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Correcting InSAR interferograms for atmospheric effects

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Summary
Over the past few decades, remote sensing methods have become an essential source of data across many fields of scientific research (agriculture, forestry, geosciences, etc.) and an integral part of everyday life. Advances in technology and the close integration of microelectronics into modern sensors have further expanded the use and accessibility of these methods. One such active technique for non-destructive, long-range sensing is radar remote sensing, which utilizes radio waves from the electromagnetic spectrum. Its key advantages include independence from weather conditions and sunlight; however, it also presents specific challenges, particularly errors introduced by the propagation medium – most notably, the atmosphere. These issues are especially significant when using data from radar instruments, and in particular synthetic aperture radar (SAR), processed through differential interferometric technique (DInSAR) and its enhanced variants. This paper focuses on the estimation and the possibilities for mitigation of errors caused by atmospheric effects, specifically those resulting from tropospheric refraction and ionospheric ionization, as both layers can significantly distort the information produced, thus biasing the final results and the conclusions made.

Introduction

With the development of improved and modern SAR instruments onboard satellites, the availability of SAR data resulted in new possibilities for researchers and practitioners to study ground instabilities caused by different natural phenomena such as earthquakes, volcanoes, glacier movements, etc., and thus delivering reliable information on their temporal evolution. The satellite SAR interferometry approach offers unprecedented possibilities for long-term observations, high repeatability, and large and inaccessible areas coverage. Remotely sensed SAR data offers several advantages, including wide area coverage, high spatial resolution, and independence from external illumination and weather.

On the other side, the usage of SAR data, similar to other remote sensing methods, has certain limitations. It needs to be mentioned that the propagation medium influences the electromagnetic waves travelling from the satellite to the Earth's surface and back to the satellite, distorting the signal. In their pivotal paper of (Massonnet and Feigl, 1998) underline the effect of the status of the atmosphere column on the SAR data providing examples for distortions caused by ionosphere and troposphere. The influences of the propagation medium affect the accuracy of amplitude and phase-based measurements (Hanssen, 2001). This is especially significant in interferometric SAR (InSAR) applications. The ionized ionosphere and the neutral troposphere are the two principal atmospheric layers that affect SAR signal propagation. Due to their unique refractive and dispersive properties, they introduce dissimilar sources for errors (Ding, 2008).

Theoretical framework for mitigation for atmosphere errors in SAR data

The ionosphere's primary influence on SAR signals is a frequency-dependent (dispersive) effect caused by variations in Total Electron Content (TEC) (Bojilova and Mukhtarov, 2023) . These effects are particularly pronounced at lower frequencies, such as L-band and P-band used by SAR instruments, where they can cause ionospheric scintillations, group delays, refraction and Faraday rotation. This can severely degrade the coherence and phase fidelity of SAR data. While less pronounced, these effects must also be considered for higher frequencies like C-band and X-band. If not properly identified and mitigated, these ionospheric distortions can introduce patterns similar to long-wavelength deformation signals and thus corrupt geophysical interpretations. Although the ionospheric delays are largest in the equatorial and high-latitude regions (above ~60°) their presence when interpreting results produced by SAR data processing should not be neglected and properly addressed.

Tropospheric effects are largely non-dispersive and appear as additional path delays. These delays are caused by spatial and temporal variations in atmospheric pressure, temperature, and water vapor. Because these delays alter the SAR signal's phase, they can lead to the misinterpretation of ground displacement in differential interferograms. The wet component, which is influenced by water vapor, is particularly challenging to model and correct due to its high spatiotemporal variability. Tropospheric delays can introduce phase biases on the order of several centimeters, especially in regions with complex topography (especially in mountain areas) or climatically dynamic ones (areas that experience frequent and often abrupt changes in climate over relatively short timescales).
With high-resolution SAR data becoming more available from missions like Sentinel-1 (currently with two satellites in orbit), NISAR (launched 30July 2025), and ALOS-4 (presently in orbit), a greater emphasis on precise atmospheric correction is necessary. The presence of uncorrected atmospheric artifacts not only reduces the reliability of deformation measurements but also compromise the effectiveness of SAR data in key applications such as geohazard monitoring, infrastructure analysis, etc. In short, the atmospheric influences are considered one of the significant sources of error in SAR processing, can be effectively characterized and mitigated. This is achieved through a combination of integrating auxiliary data, employing advanced signal processing techniques, and conducting robust time-series analysis. Continued research into near-real-time correction models and data fusion approaches is essential for unlocking the full geophysical potential of SAR remote sensing.

Methods for Atmospheric Correction of SAR data

The need for atmospheric corrections can be seen considering the following basic formula for interferometric image production from two repeat-pass SAR acquisitions having non-zero baseline between them:

$$\Delta\varphi = \{\varphi_{topo} + \varphi_{defo} + \varphi_{atmo} + \varphi_{orb} + \varphi_{noise}\} \quad (1)$$

Since the information regarding the changes that occurred on the Earth's surface is contained in $\Delta\varphi$, it is needed to calculate or at least estimate the contribution of all terms in (1). There are methods to obtain the magnitude of their effect, which is not valid for φ_{atmo}. As explained above, due to presence of several layers in the atmosphere it is not possible to mitigate the impact of the φ_{atmo} term at once it shall be decomposed into contributions from ionosphere and the troposphere:

$$\varphi_{atmo} = \varphi_{iono} + \varphi_{tropo} \quad (2)$$

Several methodologies have been developed to address the atmospheric perturbations in SAR data. Tropospheric corrections often use external data sources like GNSS-derived zenith wet delays (also known as Zenithal Tropospheric Delays), numerical weather prediction (NWP) models, and radiometric measurements to estimate atmospheric delays. On the other hand, SAR time-series techniques such as Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS) analysis are effective for averaging out tropospheric noise and isolating deformation signals, but they pose the need for producing time series of interferograms.
The ionosphere is an ionized layer of Earth's upper atmosphere, extending from approximately 60 to 1,000 kilometers in altitude. It is a region containing free electrons and ions that are primarily created by solar radiation, but their content vary with the season, time of the day, solar activity and geomagnetic conditions. Due to its frequency-dependent dispersive nature, the ionosphere's effect on a radar signal's phase is a primary concern in processing SAR data and especially when InSAR is applied. The amount of signal delay is dependent on the radar's frequency, with more pronounced effects observed at longer wavelengths e.g. L-band. Three main factors distort the SAR signal when it passes through the ionosphere –the azimuth shifts visible as strips in the SAR image, the phase delay leading to false surface deformations, and coherence loss, which causes the overall quality of the interferometric image.
The troposphere is the lowest layer of the atmosphere, extending from the Earth's surface to an altitude of approximately 12 km. This region is characterized by the presence of most atmospheric water vapor, clouds, and weather systems. In contrast to the ionosphere it is non-dispersive at microwave radar frequencies, which means that the amount of signal delay is independent of the radar's frequency and does not allow dual-frequency techniques (like those used for ionospheric correction) to isolate and remove tropospheric effects from the signal. This two-way path delay can be attributed to the variations in atmospheric refractive index (see Krishnakumar et al. 2018 for formula) and for the microwave radio frequencies these changes are a function of local fluctuations in temperature, pressure, and, most significantly, water vapor content. The two primary components of tropospheric delay are the dry delay and the wet delay. The dry delay is stable,

dominated by pressure and temperature on a large spatial scale (>100 km), and can be corrected using reanalysis weather data such as ERA5 (Hersbach et al. 2020). In contrast, the wet delay is highly variable, dominated by water vapor on a fine spatial scale (<10 km), and typically requires correction through the use of dense network of GNSS stations or high-resolution weather models (Skamarock et al. 2019).

Addressing ionospheric and tropospheric impacts on SAR data

Ionospheric corrections typically rely on processing techniques that are SAR-specific. The split-spectrum method estimates ionospheric phase screens by using the frequency dependence of ionospheric delays. While currently limited in availability, dual-frequency SAR systems offer a direct way to quantify and remove ionospheric effects. In scenarios when dual-frequency data is unavailable the external TEC maps from GNSS constellations (e.g. from Center for Orbit Determination of Europe - https://www.aiub.unibe.ch/research/code___analysis_center/index_eng.html) provide useful, though coarse, estimates for ionospheric calibration of SAR data.

One successful and widely implemented algorithm for ionosphere correction in SAR data, particularly for low-frequency systems, is commonly performed using the Split-Spectrum Method (SSM) (Van der Kooij 2003). This technique is particularly effective for low-frequency SAR missions like Japan's ALOS-2 (L-band) and the NISAR mission, where ionospheric effects are most noticeable. However, it's also been successfully applied to Sentinel-1 (C-band) data to remove subtle, but persistent ionospheric artifacts. The first step in this procedure begins by dividing the initial SAR data products into two separate sub-bands low and high. These sub-bands are then processed independently to generate two distinct interferograms from a single SAR pair. Because the ionospheric phase is frequency-dependent, the phase difference between these two sub-band interferograms is directly proportional to the ionospheric phase screen. Next this difference is scaled by a factor that accounts for the frequency difference, allowing for the precise estimation of the ionospheric phase. Finally, this estimated phase is subtracted from the original, full-bandwidth interferogram, which effectively removes the ionospheric distortion and results in a corrected SAR interferogram with improved accuracy for deformation measurements.

The variations in the troposphere between two SAR acquisitions lead to inclusion of artifacts in phase that can be observed in several ways. These include the appearance of long-wavelength fringes in interferograms that can resemble tectonic deformation, localized distortions in areas of high atmospheric turbulence such as near storm systems, mountainous terrain, or coastal zones, and temporal decorrelation, which makes the usage of time-series analysis by means of techniques like Persistent Scatterer (PS) and Small Baseline Subset (SBAS) interferometry more difficult to implement. Estimating correctly the tropospheric delays and their subsequent removal is considered as serious challenge in SAR interferometry since it is crucial for accurate surface deformation measurements using SAR data. Following the (Guo et al. 2024) the approached used to estimate these delays can be broadly categorized into three groups: predictive are those based on auxiliary data, those that use statistical methods as filtering or stacking, and empirical modification are those that model the relationship between phase and topography.

For troposphere corrections of SAR data the numerical weather prediction (NWP) approach is a solution. The NWP is essentially a digital, three-dimensional representation of the atmosphere at defined moment in time. In it included is detailed information about temperature, pressure, and, most importantly, the distribution of water vapor—the primary cause of tropospheric delay. The correction process typically involves these steps – NWP with high-resolution meteorological data is created, next its outputs are then spatially and temporally co-registered with the exact acquisition parameters of the SAR satellite's overpass, after that a ray-tracing algorithm is executed, which simulates the path and calculates the total phase delay experienced by the SAR signal through the atmosphere producing synthesized atmospheric phase screen for the entire interferogram scene, finally calculated APS, which represents the tropospheric noise, is subtracted from the raw InSAR interferogram. The last step is critical since this phase correction isolates the true deformation signal, removing the atmospheric artifact and enabling more accurate and reliable monitoring of ground movements. Thus by removing the tropospheric delay the accurate ground deformation is obtained.

Conclusions

To conclude, atmospheric influences represent a significant source of error in SAR processing. However, they can be effectively characterized and mitigated by integrating auxiliary data, employing advanced signal processing techniques, and conducting robust time-series analysis. Continued research focused on near-real-

time correction models and data fusion approaches is crucial for realizing the full potential of SAR remote sensing in resolving different geophysical problems more precisely.
The presented SSM approach effectively isolates and removes the ionospheric contribution to the SAR signal, leaving the remaining interferometric phase for accurate deformation or other analysis. Regarding the troposphere effects currently advanced methods are being developed for estimation of tropospheric delays in SAR data that include the integration of real-time Zenith Total Delay (ZTD) from Global Navigation Satellite Systems (GNSS), the use of high-resolution weather models for sub-kilometer scale atmospheric modeling (e.g., WRF), AI/ML-based corrections that learn patterns from a combination of weather, SAR, and terrain data, and the synergy with satellite-based humidity observations from instruments such as GNSS-Radio Occultation or radiometers.

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