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Generic Interferometric Synthetic Aperture Radar Atmospheric Correction Model and Its Application to Co- and Post-Seismic Motions

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Abstract

The Interferometric Synthetic Aperture Radar (InSAR) technique has experienced a tremendous development during the past 10 years that enables research for mapping the Earth's surface movements at larger scales and with smaller amplitudes than ever before. Apart from already in orbit satellites such as Sentinel-1A/B, Gaofen-3 and ALOS-2, many more have been scheduled for the period from 2018 to 2025 (e.g., Sentinel-1C/D, Gaofen-3B/C, RADARSAT Constellation). One of the most critical challenges when utilizing these data, hampering all techniques that require microwaves passing through the Earth's atmosphere, is to mitigate their atmospheric effects due to the spatial and temporal variations of water vapour. This effect may dominate over large scales and completely mask the actual displacement due to tectonic or volcanic deformation. Accordingly, the aim of this thesis is to provide a generic atmospheric correction model through an operational high-resolution numerical weather model, the Global Positioning System (GPS), and/or their combination, with particular application to co- and post-seismic studies.

Previous attempts that used observations from GPS and Numerical Weather Models (NWMs) are limited by (i) the availability (and distribution) of GPS stations; (ii) the time difference between NWM and radar observations; and (iii) the difficulties in quantifying their performance. To overcome these limitations, we have developed the Iterative Tropospheric Decomposition (ITD) model to reduce the coupling effects of the troposphere turbulence and stratification and hence achieve similar performances over flat and mountainous terrains. High-resolution European Centre for Medium-Range Weather Forecasts (ECMWF) and GPS-derived tropospheric delays were properly integrated by investigating the GPS network geometry and topography variations. These led to a generic atmospheric correction model (GACOS) with a range of notable features: (i) global coverage, (ii) all-weather, all-time usability, (iii) available with a maximum of two-day latency, and (iv) indicators available to assess the model's performance and feasibility.

The generic atmospheric correction model enables the investigation of the small magnitude co-seismic deformation of the 2017 Mw-6.4 Nyingchi earthquake from InSAR observations in spite of substantial atmospheric contamination. It can also minimize the temporal correlations of InSAR atmospheric delays so that reliable velocity maps over large spatial extents can be achieved. Its application to the post-seismic motion following the 2016 Kaikoura earthquake shows a success to recover the time-dependent afterslip distribution, which in turn evidences the deep inactive subduction slip mechanism. This procedure can be used to map surface deformation in other scenarios

including volcanic eruptions, tectonic rifting, cracking, and city subsidence.

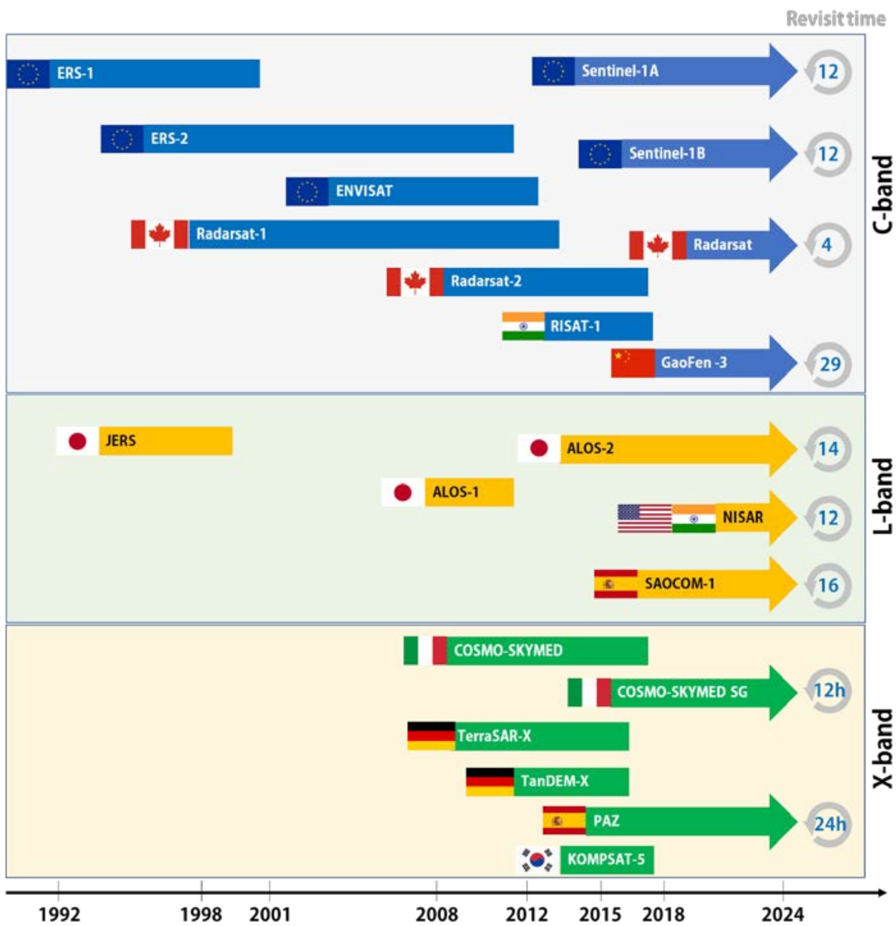

Figure 1 *An overview of SAR satellites with interferometry capacity, including historic, current and planned missions. The revisit time is in days, except for X-band satellites which can be in hours.*

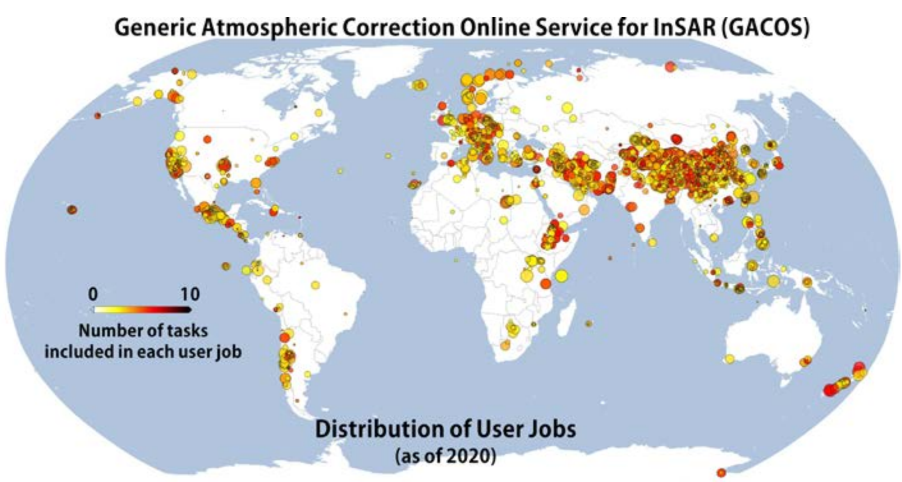

Figure 2 *Distribution of Area of Interests (AOIs) submitted to GACOS by worldwide users.*

The thesis is structured as follows:

Chapter 1 gives an introduction to this thesis.

Chapter 2 is a concise introduction to InSAR principles, error sources, and features of the atmospheric error on interferograms.

Chapter 3 introduces and validates real-time mode GPS tropospheric delay estimates, after which an Iterative Tropospheric Decomposition (ITD) model is proposed. The model is carefully evaluated through internal cross tests and against the high-resolution (1 km) MODIS water vapour map.

Chapter 4 develops a framework to routinely use GPS to reduce tropospheric effects on InSAR measurements. The method is validated on five Sentinel-1A interferograms in Southern California (with a 10–20 km station spacing network) and Southern England (with a 50–80 km station spacing network). The impact of the station spacing on the model performance is evaluated.

Chapter 5 develops a generic InSAR atmospheric correction model by tightly integrating the high-resolution ECMWF product and GPS ZTD pointwise estimate using the ITD model. The model's performance is tested using eight globally-distributed Sentinel-1 interferograms under various environments. Performance indicator metrics for quality control and model applicability are developed. A Generic Atmospheric Correction Online Service (GACOS) is developed based on the main methodology of this chapter which automatically generates correction maps per user request.

Chapter 6 applies GACOS atmospheric correction maps to co-seismic interferograms, and successfully extracts co-seismic surface displacements for the 2017 Mw 6.4 Nyingchi earthquake. The buried fault geometry located south of the Jiali fault and its slip distribution are investigated.

Chapter 7 recovers the time-dependent afterslip distribution on the southwest Hikurangi Subduction Zone by two tracks of Sentinel-1 data after mitigating the spatial-temporally correlated atmospheric errors. This gives insights into reviewing the co-seismic slip sources, the present status of the inactive subduction plate and future seismic hazards.

Chapter 8 highlights the major innovations and the conclusions of this thesis.