MFP configuration:

- The *plasma generator* (in this case the High-Frequency Ion Source);
- The *central tube*, with the magnetic nozzle at the exit;
- The *primary coil*, which generates a timely constant but spatial inhomogeneous magnetic field that also defines the magnetic nozzle;
- The *secondary coil*, which is powered by current pulses, generating a periodic varying magnetic field that counteracts the primary field; and
- The *supply and control units* for the gas flow, the plasma generator and the two coils (e.g. the on/off valve, the MOA control computer, etc.).

Naturally, all these coils lead to an extensive variable magnetic field, creating an effect, which is wholeheartedly wanted as it is the root cause of the magnetic pressure wave fuelling the acceleration of the particles. It will however cause negative effects on the environment - as well as the testing area - if not properly controlled. As such, semiconductors and electronic circuits, which are not properly shielded, will undergo rapid destruction, if exposed to the plasma wave leaving the magnetic nozzle. The destructive effect is primarily based on the rapid change of the space charge, leading to a negative effect on the p-n junction - similar to the events that happen at a (Nuclear) Electromagnetic Pulse ((N)EMP). If $MOA^2$ is therefore implemented in a set-up (satellite, test rig, etc.), sensitive equipment (sensors, solar arrays, etc.) needs to be kept away from the exhausted plasma particles. The accelerator's electronics are not affected, as $MOA^2$ features a "Magnetic Shielding", providing protection (refer to Figure 7-15). While semiconductors are in danger of being damaged or destroyed, biological and metallic - even ferromagnetic - materials are not negatively affected by the plasma beam. This is discussed in detail in chapter 7.2.5 "Coating, Implanting, Etching and medical Treatment – numerous Applications with the same Accelerator" of this paper.

If $MOA^2$ is used in a vacuum chamber then one has to make sure that the plasma beam is properly deflected to avoid a coating of the vacuum chamber's walls. While this might not be a major issue if gases are used as projectiles (such as $N_2$ for the nitriding of metallic targets), the issue attains significant importance if metallic or aggressive projectiles are used. The latter one might be the case if $MOA^2$ is to perform etching operations.

### 7.2.3 MOA² in the Context of advanced Propulsion

Due to the sheer remoteness and limited accessibility of space, the spacecraft's on-board resources are the most valuable asset and should therefore be utilised as efficiently as possible. This requirement is inherent in every space mission but becomes absolutely imperative if one wants to overcome the "space-time gap", that is flying either far away and/or staying in space for a long time.

Whilst the first objective is typical at the very heart of scientific space missions, which reach out for interplanetary and even interstellar space, the latter one is of general importance to all space missions. Increasing the life time of a satellite in general will enable increased mission flexibility, a better scientific output and/or a higher profit margin.

The most limited resource onboard of any spacecraft is typically the propellant as it is a real consumable - at least as long as we have to rely on Newton's third law "actio et reactio" to generate thrust by expelling mass in one form or the other. Power should be considered critical as well, however to a lower extent because one can make use of systems that are either regenerative (solar cells with secondary batteries) and/or have a high energy density (especially nuclear power reactors).

When trying to tackle the propellant problem it turns out that the most effective approach is to use advanced propulsion systems, with a high exhaust velocity/specific impulse ($I_{SP}$) and therefore a low fuel consumption. The importance becomes obvious, when looking at the interdependence of propellant mass $m_{propellant}$, velocity change $\Delta V$ and the specific impulse $I_{SP}$, as discussed in Equation 7-2 on how to calculate the propellant mass to the dry spacecraft ratio [3].

In the search for the most suitable propulsion system, numerous sorts of systems have been studied, ranging from "classical" chemical to the various electric and finally the nuclear systems in all their different facets.

Table 7-2 compares the fuel consumption of four exemplary systems (Space Shuttle Main Engine (SSME) as a chemical system, NERVA as a nuclear fission Nuclear Thermal Propulsion (NTP) system, MOA as an advanced electric and the Gas Dynamic Mirror (GDM) as a nuclear fusion NTP system) for different planet destinations [4]:

As it can be seen from Table 7-2 the specific impulse is of utmost importance when one aims for low fuel consumption. Still thrust is not to be neglected, as lots of loss mechanisms like gravitational loss exist, which can lead to an increased fuel consumption that decreases the gains of using high $I_{SP}$ systems. Similar considerations are true for the power consumption. One has to carefully trade-off the extra mass of the power system to the gain in lower fuel consumption for a given mission, before deciding which propulsion system is to be taken onboard.

Because of all these trade-offs, plenty of propulsion concepts exist, all differing in their characteristics ($I_{SP}$, thrust, power consumption, physical characteristics, cost, etc.), level of complexity and the state of technical maturity. Figure 7-7 tries to compare the different systems and concepts in terms of specific impulse, complexity and maturity [1], [5] - [14].

As can be easily depicted in Figure 7-7, the low $I_{SP}$ Systems, cold gas and chemical propulsion, are the ones with the highest maturity. This has mostly historical reasons, as these systems have seen the longest period of development, because of their applications in missile systems. Superior to the chemical systems in terms of $I_{SP}$ are the different fission based Nuclear Thermal Propulsion (NTP) systems. Some of these have nearly made it to space qualification, like the US NERVA programme in the early 1970s. Nowadays they are again under discussion for being used as propulsion systems for human exploration missions in the Solar System. Even better than these systems are the fission fragment and fusion based NTP systems. While the first ones are only at study level, some of the fusion systems have already been realised as breadboards for deeper studies (e.g. the Gas Dynamic Mirror (GDM) Fusion concept at NASA MSFC [13] and the Dense Plasma Concept (DPF) at the University of Illinois) [4].

A class on their own are the electric propulsion systems. Featuring high to very high specific impulse values, these systems are usually hampered by relatively low thrust values, because of their power dependability. A likely word-around solution would be the use of a powerful nuclear power reactor, generating the required high power values. Such a system is in general called a Nuclear Electric Propulsion (NEP), whereby the electric thruster can be any sort of system, such as an arcjet, ion, hall, magnetoplasmadynamic, pulsed plasma thruster, the VASIMR [8] or the MOA Thruster.

Table 7-3 shows how the MOA Thruster compares to some of the other electric propulsion systems:

As it is clearly visible from this table, MOA is comparable in most of its characteristics to all other electric propulsion systems, but features two particular advantages:

a) the highest achievable $I_{SP}$ value and

b) its real-time attune ability in terms of power consumption, thrust and $I_{SP}$[51]

While point a) definitely qualifies MOA as an advanced propulsion system that matches performances of the yet to be developed fusion propulsion systems, point b) is not to be underestimated as well, as it makes the MOA concept the most flexible of the advanced propulsion systems, and the only one to allow for a high flexibility with respect to in-flight mission planning.

### 7.2.4 MOA² - the Paradigm Buster

Obviously, MOA$^2$ features a modular set-up for the sake of simplicity, high versatility and limited prototype cost, as can be seen in Figure 7-15: Cross section of the MOA Accelerator in the P3-MFP configuration on page 161, and since the MOA concept is designed to be corrosion free, low cost commercial off the shelf (COTS) materials can readily be used as well.

Although this is a great achievement, it would clearly not provide enough credence to the claim of calling MOA$^2$ “a paradigm buster”. There must be something more to it – and yes, there is.

Clearly one has to acknowledge that there are numerous space propulsion systems and concepts in the space arena. A significant subgroup of these is the one of electric propulsion systems, of which the plasma thruster form yet another sub-subgroup. At this point we are talking of a handful of concepts only. Already now, the MOA thruster stands out because of its distinguished tune ability of thrust, power and $I_{SP}$. But the real crack is that we have only talked of the MOA thruster so far and while that is all there is for 99.9% of the space thrusters in the world, MOA has another face – namely MOA$^2$ – the Magnetic field Oscillating Amplified Accelerator.

To obtain a feeling for the gravity of this statement, Figure 7-14 can be used to provide some insights. As stated herein, MOA$^2$ was used to coat a steel sample with Nitrogen and in a mere time period of 20 minutes a considerable amount of Nitrogen was deposited in the metal, thereby forming a Bragg peak distribution curve. Of particular interest are hereby three observations:

a) Although the curve starts at the surface, nearly no Nitrogen has been deposited near the surface.

b) The maximum implantation has happened at a depth of 0.4 µm.

c) From the implantation maximum there is a slower decline to a maximum penetration depth of 1.7 µm.

By making use of Linear Energy Transfer (LET) models and cross-section analysis tools, one can correlate these various depths with energies [15]. As such the maximum implantation at 0.4 µm relates to a particle energy of 375 keV. To achieve the maximum penetration depth at 1.7 µm, a Nitrogen molecule ($N_2$) will have to have an energy of 2.75 MeV. In the case that the

[51] Note: all three MOA data sets are different operating modi of only one propulsion system

Nitrogen has dissociated into N+N, hence is in its atomic form, such a particle will need a kinetic energy of 4 MeV to achieve a range of 1.7 µm.

While these numbers are already impressive on their own, there is an additional facet to it that has not been mentioned yet, which is that the total power consumption of the accelerator was 400 W, of which 300 W, were provided to the coils and 100 W to the ionisation stage. And even better, the ionisation stage, which a particle has to pass before it will encounter the two coils (refer to Figure 7-15), can only deliver a maximum particle energy of 1000 eV.

This however means that the magneto-acoustic coupling mechanism is very strong, since it allows to accelerate a particle from an energy of 1 keV (after the ionisation stage) to 375 keV (maximum implantation number) and up to 4 MeV (maximum penetration depth) – at a mere power consumption of 300 W. While this is already a rather low power consumption in the space world, it is even more ground breaking in the industrial sector and hence $MOA^2$ did quickly attract the interest of various experts from the coating industry. And this is where the commercial paradigm shift starts.

### 7.2.5 Coating, Implanting, Etching and medical Treatment – numerous Applications with the same Accelerator

At the very beginning, when the developers were focussed on the space thruster application, it was not evident what ground breaking innovations would be enabled by $MOA^2$.

Only when the first experiments with an industrial partner from the steel sector were accomplished successfully, $MOA^2$'s potential started to reveal itself.

As mentioned in the chapter before, this steel nitriding experiments proved that $MOA^2$ could deposit $N_2$ in a very effective manner. A thorough analysis of the quantitative depth profile in Figure 7-14 showed that 89% of the Nitrogen had been deposited in a depth range between 0.1 and 1.1 µm. The overall amount of Nitrogen surmounts to 3.5 µg/cm², which correlates with a film thickness of 44 nm. If one takes into account that the experiment was performed in a timeframe of 20 minutes, an evaporation rate of 0.36 Å/s was achieved. This rate is comparable to the evaporation rates, which can be provided by Electron Beam Physical Vapour Deposition (EBPVD). EBPVD systems however, do not implant, but coat on the surface only.

With this result, the MOA Accelerator had proven that it could provide high implantation energies and high deposition rates at low power consumption. But there was still more to come.

As $MOA^2$ resembles a pulsed plasma accelerator, all sort of projectiles can be accelerated, as long as they are electric conductive. In addition all sort of targets can be used as well, be they made out of metal, plastic or even paper. This sounds odd at the beginning: How can a 4 MeV particle beam penetrate paper or plastic (e.g. PMMA) without burning the substrate?

To prove the claim that the $MOA^2$ particle beam is indeed "cold", a coating experiment with a 30 x 30 cm PMMA (also dubbed Plexiglas) sample was performed. A $MOA^2$ $N_2$ plasma beam was directed for several minutes onto this PMMA target, which was later on analysed by the Institute of Solid State Physics of the University of Technology in Vienna and Prof. Christoph Eisenmenger-Sittner. The following figures outline the results of the test (Figure 7-16 and Figure 7-17).

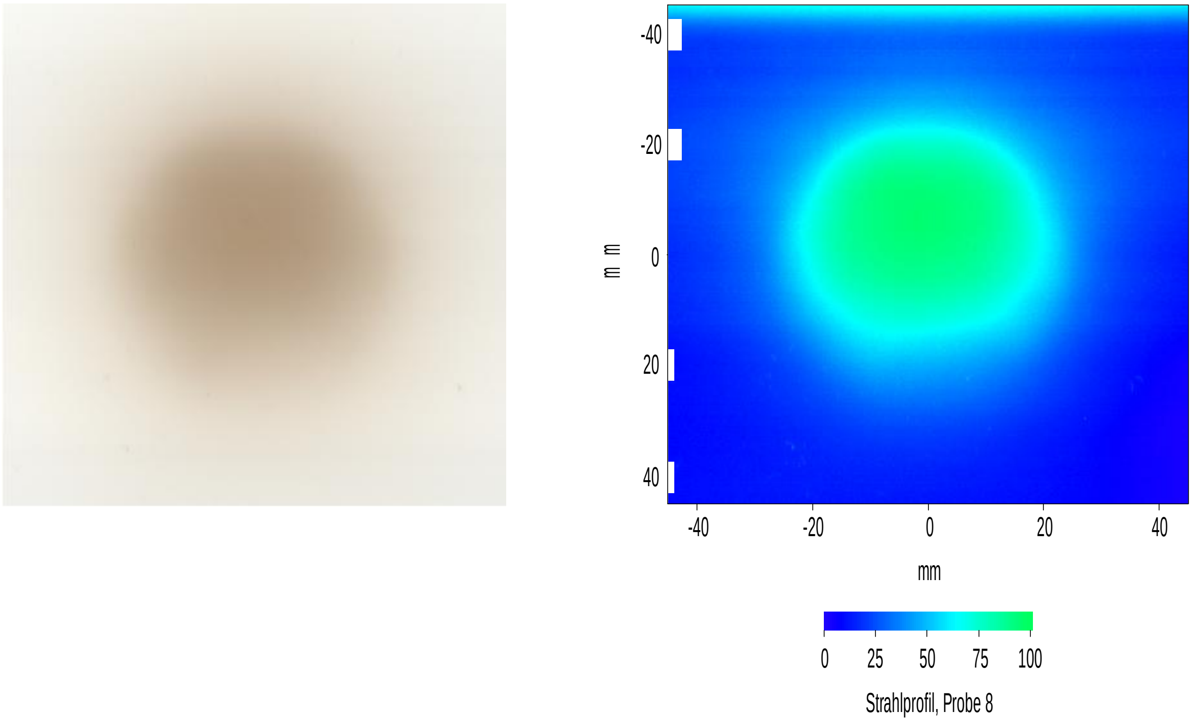


*Figure 7-16: Photo (left) of the coated PMMA Sample. Length of the edge: 9 cm. The discolouration relates to the deposition of N2 in the PMMA sample. Intensity Profile (right) of the coated PMMA sample. The Plasma beam features a cross-section of ca. 3 cm with a very high homogeneity, relating to an aperture angle of 22°.*

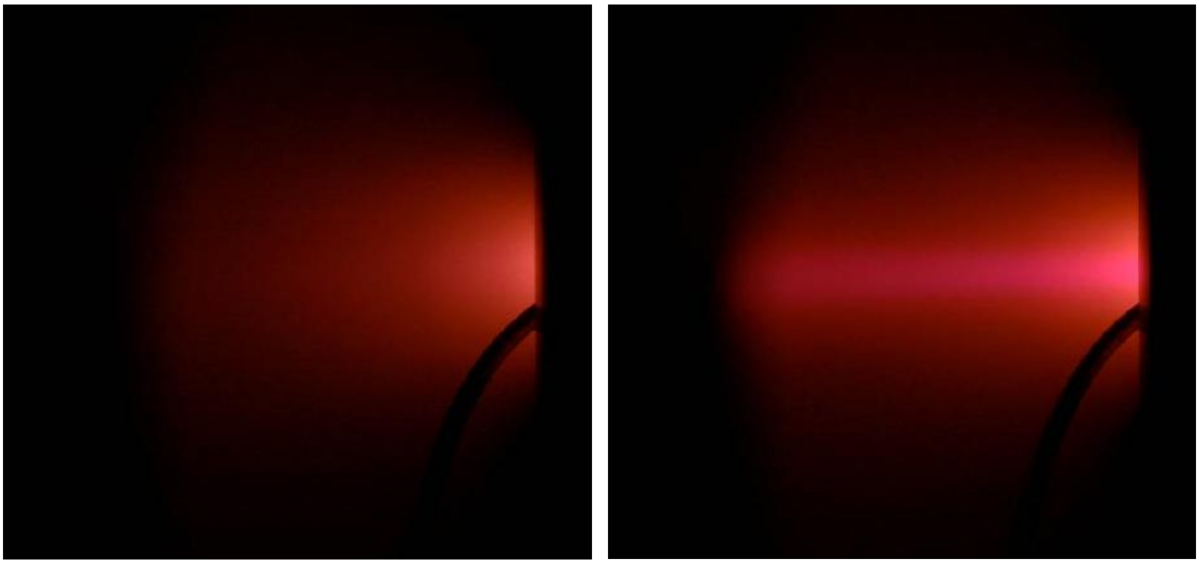

*Figure 7-17: A Nitrogen plasma stream coming out of an ion source (left) and the same plasma stream streaming out of the ion source and the follow-up MOA$^2$ system (right). Camera set-ups are identical. The high energetic focused plasma beam is easily depicted, leaving the P3-MFP exhaust nozzle in both pictures on the right side and hitting the target on the left side. The dark feature in the foreground is a cable, lying between the P3-MFP and the objective of the camera. It shall be noted that the colour of the plasma represents the density of the plasma, but not its energy/velocity.*

After a careful analysis of the sample, Prof. Eisenmenger-Sittner, of the TU Vienna, affirmed that the MOA$^2$ treated PMMA samples:

a) feature a discolouration due to the deposition of Nitrogen in the PMMA, but
b) show no thermally influenced tension distortions, although the flow point of PMMA is at 70 to 100°C.

The possibility to coat all sort of target with all sorts of projectiles at low target temperatures is a feature, which has spurred the interest of several firms in the industrial sector. But of course, it is also possible to concentrate the plasma beam to achieve higher temperatures – this might be necessary to perform etching operations.

As stated in the heading, MOA$^2$ might as well be used for medical treatment purposes. One might immediately think of using the accelerator to perform cancer treatment, but this is not the first application. It is rather making use of the specific magnetic fields to accelerate Iron Nano-beads coupled to an antibody. The proposed concept is similar to the one of hyperthermia cancer treatment [16], where an antibody doped with an Iron Nano-bead is applied to the malign tissue and exposed to alternating magnetic field, which heats up the tissue to a temperature where the proteins will suffer from hyperthermia.

While the MOA$^2$ method uses also Iron-doped antibodies, the method of choice to destroy the malign cells is not hyperthermia, but a magneto-mechanical coupling of the antibodies, which rips apart the malign cells (Figure 7-18).

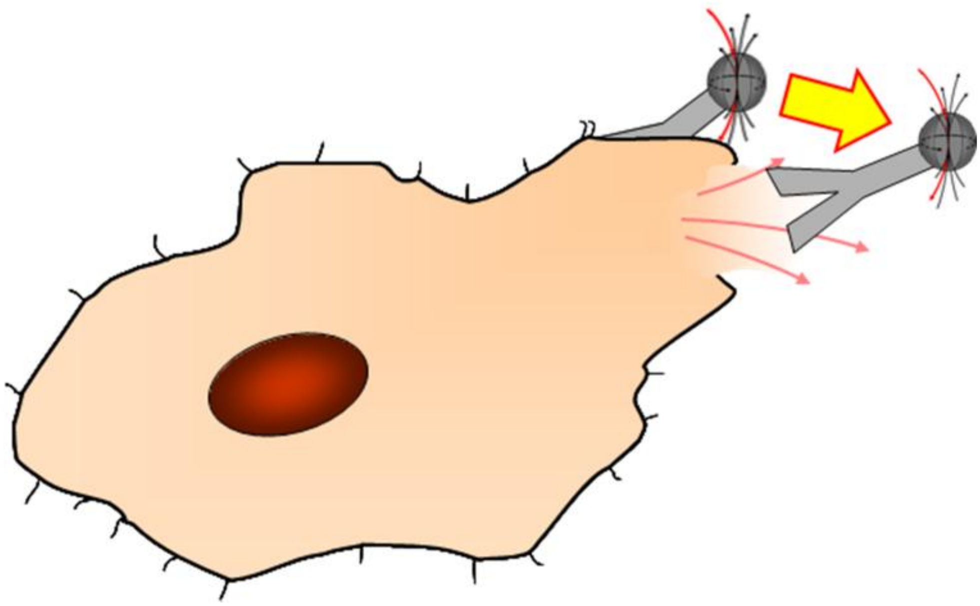

*Figure 7-18: Schematic illustration of the MOA$^2$ magneto-mechanical coupling to an Iron Nano-bead (the little grey ball) connected to an antibody (the "Y-shaped" figure), which is forced to dislocate, thereby ripping apart the tumour cell.*

The advantage is that the effect is easier to control than the hyperthermia process as it does only affect the cells, interacting with the antibodies and does not "flow out" to surrounding tissue, as the thermal process does.

### 7.2.6 Conclusions

More than 60 years after the later Nobel laureate Hannes Alfvén had published a letter stating that oscillating magnetic fields can accelerate ionised matter via magneto-hydrodynamic interactions in a wave like fashion, the technical implementation of Alfvén waves for propulsive, coating and medical purposes – the MOA Accelerator - has been proposed, patented and examined for the first time by a group of inventors.

Different studies, expert opinions and practical tests have shown the technical feasibility of $MOA^2$, the Magnetic Field Oscillating Amplified Accelerator, a fact attributable to the simple modular set-up, the corrosion free behaviour and the possibility to use COTS components.

In terms of potential application areas, $MOA^2$ is the first space propulsion concept, which has a solid terrestrial application portfolio, making the system highly suited for a common space-terrestrial application research and utilisation strategy. It can therefore act as a paradigm buster, connecting for once and for all the last missing space area – the space propulsion sector - to the terrestrial industrial area, thereby breaking up the cost dilemma of these systems. Contrary to energy, computer and communication systems on board of spacecraft, space propulsion systems had so far not found a "real" terrestrial application. This had hampered their progress in terms of performance-to-price ratio –as seen with computers, solar-cells, light-weight materials, etc. Still, propulsion systems remain a major cost driver for satellites and rockets; mostly due to their small unit numbers, which make most of these systems nearly unique specimens – consequently bearing a huge price tag.

$MOA^2$ has the potential to change these rules of the game. Being an accelerator, which utilises a highly effective magneto-acoustic coupling, it:

a) is highly tune able in terms of thrust/mass flow, plasma beam energy/$I_{SP}$ and power consumption,

b) can accelerate nearly all sorts of particle onto nearly every possible target at very low target temperatures (70-100°C),

c) operates at high ambient pressures (16 Pa) and

d) features a simple modular set-up and performs in a corrosion-free, flexible and highly effective way

These features enable numerous applications, ranging from an Attitude Control System Thruster (ACST) and/or NSSK thruster to a coating/implantation/etching device and a system for cancer treatment, as well as several others. At this point it is unclear which application will be the first to hit the market, but the one that does will definitely change the rules of the game. Once this has happened, $MOA^2$ will have truly established itself as an R&D Paradigm Buster enabling Space Propulsion by commercial Applications.

### 7.2.7 Acknowledgements

The authors of this paper would like to express their thanks to all individuals and organisations for providing their valuable support in the development activities of the MOA Accelerator.

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# 8. Summary and Conclusions

**Technology transfer has always been an important part of spaceflight in the domains of exploration, satellite communication and navigation**. Possibly the first examples stem from the Apollo Programme of NASA, conducted in the 1960s, eventually leading to the highest level of miniaturisation of computer technology – the integrated circuit (IC)-based computer using microchips based on silicon technology. These technology transfers are therefore to be classified as **spin-offs** from a human **space exploration** programme.

Equally or even more important nowadays are the technology transfer activities enabled by space communication, satellite navigation and Earth observation, which all together form the group of **space applications**. These three areas are today the only branches of the space sector, which are governed by commercial rules, or which are at least developing rapidly into that direction. Given that set-up, the commercial pressure is likely to trigger the **spin-in** of terrestrial technologies into these areas; hence **technology transfer is an integral part of the game**.

With space exploration and applications being the most vibrant domains where technology transfer happens within spaceflight, the next step was to conduct an analysis of the requirements and constraints that govern this process. Based on the assessment of three distinctive players, which are active in very different domains, follow different approaches and adhere to completely different key requirements, such as:

- **CERN and its R&D activities related to hi-end particle detectors for its accelerators LEP and LHC** - aiming to achieve the highest scientific performance;
- **ESA's activities to develop the Navigation and Communication System of the ATV (Automated Transfer Vehicle)** - rating the safety of the astronauts as the top priority that every other design aspect has to adhere to; and
- **The JRC-IET and its role in supporting the development of hydrogen fuel cells and tanks in support of the Hydrogen Economy** - featuring simplicity of use and highest safety at low cost as the main drivers;

We could show that **technology transfer is not a "clear cut"**, as it does often span over several domains, such as communication, propulsion, navigation, energy, etc., governed by requirements and constraints like highest safety, best performance, lowest cost, etc., which cannot be easily rated in terms of importance – not even for a specific application.

CERN, ESA, the JRC-IET and others, all these entities perform technology transfer - all at different levels. Given the specific constraints that these different players are confronted with, both the technologies transferred as well as the encompassing strategies will vary, as will the partners, which participate to this transfer. Consequently **every technology transfer example is unique, very much dependent on the involved technology, the partners and the specific constraints of the encompassed sectors**. Therefore the technology flow, hence the decision whether the technology transfer will be a spin-off or a spin-in depends very much on the involved R&D strategies and the possible applications. Naturally **terms like spin-in and spin-off are of relative nature; one entity's spin-in is the other one's spin-off.**

Obviously space activities, and especially the commercial ones, are especially prone for technology transfer as the know-how generated within space projects may be used for other industrial sectors, which distinguish themselves by the need for high quality standards, the requirement to control harsh environments and/or the necessity to deal with potentially high energies. Based on this observation, it became clear why **technology transfer has been utilised**

**predominantly between space, aviation, automotive as well as the ICT sector** for the last decades. This is likely no to change in the years to come, but what one can expect to change is the direction of the technology flow. **While the early stages of technology transfer favoured spin-offs, hence the knowledge transfer from space to the respective terrestrial sector, recent developments have shifted the pendulum towards the spin-in side, with the space sector employing more and more the strategy of 'importing and adopting' terrestrial technologies for its activities**.

We could show that the drivers for this pendulum swing towards 'spin-in' are twofold, being attributed to varying technology generation cycles on one side and different scales for R&D budgets and the attributed technological progress on the other side.

- **Moore's law served as a showcase for the generation cycle spin-in driver**; with transistor counts and densities doubling every two to three years, this generation cycle is still much shorter than the one within the aerospace sector, which features a cycle in the order of 7-10 years. By introducing new technological generations at a pace which is three to five times faster, the ICT sector is prone to progress more rapidly than the space sector; therefore **one can assume that the technology flow between the ICT and the space sector will not only continue to remain in a spin-in pattern but also that the ICT sector will maintain and expand its role as a major technology contributor for the space arena in the years to come.**
- While shorter generation cycles of specific terrestrial sectors are one key driver for the pendulum swing towards 'spin-in', **the magnitude of the associated R&D expenditures are another key item, which amplifies the possibility of spin-ins vs. spin-offs**. A recent study published in a JRC Technical Note has assessed the R&D expenditures of the automotive industry and the aerospace and defence sector, confirming that the automotive industry is the largest R&D investor in the EU-27, accounting for one quarter of total industrial R&D investments. With a worldwide R&D investment of the automotive sector outweighing the one of the aerospace and defence sector by a factor of 5.1 worldwide and by 4.4 in the EU-27 the conclusion is clear; **the sheer difference in R&D expenditure in the aerospace and the automotive sector clearly favours a spin-in of terrestrial automotive technologies into the space sector.**

Another key item, which must not be neglected is the topic of **'disruptive technologies', turning an already existing market and value network (over a few years or decades) upside down, eventually displacing an earlier technology**. From what we have seen in space in the last years and decades, the likelihood for disruptive space innovations is rather small, while terrestrial sectors have experienced such events rather frequently throughout history. Although no one can say, what the next disruptive innovation will be and where it will happen, **chances are high that any disruptive innovation will not happen within the space but rather in the ICT (short generation cycles) or the transportation sector (high R&D budgets), further establishing the already existing spin-in trend.**

**But how strong are the influences from the transportation and the ICT sector? How many technologies are still driven 'in-house' by the space sector, how many are being 'imported and adopted'?** In aiming to answer these questions we have assessed the technology flows along the technology domains of ESA's Technology Tree V3, the results provide for some interesting insights:

- The **technology flow between space and the ICT sector** covers nearly two thirds of all technology domains and 94% of these technology flows are spin-ins

- The **technology flow between space and the transportation sector** covers 84% of all technology domains and 62% of these technology flows are spin-ins
- **Spin-ins from the ICT sector are mostly based on the progress of chipsets** (Moore's Law)
- **Technology flows between space and the transportation sector encompass predominantly the aviation sector**; with the advent of electric cars, the automotive sector is likely to become another spin-in contributor
- **Propulsion is the only technology domain without a noteworthy technology flow**; neither spin-in nor spin-off alleviate the cost pressure

To substantiate the last two bullets, an analysis of an upcoming spin-in process, which is likely to occur in the satellite communication domain has been performed, showing that fuel cells, which are being developed for the automotive sector will likely be adapted and utilised in the next generation of telecommunication satellites.

What was therefore left was to have a closer look at the last statement in the bullet, rating propulsion as the only technology domain without a noteworthy technology flow, hence making propulsion a "puristic space undertaking". We could show that rocket engines remain to be a major cost factor in the space transportation equation, especially the fact that propulsion systems are very complex drives up the cost. This however is not God-given, as is demonstrated by the aviation sector; where **an A380 is as - or even more – complex than the Space Shuttle, and it nonetheless a commercial competitive system, albeit very expensive.**

How is it possible that such a complex airplane is commercially viable? Obviously airplanes can rely on a fully established market, which provides for the 'plus' on the balance side. On the 'minus' side – hence the cost – airlines thrive on another item that makes airplanes affordable and that is – again(!) – technology transfer. While an A380 can only fly because it uses a multi-suite of the latest technologies, comprising composite materials, avionics, control systems, metallurgy, etc., 99% of these technologies are not developed for this one airplane only, but rather for several systems within and beyond the aviation sector. Consequently **airplanes like the A380 are "spin-in machines", incorporating outside technologies and adapting them for their specific requirements**. What separates space from aviation in this respect is that space has not yet managed to transform itself into a sector using spin-ins as much as possible. Still there are a few technology domains where spin-ins are not yet fully realised – propulsion is the most outshining of these.

While it may not be possible – at least in the short/medium run - to spin-in a full-fledged chemical rocket engine like the SSME or the F-1, smaller, less complex concepts might stand a chance to feature spin-ins at a certain portion. Electric propulsion systems offer the best chances for such technology flows, as their limited size and complexity allows for certain applications in the terrestrial domain, such as coating, surface treatments, etc.

**When it comes to the utilisation of propulsion concepts in the terrestrial sector, classical space requirements like thrust to weight ratio, specific impulse ($I_{SP}$) and reliability are of less importance, while cost (= lowest complexity), versatility and durability become dominant factors.** Naturally a jack of all trades device does not exist per se, there is however one concept that answers to most of the beforehand mentioned needs – $MOA^2$, the Magnetic field Oscillating Amplified Accelerator.

**While propulsion has so far been exclusively a topic for spin-offs, MOA² is the first 'spin-in propulsion game changer', a fact attributable to the simple modular set-up, the corrosion free behaviour and the possibility to use COTS components.**

In terms of potential application areas, MOA² is the first space propulsion concept, which has a solid terrestrial application portfolio, making the system highly suited for a common space-terrestrial application research and utilisation strategy. It can therefore act as a paradigm buster, connecting for once and for all the last missing space area – the space propulsion sector - to the terrestrial industrial area, thereby breaking up the cost dilemma of these systems**. Contrary to energy, computer and communication systems on board of spacecraft, space propulsion systems had so far not found a "real" terrestrial application. This had hampered their progress in terms of performance-to-price ratio –as seen with computers, solar-cells, light-weight materials, etc.** Still, propulsion systems remain a major cost driver for satellites and rockets; mostly due to their small unit numbers, which make most of these systems nearly unique specimens – consequently bearing a huge price tag.

**MOA² has the potential to change these rules of the game.** More than 60 years after the later Nobel laureate Hannes Alfvén had published a letter stating that oscillating magnetic fields can accelerate ionised matter via magneto-hydrodynamic interactions in a wave like fashion, we have proposed, patented and examined for the first time a technical implementation of Alfvén waves for propulsive, coating and medical purposes – the MOA Accelerator. Different studies, expert opinions and practical tests have shown the technical feasibility of MOA², a fact attributable to the simple modular set-up, the corrosion free behaviour and the possibility to use COTS components. With these features, MOA² is already standing out against from the crowd of existing propulsion systems. Its real uniqueness however is due to the fact that **MOA² is not a 'mere' thruster but rather an accelerator, which utilises a highly effective magneto-acoustic coupling methodology. Consequently MOA²:**

e) **is highly tune able** in terms of thrust/mass flow, plasma beam energy/$I_{SP}$ and power consumption;

f) **can accelerate nearly all sorts of particle onto nearly every possible target at very low target temperatures** (70-100°C);

g) **operates at high ambient pressures** (16 Pa); and

h) **features a simple modular set-up and performs in a corrosion-free, flexible and highly effective way.**

These features enable numerous applications, ranging from an Attitude Control System Thruster (ACST) and/or NSSK thruster to a coating/implantation/etching device and a system for cancer treatment, as well as several others. At this point it is unclear which application will be the first to hit the market, but the one that does will definitely change the rules of the game. Once this has happened, **MOA² will have truly established itself as an R&D Paradigm Buster enabling space propulsion by commercial applications, eventually helping to make space systems truly commercial for once and for all.**

# 9. Acknowledgement / Danksagung

*"I can no other answer make, but, thanks, and thanks."*

William Shakespeare, "Twelfth Night or What You Will", 3rd act

William Shakespeare is right; at that point I can no other answer make, but thanks and thanks. And this thanks has to be addressed to several persons, who have made this dissertation possible within those 16 years that have passed after I had finished my diploma thesis on this very 22nd of April 1998, six days after the birth of my daughter Carina. Hence my 'thank you' cannot be restricted to the academic area, but must cover persons from family, friends and colleagues.

As the name had already been mentioned, I want to say thanks first and foremost to my family "ABC"; Andreas – my son -, Bettina (Tina) – my wife and Carina FRISCHAUF – my daughter. This dissertation would have not been possible without the support of this triumvirate. It starts right away in 1990 with Tina supporting my intentions to study, against the original plannings. It continues a few years later when Tina gave me the freedom to pursue my research avtivities abroad – which was also against the original plannings - and conducting my diploma thesis at CERN. And it reaches its peak by having Tina relocate with me to the Netherlands so that I can work for ESA, once I had finished my studies. All in all, my "queen of hearts" is much more flexible and understanding as I ever am.

My children Carina and Andreas have to be especially thanked for. Not only for accepting my scientific-technical related frequent flying but also and specifically for their considerateness in the final stages of this dissertation. Carina's and Andreas' thoughtfulness goes far beyond of what one can expect from a 15/16-year and an 11/12-year 'old'.

My mother, although not directly connected to this scientific work, needs to be thanked for as well, as she tried heavily to make a "straight" person out of me. One might argue whether she was really successful, but I am in any case deeply thankful for that she has raised me giving me the ability to dream and the self-confidence to dare making these dreams come true.

Another "thank you" goes to my grand mother Hermine, to Tina's parents Horst and Karoline and to my step father Franz. Even persons with a certain level of self-confidence entertain doubts – I am no exception. Latest at that stage it is great to have people around, who unconditionally belief in one, such as those 'fantastic four'.

My two uncles Peter FRISCHAUF and Max WLASCHEK are the ones that make up for the link between family and friends. While Peter was the one to initiate my technical interest, Max sparked inside of me the enthusiasm for science by sharing with me with love for the stars. Both exerted their influence on me when I was five years old – and both their actions have an effect on me until today.

My best friend Martin MÜLLER could fill an entire chapter. I had the good luck of getting to know and befriend him in the 3rd class of the TGM. Our friendship was so special that we got nicknamed "the twins" by our comrades, not because we were look-alikes, but due to the fact that also were seen together in and outside of school. Our sticking tother should continue throughout the military service and thanks to Martin I would join him in studying technical physics thereafter, something I had not have planned for and which came as a total surprise to my fiancé at that time, who is my wife of today. Martin had allured me by my interest for astro and particle physics. My dear twin – Thanks a lot for that!

This very time frame with Martin and me going together to school saw also an encounter with another important person for my later scientific and space-related career; Johannes ORTNER, at that time managing director of the Austrian Space Agency ASA. He was very instrumental in guiding my space interest towards spaceflight in general and ESA specifically. I would have not attended the ASA/ESA Alpbach summer school, finished the International Space University and made it to ESA without his encouragement.

However before coming to ESA, I had to finish my studies of techncial physics and doing so required me to guide it into a direction for which I had started it in the first place – particle physics. In Manfred KRAMMER, the project lead oft the DELPHI VFT MINISTRIP DETECTOR at CERN, I did find a competent and amiable supervisor for my diploma thesis, which I did pursue at the Institute for High Energy Physics of the Austrian Academy of Sciences and at CERN in Geneva. CERN is indeed a fascinating place and due to Manfred's support it has become an integral part of my scientific-technological career.

In July 1998 – France had just won the football championship – my time at CERN drew to a temporary end. My occupation at the VFT and the FCA (two detectors of the DELPHI experiment) was finished, August saw me starting my new assignement at ESA/ESTEC in the Netherlands. Looking back to that point I want to sincerely thank George SCOON, an ESA study manager for science missions. In countless conversations at ESA and before at the ASA/ESA Alpbach summer school and the International Space University, he did familiarise me to spaceflight, while at the same time showing me the fine line between creativity and feasibility. The knowledge gained in this process proofed to be extremely helpful in my later activities within the ESA project team of the Automated Transfer Vehicle (ATV). And as I had mentioned the ATV, I have to acknowledge two more persons; Joachim EBI and Ignacio "Nacho" AGUILAR-SANCHEZ. While Joachim was my boss within the ATV team, Ignacio was my colleague and mentor, my participation to the ATV would have been only half as educative and enjoyable without these two persons.

When I changed my career path from ATV avionics engineer to become a futre studies systems engineer at ESA's exploration programme "Aurora", which gave me the opportunity to bring in my nuclear expertise, I got to meet Michael FÜTTERER, who would eventually help me realigning my career to be a bit more scientific again. Michael was the original driving force for me to attend an EU Concours, which enabled me some years later to work at the JRC-IET, the energy research centre of the European Commission. I was lucky again as I happened to be involved within Hydrogen storage research, an area of particular interest to me due to its closeness to the automotive and the aerospace sector. In addition I got to know two more persons, who made it possible that I could work on the Hydrogen storage area from a system viewpoint; Pietro MORETTO and Marc STEEN. Both gave me the freedom and support to interconnect the Hydrogen research activities at the JRC-IET with the associated technology development actions at ESA/ESTEC - the ESA-JRC-interdisciplinary scientific paper "The Hydrogen Vaue Chain - Applying the automotive Role Model of the Hydrogen Economy in the Aerospace Sector to increase Performance and reduce Costs (Frischauf, et al., 2013)" is the direct result of that work.

Technology Transfer (TT) is both a technological and a commercial-strategic topic. My scientific-technical education has given me the ability to address TT from a technological viewpoint. The associated economic aspects however would have been beyond my intellectual grasp, if I had not participated in various commercial projects at Booz Allen Hamilton, thereby gaining the necessary knowledge. Especially the long-term assignement within the Galileo and EGNOS programmes proved to be very beneficial and it is due to my colleague and friend Rainer HORN that I could seize these opportunities. Rainer is in several aspects a partner and mentor to me. His economic

point of view is not always immediately intuitively comprehensible to me, still it has always been enriching.

Manfred HETTMER and Manfred WITTIG shall not be unmentioned here. Both M. HETTMER and I have served as managing director at QASAR Technologie(s) and as such it is thanks to Manfred’s work and support that this dissertation includes MOA$^2$ as an example for a technology transfer. M .WITTIG on the other hand has always been an important scientific-technological ‘sparring partner’ for me. His ESA expert knowledge within the application area has helped me a great deal, when I had to check ideas and concepts in the satellite navigation and communication domains for their feasibility.

Two more persons need to be acknowledged in this context; Julius KRATKY and Gert BALDAUF, both are TV journalists at the Austrian Broadcasting Corporation ORF. I owe to Julius “Buddy” KRATKY that I found my role as science communicator at TV. Julius is most probably one of the most charming and persistent persons that I know. Once I had finished the AustroMars expedition, Julius had ‘pestered’ me for months to consider becoming an editor and anchorman at the Austrian TV science channel ALPHA Austria. Once I had accepted – and I am endlessly grateful that I have done so – Gert is the one, who took the action to make me ‘TV compatible’. More than 20 collective scientific TV documentaries and discussion telecasts are the result of our endeavours. And if one looks carefully into this dissertation, both Julius’ and Gert’s journalistic influence is visible in every other line of text – many thanks you two!

That brings me to the area, which features the strongest causal connection with this dissertation – the academic sector. And in here I would like to first and foremost extend my thanks to my two advisors René LAUFER and Pascale EHRENFREUND. Both are the perfect role model that one can treat one’s work with passion and enthusiasm and that it can be fun to face challenges, while still moving along one’s way. Both are for a great deal responsible that I pursued this doctoral thesis ALBEIT the manifold distractions caused by job, interests and commitments. Especially René is to be thanked for as he showed me a way out of the MOA$^2$-IPR dilemma, when he triggered the idea of not focussing my dissertation exclusively on MOA$^2$, but rather tuning it into a collection of several publications.

And so there is only one person left to whom I would like to express my heartfelt thanks for; Otto KOUDELKA, my Ph.D. supervisor. It is mostly due to his support that this dissertation had been started, pursued and finalised. Due to his help, Manfred HETTMER and I could do the first experiments with the MOA accelerator in the vacuum chamber at the TU Graz. That was in 2005 and hence long before the first ‘dissertation related’ letter had ever been written onto a sheet of paper. When we aimed to condense our acquired results into our first scientific paper, Otto KOUDELKA helped us with words and deeds, such as in 2007, when he agreed to become my Ph.D. supervisor. The whole time Prof. KOUDELKA interacted with me with the greastest level of friendliness and patience. Even when I wanted to change the spin of the dissertation, due to IPR-strategic considerations, from a pure technological thesis to a collection of several publications, Otto KOUDELKA was open-minded to that idea. My dear ‘Doktorvater’, I can make no other answer, “… but, thanks, and thanks.”

*„Ich kann keine andere Antwort geben als Danke, und nochmals Dank."*

William Shakespeare, „Was ihr wollt", Dritter Aufzug

William Shakespeare hat recht; an diesem Punkt kann und will ich nur mehr eines tun – mich bedanken. Und dieser Dank geht an viele Personen ohne die diese Dissertation nie zustande gekommen wäre; immerhin sind 16 Jahre ins Land gegangen seit dem Abschluss meiner Diplomarbeit am 22.04.1998, sechs Tage nach der Geburt meiner Tochter Carina. Mein Dank kann daher nicht nur im akademischen Umfeld seinen Widerhall finden, vielmehr erstreckt er sich über meine Familie, Freunde und Kollegen und das oftmals mit fließenden Grenzen.

Nachdem der Name bereits gefallen ist, möchte ich mich als allererstes bei meinem familiären „ABC" bedanken; Andreas - meinem Sohn -, Bettina (Tina) – meiner Frau – und Carina FRISCHAUF – meiner Tochter. Ohne die Unterstützung dieses Dreigestirns hätte ich diese Dissertation niemals schreiben können. Das beginnt damit, dass Tina keine Einwände vorgebracht hat als ich mich entgegen der ursprünglichen „Planungen" entschieden habe zu studieren. Es setzt sich fort indem sie mir – ebenfalls entgegen der ursprünglichen „Planung" - meine Forschungsaufenthalte und die darausfolgende Diplomarbeit am CERN ermöglicht hat und es drückt sich wohl am stärksten dadurch aus, indem Tina mit mir nach Holland gezogen ist, als ich nach Abschluss des Studiums für die ESA zu arbeiten begonnen habe. Meine Herzensdame ist in vielerlei Hinsicht viel flexibler und verständnisvoller als ich.

Meine beiden Kinder Carina und Andreas verdienen ebenso ein großes Dankeschön. Haben sie doch immer meine wissenschaftlich-technische „Vielreiserei" akzeptiert und sind mir zusätzlich in den Schlussphasen meiner Dissertation mit einer Rücksichtnahme entgegengekommen, die weit über das hinausgeht, was man von einer 15/16- bzw. einem 11/12-jährigen erwarten darf.

Meine Mutter darf an dieser Stelle nicht fehlen. Wenn sie auch nicht direkt an dieser Dissertation mitgewirkt hat, so hat sie doch alles versucht um aus mir einen „vernünftigen" Menschen zu machen. Man mag geteilter Meinung sein ob ihr das wirklich gelungen ist, in jedem Fall bin ich ihr unendlich dankbar, dass sie mich mit der Fähigkeit zu Träumen erzogen hat und mir gleichzeitig das Selbstvertrauen vermittelt hat, um diese Träume umzusetzen.

Ein weiteres Dankeschön gebührt meiner Großmutter Hermine, Tinas Eltern Horst und Karoline, sowie meinem Stiefvater Franz. Auch Personen mit einer gehörigen Portion Selbstvertrauen haben Zweifel; ich bin da keine Ausnahme. Schön, dass es dann Menschen gibt, die bedingslos an einen glauben und einem den Rücken stärken, so wie diese ‚fantastischen Vier'. Danke!

Die Überleitung von der Familie zu den Freunden obliegt meinen beiden Onkeln Peter FRISCHAUF und Max WLASCHEK. Während der Erste zu einem Großteil für mein technisches Interesse verantwortlich zeichnet, ist der Zweite derjenige, der in mir das Feuer der Wissenschaftsbegeisterung entfacht hat, indem er mit mir seine Liebe zu den Sternen geteilt hat. Beide begannen auf mich einzuwirken, als ich gerade mal fünf Jahre alt war – ihr Einfluss wirkt bis heute nach.

Mein bester Freund Martin MÜLLER wäre ein Kapitel für sich. Ich hatte das unendliche Glück ihn in der 3. Klasse des TGM kennenzulernen und mich mit ihm anzufreunden – die Freundschaft war so inniglich, dass uns unsere Schulkollegen als „die Zwillinge" bezeichneten; nicht weil wir einander so ähnlich sahen, sondern weil wir unzertrennlich waren; nicht nur in der Schule, sondern auch außerhalb. Auch bei und nach dem Präsenzdienst sollte sich dies fortsetzen, denn Dank der Intervention meines besten Freundes begannen wir nach den acht Monaten im Zeichen der Landesverteidigung mit dem Studium der technischen Physik – ganz entgegen meiner

ursprünglichen „Lebensplanung“ und zur Überraschung meiner damaligen Freundin und späteren Frau. Martin hatte mich mit meinem Interesse für Astro- und Teilchenphysik geködert. Lieber Zwilling, vielen Dank!

In die Zeit meiner gemeinsamen Schulzeit mit Martin fällt auch das Zusammentreffen mit einer weiteren wichtigen Persönlichkeit in meiner akademischen und v.a. weltraummäßigen Laufbahn; Johannes ORTNER, damals Chef der österreichischen Weltraumagentur ASA. Dank seiner Hilfe wurde mein Interesse am Weltraum in Richtung Weltraumfahrt und ESA gelenkt. Ich hätte wohl niemals die ASA/ESA Alpbach Sommerschule besucht, die International Space University abgeschlossen und es letztendlich zur ESA geschafft, wenn er nicht gewesen wäre.

Bevor ich aber zur ESA kam, galt es es noch das Physikstudium abzuschließen und es in die Richtung zu lenken, wegen der ich es begonnen hatte – die Teilchenphysik. In Manfred KRAMMER, dem Projektleiter des DELPHI VFT MINISTRIP DETECTORs am CERN, fand ich einen kompetenten und liebenswürdigen Betreuer für meine Diplomarbeit, die ich am Hochenergiepysik der österreichischen Akademie der Wissenschaften und am CERN in Genf durchführte. Das CERN ist ein faszinierender Ort und dank Manfreds Unterstützung ist es ein wesentlicher Teil meiner wissenschaftlich-technischen Karriere geworden.

Im Juli 1998 – Frankreich war gerade Fußballweltmeister geworden – fand meine Zeit am CERN ihr vorläufiges Ende. Meine Arbeiten am VFT und der FCA (zwei Detektoren des DELPHI-Experiments) waren erledigt; im August begann ich bei ESA/ESTEC in den Niederlanden zu arbeiten. George SCOON, einem Study Manager für Wissenschaftsmissionen der ESA gebührt in diesem Zusammenhang mein großer Dank. In unzähligen Gesprächen bei der ASA/ESA Alpbach Sommerschule und der International Space University hat er mir die Weltraumfahrt nähergebracht und mir den schmalen Grat zwischen Kreativität und Machbarkeit aufgezeigt. Das von ihm vermittelte Wissen konnte ich später in vielfältiger Weise in meinen Tätigkeiten des ESA-Projektteams für das Automated Transfer Vehicle (ATV) einbringen. Hier möchte ich mich bei zwei weiteren Persönlichkeiten bedanken; Joachim EBI und Ignacio „Nacho“ AGUILAR-SANCHEZ. Joachim war mein Chef im ATV Projektteam, Ignacio mein Kollege und Mentor - meine Mitarbeit am ATV wäre ohne diese beiden Personen nur halb so lehrreich und angenehm gewesen.

Als ich im Laufe meiner ESA-Karriere von der ATV-Avionik zum Explorationsprogramm „Aurora“ wechselte und dort meine Nuklearexpertise einbringen konnte, eröffnete sich mir durch Michael FÜTTERER ein weiterer Karriereabschnitt; das JRC-IET. Michael ist es zu verdanken, dass ich mich an einem der EU-Concours beteiligte und in weiterer Folge beim Energieforschungszentrum der europäischen Kommission (JRC-IET) zu arbeiten begann. Wieder hatte ich Glück; einerseits weil ich im Bereich Wasserstoffspeicherung tätig war, ein Gebiet, das schon aufgrund der Nähe zum Automobil- und Luftfahrtsektor sehr interessant war und andererseits weil ich zwei Personen kennenlernen durfte, die es mir ermöglichten das Thema Wasserstoffspeicherung aus der Systemsicht zu betrachten. Dank Pietro MORETTO und Marc STEEN konnte ich auf diese Weise die Wasserstoffforschung am JRC-IET mit der zugehörigen Technologieentwicklung bei ESA/ESTEC verbinden – die ESA-JRC-interdisziplinäre wissenschaftliche Arbeit „The Hydrogen Vaue Chain - Applying the automotive Role Model of the Hydrogen Economy in the Aerospace Sector to increase Performance and reduce Costs (Frischauf, et al., 2013)“ war die direkte Konsequenz daraus.

Technologietransfer ist sowohl ein technologisches und ein kommerziell-strategisches Thema. Meine technisch-wissenschaftliche Ausbildung hat mir zwar das Rüstzeug mitgegeben um das Thema von der technologischen Sichtweise zu betrachten, die wirtschaftlichen Aspekte allerdings

hätten sich mir wohl nicht erschlossen, hätte ich nicht das dafür nötige Wissen durch die Mitabeit in verschiedenen kommerziellen Projekte bei Booz Allen Hamilton erlangt. Speziell die mehrjährige Arbeit für Galileo und EGNOS hat mich in dieser Hinsicht viel gelehrt und das mir dies ermöglicht wurde verdanke ich v.a. meinem Kollegen und Freund Rainer HORN. Rainer ist in vielerlei Hinsicht ein Partner und Mentor für mich, seine wirtschaftliche Sicht der Dinge ist für mich zwar nicht immer gleich intuitiv nachvollziehbar, aber in jedem Falle bereichernd.

Manfred HETTMER und Manfred WITTIG sollen nicht unerwähnt bleiben. Während ersterer mein Mitgeschäftsführer bei QASAR Technologie(s) war und als solcher einen immensen Anteil daran hat, dass diese Dissertation mit dem Technologietransferbeispiel MOA² aufwarten kann, ist M. WITTIG zu einem wichtigen wissenschaftlich-technologischen ‚Sparringpartner' für mich geworden. Sein ESA-Expertisenwissen im Applikationsbereich hat mir wesentlich weitergeholfen, wenn es darum ging Ideen und Konzepte im Satellitennavigations- und –kommunikationsbereich auf ihre Machbarkeit hin zu überprüfen.

Zwei weiteren Personen möchte ich in diesem Zusammenhang ebenfalls meinen Dank aussprechen: Julius KRATKY und Gert BALDAUF; beide sind Fernsehjounalisten beim ORF. Julius „Buddy" KRATKY habe ich es zu verdanken, dass ich eine Rolle als Wissenschaftskommunikator im TV gefunden habe. Julius ist wohl einer der charmantesten und zugleich hartnäckigsten Personen die ich kenne. Monatelang hat er mich nach der AustroMars Expedition ‚bearbeitet', um mich als Co-Gestalter und Moderator für den Wissenschaftskanal ALPHA Österreich zu gewinnen. Nachdem ich zugesagt hatte – und ich bin unendlich froh es getan zu haben – war es Gert, der die Arbeit auf sich nahm mich ‚fernsehtauglich' zu machen. Mehr als 20 gemeinsame wissenschaftliche TV-Dokumentationen und Diskussionsrunden sind das Ergebnis seiner - unserer Anstrengungen. Und bei genauerem Hinsehen erkennt man Julius' und Gerts journalistischen Einfluss in fast jeder zweiten Zeile dieser Dissertation - vielen Dank ihr Zwei!

Damit komme ich zu dem Bereich, der am ursächlichsten mit dieser Dissertation zusammenhängt – dem universitären Bereich. Und hier möchte ich mich zuallerst bei meinen beiden Betreuern René LAUFER und Pascale EHRENFREUND bedanken. Beide sind das perfekte Rollenmodell dafür, dass man seine Arbeit mit Herzblut und Begeisterung verfolgen kann und dass es durchaus Spaß macht sich Herausforderungen zu stellen und seinen Weg zu gehen. Beide sind zu einem großen Teil mitverantwortlich, dass ich diese Dissertation TROTZ der vielfältigen Ablenkungen durch Job, Interessen und Verpflichtungen weiterverfolgt habe. Speziell René gebührt mein großer Dank, weil er mir in unserem Gespräch in Paris den Weg der Manteldissertation vorgeschlagen und mir damit einen Ausweg aus dem Dilemma des MOA²-IPR aufgezeigt hat.

Somit bleibt nur noch eine Person übrig, bei der ich mich auf das herzlichste bedanken möchte; Otto KOUDELKA, mein „Doktorvater". Prof. KOUDELKA hat einen wesentlichen Anteil daran, dass diese Dissertation zustande gekommen ist, denn Dank seiner Hilfe konnten Manfred HETTMER und ich die ersten Experimente mit dem MOA Beschleuniger in der Vakuumkammer an der TU Graz durchführen. Das war im Jahre 2005 und somit lange bevor der erste ‚dissertationsnahe' Buchstabe auf ein Blatt Papier geschrieben worden ist. Als es in weiterer Folge darum ging aus den ersten Resultaten ein wissenschaftliches Papier zu erstellen war Otto KOUDELKA mit Rat und Tat zur Stelle, genauso wie im Jahre 2007, als er sich bereit erklärte das Thema als Doktorarbeit zu betreuen. Während der ganzen Zeit kam mir Otto KOUDELKA mit sehr viel Geduld und Freundlichkeit entgegen – selbst als ich die Dissertation aufgrund von patentstrategischen Gründen in eine Manteldissertation ändern wollte/musste, war er dieser Idee gegenüber aufgeschlossen eingestellt. Lieber ‚Doktorvater', ich kann wirklich: „… keine andere Antwort geben als Danke, und nochmals Dank!"

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# 14. Glossary

| | | | |
|---|---|---|---|
| AP | Availability Payment | ITC | Information Technology and Communication |
| AP-MCSTA | Asia Pacific Multilateral Cooperation in Space Technology and Applications | ITAR | International Traffic in Arms Regulations |
| APSCO | Asia-Pacific Space Cooperation Organization | JAXA | Japan Aerospace Exploration Agency |
| BFSI | Banking, Financial Services and Insurance | JV | Joint Venture |
| CAGR | Compound Annual Growth Rate | KPI | Key Performance Indicator |
| CAPEX | CAPital EXpenditure | LBS | Location Based Services |
| CAST | China Association for Science and Technology | LEO | Low Earth Orbit |
| CGWIC | China Great Wall Industry Corporation | LTE | Long Term Evolution |
| CLTC | China Academy of Launch Vehicle Technology | M&A | Mergers and Acquisitions |
| COTS | Commercial Off The Shelf | M2M | Machine-to-Machine (communications) |
| CS | Commercial Service | MC | Merged Consortium |
| DBS | Direct Broadcasting System | MEO | Medium Earth Orbit |
| DFH | Dongfanghong | MMI | Man-Machine-Interface |
| DLR | Deutsches Zentrum für Luft- und Raumfahrt | MNC | Multi-National Corporation |
| DOS | Department of Space | MNO | Mobile Network Operator |
| DSTB | Digital Set Top Box | MPEG | Moving Picture Experts Group |
| DTH | Direct To Home | NASA | National Aeronautics and Space Administration |
| DVB-S2 | Digital Video Broadcasting - Satellite - Second Generation | OPEX | OPerating EXpenditure |
| EBIT | Earnings Before Interest and Taxes | OS | Open Service |
| EBITDA | Earnings Before Interest, Taxes, Depreciation and Amortization | PDA | Personal Digital Assistant |
| EC | European Commission | PLC | Product Life Cycle |
| EGNOS | European Geostationary Navigation Overlay Service | PLC | Programmable Logic Controller |
| EIRP | Equivalent Isotropic Radiated Power | PND | Personal Navigation Device |
| ELV | Expendable Launch Vehicles | PPDR | Public Protection and Disaster Relief |
| EO | Earth Observation | PPP | Public Private Partnership |
| EOL | End Of Life | PRS | Publuc Regulated Service |
| ESA | European Space Agency | PSLV | Polar Satellite Launch Vehicle |
| ESSP | European Satellite Service Provider | QoS | Quality of Service |
| EU | European Union | R&D | Resarch and Development |
| FDD | Frequency Division Duplex | RFID | Radio Frequency Identification |
| FEC | Forward Error Correction | ROI | Return On Investment |
| FOC | Full Operational Capability | ROT | Receive Only Terminal |
| FOTA | Firmware-Over-The-Air | RTU | Remote Terminal Unit |
| FSS | Fixed Satellite Service | SAR | Search and Rescue |
| GAGAN | GPS Aided Geo Augmented Navigation | SAST | Shanghai Academy of Space Technology |
| GEO | Geostationary Earth Orbit | SCADA | Supervisory Control and Data Acquisition |
| GIS | Geographic Information System | S-DMB | Satellite Digital Multimedia Broadcast |
| GJU | Galileo Joint Undertaking | SIM | Subscriber Identity Module |
| GMES | Global Monitoring for Environment and Security | SIS | Signal In Space |
| GNSS | Global Navigation Satellite System | SIT | Satellite Interactive Terminal |
| GOC | Galileo Operating Company | SLA | Service Level Agreement |
| GPS | Global Positioning System | SOA | Service-Oriented Architectures |
| GSLV | Geosynchronous Satellite Launch Vehicle | SoL | Safety of Life |
| GSM | Global System for Mobile communications | SSPA | Solid State Power Amplifier |
| GTO | Geostationary Transfer Orbit | SWOT | Strengts-Weaknesses-Opportunities-Threats |
| HMI | Human-Machine-Interface | TBD | To Be Defined |
| IMT-2000 | International Mobile Telecommunications-2000 | TE | Transponder Equivalent |
| IOV | In-Orbit Validation | TRX | Transponder |
| IP | Internet Protocol | TWTA | Travelling Wave Tube Amplifier |
| IPR | Intellectual Property Right | UMTS | Universal Mobile Telecommunications System |
| IPTV | Internet Protocol Television | VSAT | Very Small Aperture Terminal |
| IRR | Internal Rate of Return | WiFi | Wireless Fidelity |
| ISRO | Indian Space Research Organisation | WiMAX | Worldwide Interoperability for Microwave Access |
| IT | Information Technology | WLL | Wireless Local Loop |

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