13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-167

Satellite-based InSAR for monitoring and safeguarding high-voltage power pylons amid the energy transition

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ABSTRACT: Resilient high-voltage grids are essential for ensuring energy supply and preventing. However, climate change, the energy transition and the required expansion of electricity grids pose growing challenges for infrastructure operators in the energy sector. In Austria, landslides in alpine regions and decreasing groundwater levels in flat areas represent significant potential risks to power pylons. The Austrian Power Grid AG (APG), which operates the Austrian transmission grid, faces growing demands to detect damage at an early stage and to guarantee grid security amid changing climatic conditions. Satellite-based Interferometric Synthetic Aperture Radar (InSAR) potentially provides millimeter-precise, area-wide monitoring of ground motion and structural deformations. Periodic InSAR data updates (e.g. semi-annually) enable a complete and continuous analysis of all single structures such as power pylons and thus facilitate an assessment of the structural integrity of the entire grid. This allows the early identification of risks such as landslides or structural changes and the implementation of predictive maintenance. This paper highlights previous experiences and future potentials of integrating the InSAR technology into APG's workflows and risk management, which contributes to sustainable planning and increased grid stability in an increasingly complex system.

KEY WORDS: Wide-area InSAR; Power Grids; Monitoring; Predictive maintenance.

1 INTRODUCTION

The Austrian Power Grid AG (APG) plays a central role in Austria’s energy infrastructure. As the operator of the Austrian electricity transmission network, APG is responsible for ensuring a continuous and reliable power supply. A critical factor in maintaining efficient and secure grid operations is the early detection of potential disruptions or structural changes in the transmission infrastructure.

APG manages an extensive network of power lines, substations and more than 12.000 power pylons in Austria, that require regular monitoring. Identifying ground movements, structural deformations, and other potential risk factors is essential to minimize unplanned outages and enhance operational security. In this context, a feasibility study is being conducted to evaluate the integration of satellite-based InSAR technology into APG’s monitoring strategy, aiming to enhance early-warning capabilities and risk mitigation.

2 BASICS OF INSAR TECHNOLOGY

Synthetic Aperture Radar (SAR) satellites use radar signals to generate high-resolution images of the Earth's surface, independent of weather conditions or daylight. The principle is based on transmitting microwave pulses, which are reflected by the Earth's surface or manmade objects and received by the satellite. These signals are processed to create detailed images through complex signal processing techniques.

2.1 Reflection of Radar Waves

The reflection of radar waves follows the physical principles of electromagnetic wave propagation. The strength of the reflected signal depends on two main factors:

- Geometry of the Reflector: When incoming radar waves are reflected at an appropriate angle, a significant portion of the signal returns to the satellite. Smooth, metallic surfaces or structural elements enhance reflection.
- Material Properties of the Surface: Materials with high electrical conductivity, such as metals, reflect radar waves effectively, whereas natural surfaces like vegetation or snow scatter waves in various directions, reducing the returned signal strength.

2.2 Different Frequency Bands for Various Applications

SAR satellites operate at different frequency bands to serve specific applications:

- L-Band (1-2 GHz): Commonly used for agricultural and forestry monitoring due to its ability to penetrate vegetation.
- C-Band (4-8 GHz): Frequently used by Earth observation satellites like Sentinel-1, offering a balance between resolution and penetration depth.
- X-Band (8-12 GHz): Employed in high-resolution applications such as infrastructure monitoring and military surveillance, providing high spatial resolution but limited penetration capability.

2.3 Orbit and Imaging Geometry

SAR satellites typically follow a polar or sun-synchronous orbit, capturing data in both ascending (ASC) and descending (DSC) imaging geometries. In the ascending geometry, the satellite moves from the South Pole toward the North Pole, while in the descending geometry, it moves from the North Pole toward the South Pole. A schematic representation of the flight

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directions can be seen in Figure 1. This configuration allows for continuous monitoring of the Earth's surface.

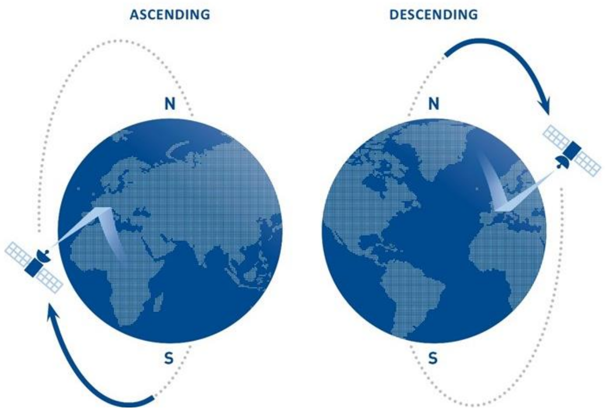

Figure 1. Ascending (ASC) and descending (DSC) geometry [2].

2.4 Line of Sight (LOS) and Incidence Angle

The SAR system's viewing direction (azimuth angle) is typically oriented sideways (90° to the flight path). In the ASC geometry, the satellite looks eastward, while in the DSC geometry, it looks westward. The incidence angle is the angle between the vertical and the incoming radar beam, varying depending on the satellite system and terrain conditions. A larger incidence angle occurs further from the nadir (directly below the satellite), affecting shadowing, measurement accuracy, and displacement detection.

Since SAR images capture displacements along the LOS, movements perpendicular to this direction remain partially undetected. This limitation can be mitigated through multi-orbit analysis (see chapter 2.6) or integration with ground-based data sources.

2.5 From SAR to InSAR

As SAR satellites repeatedly capture images of the same area over time, they provide insights into surface changes. Each SAR acquisition records two essential parameters: (a) Amplitude, representing the energy of the reflected signal, and (b) Phase, related to the distance between the sensor and the target.

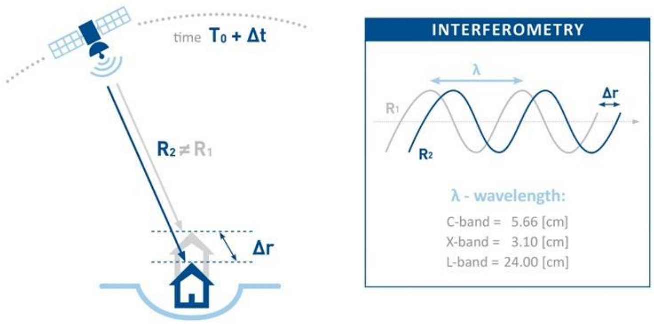

Figure 2. Schematic representation of how InSAR (interferometric SAR) works. The phase shift (Δr=R2-R1) results from the phase information (R) of two or more images of the same area at different times or different positions [2].

Interferometric SAR (InSAR) compares phase differences between two or more SAR images to detect changes in distance between the satellite and the Earth's surface along the LOS-vector. [1] This technique enables millimeter-accurate measurements of slow ground movements, such as landslides, earthquakes, and subsidence. Figure 2 shows the phase calculation that is performed for each individual measurement pixel.

2.6 Displacement Vectors and 2D Decomposition

InSAR primarily measures displacement along the LOS. To derive vertical or horizontal displacement components, a 2D decomposition technique is applied using data from both ASC and DSC imaging geometries. This method allows for estimating movement in the east-west and vertical directions, while north-south displacement remains largely undetectable or at least underestimated and requires complementary data sources, such as GNSS measurements.

3 DATA PROCESSING

3.1 SqueeSAR® Analysis

In this study, the applied SAR data was processed using the multi-interferogram technique known as SqueeSAR® [1]. SqueeSAR®, a patented method developed by TRE ALTAMIRA, improves the reliability of InSAR measurements in heterogeneous environments by reducing phase decorrelation in areas with vegetation or urban structures. It combines Persistent Scatterers (PS) and Distributed Scatterers (DS) to achieve a high spatial density of measurement points.

To ensure high precision and accuracy, SqueeSAR® requires a dataset of at least 15 to 20 SAR images acquired over the same area using the same acquisition mode and geometry. By combining PS, which are stable and well-defined radar reflectors, with DS, which represent diffuse scattering signals, SqueeSAR® can extract reliable movement data even in areas with low signal stability. This enables comprehensive monitoring of ground deformations.

3.2 Precision and Accuracy

Precision and accuracy are crucial in measurement science:

- Precision refers to the consistency of repeated measurements. A measurement series is precise if repeated observations under the same conditions yield similar values, regardless of their deviation from the true value.
- Accuracy describes how close a measurement is to the actual (true) value, meaning a measurement is accurate if systematic errors are minimal.

3.3 Determining Precision in InSAR Data

The precision of InSAR results is influenced by:

- Measurement Point Locations: The geolocation accuracy of measurement points depends on the SAR coordinates and the derived height from the InSAR analysis. Higher resolution sensors improve geocoding precision.
- Displacement Time Series: The standard deviation (σ) of individual measurements quantifies the variation around the mean displacement rate. Lower σ values indicate higher precision, while higher values suggest greater measurement variability.

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For a dataset of at least 30 SAR images covering a two-year period, measurement points within 1 km of a reference point typically exhibit a standard deviation of less than 1 mm/year. The average standard deviation for a single measurement is usually ±5 mm. While InSAR precision is statistically derived, measurement accuracy is usually validated with ground-based reference data, such as geodetic surveys, achieving accuracy in the sub-millimeter range [1].

3.4 MatchSAR® - Transformation of InSAR measurements into objects

MatchSAR® is an advanced algorithm developed by AUGMENTERRA in collaboration with TRE ALTAMIRA. It transforms millions of InSAR measurement points across Austria by aligning them with physical structures such as buildings, power pylons, dams, roads, and railways.
The transformation process consists of several key steps. First, a spatial analysis and quality control of all available InSAR measurement points are conducted to ensure accurate attribution of ground movements to the corresponding structures. Additionally, the algorithm integrates InSAR data with other terrain and structural datasets, creating a comprehensive, multidimensional view of each object. As a result, every object processed by MatchSAR® is assigned a displacement time series covering at least two to three years, enabling in-depth movement analysis (e.g., steady vs. accelerating displacement).

MatchSAR® is a core component of the *'AUGMENTERRA Observer'*, a Software-as-a-Service (SaaS) platform featuring state-of-the-art 3D visualization. The 'AUGMENTERRA Observer' is accessible via various devices, including PCs, smartphones, and tablets, allowing users to retrieve structural and ground movement data within seconds. By automatically updating measurement data every six months, MatchSAR® ensures continuous tracking of structural movements, significantly reducing manual processing efforts and improving long-term risk assessment capabilities.

4 USE CASE: WIDE-AREA MONITORING OF STRUCTURAL MOVEMENTS AT APG

For the APG power pylon monitoring use case, Sentinel-1 data is automatically reprocessed every six months for all locations. Using a three-year moving window, updated measurement data is consistently incorporated into structural stability assessments. This approach ensures up-to-date risk evaluations, with new measurement pixels available every six to twelve days depending on Sentinel-1A/B availability. This guarantees a consistent and up-to-date analysis of structural stability over time. The results are implemented directly into APG's internal GIS using an API solution to ensure maximum availability and up-to-date information. Data access and visualization in the customer interface is displayed in Figure 3. A detailed time series of a moving pylon with an average movement of about 19 mm/year is shown in Figure 4.

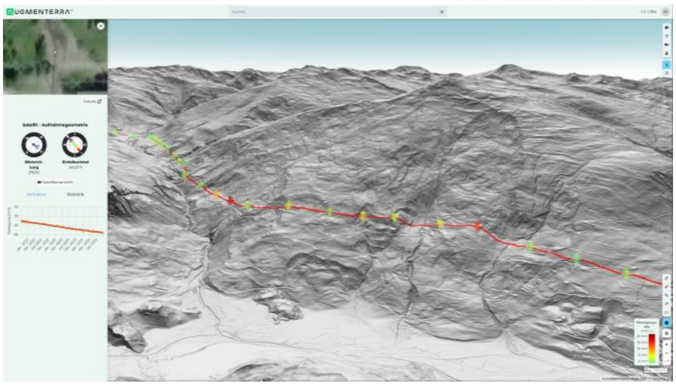

Figure 3. Structural movement measurements from InSAR and locations of the APG power pylons, visualized using the 3D WebGIS application 'AUGMENTERRA Observer'.

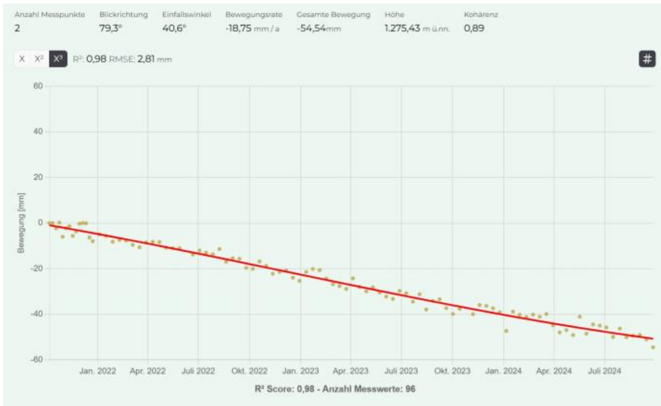

Figure 4. Time series of a power pylon located in Figure 3. The pylon shows an average movement of approx. 19 mm/year in the LOS direction. The movement behavior is homogeneous.

4.1 Monitoring Ground Deformation and Stability

One of the primary applications of InSAR for APG is detecting and analyzing ground deformations that could compromise the stability of power pylons. Subsidence, landslides, and soil compaction can lead to shifts in foundation structures, potentially endangering the transmission network. This allows the definition of hotspots that can be subjected to more intensive monitoring. A distinction is made between two main processes:

- Landslide and erosion detection: InSAR can identify gradual slope movements that may threaten pylon stability.
- Subsidence monitoring: Infrastructure near mining areas, groundwater extraction zones, or soft soil regions can be monitored for ground subsidence.

4.2 Structural Health Monitoring of Power Pylons

In addition to assessing ground stability, InSAR can also detect internal deformations of transmission pylons. While traditional structural monitoring relies on ground-based sensors, satellite-based InSAR provides:

- Large-scale coverage: Continuous monitoring of the entire power grid, including remote areas.

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- Millimeter-level accuracy: Detection of slight tilting or deformation of pylons over time.
- Historical data comparison: Analysis of past SAR images to identify long-term structural trends.

4.3 Integration with Other Monitoring Technologies

For optimal monitoring, InSAR data can be combined with:

- Ground-based sensors: Combining InSAR with GPS, inclinometers, and strain gauges enhances measurement reliability.
- Drone and LiDAR surveys: High-resolution aerial surveys provide additional validation of deformation patterns detected via satellite.

ACKNOWLEDGMENTS

We extend our gratitude to the Austrian Power Grid team, particularly Alois Ammerer, Christian Laister, and Gabriel Stollhof, for their continued collaboration and trust in our data. Their expertise and insights have played a key role in refining our automated monitoring system to meet the evolving demands of the energy sector.

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