Successful applications of Generic Atmospheric Correction Online Service for InSAR (GACOS) to the reduction of atmospheric effects on InSAR observations

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Abstract: The tremendous development of Synthetic Aperture Radar (SAR) missions in recent years facilitates the study of smaller amplitude ground deformation over greater spatial scales using longer time series. However, this poses greater challenges for correcting atmospheric effects due to the wider coverage of SAR imagery than ever. Previous attempts have used observations from Global Positioning System (GPS) and Numerical Weather Models (NWMs) to separate atmospheric delays, but they are limited by (1) the availability (and distribution) of GPS stations; (2) the low spatial resolution of NWM; and (3) the difficulties in quantifying their performance. To overcome these limitations, we have developed the Generic Atmospheric Correction Online Service for InSAR (GACOS) which utilizes the high-resolution European Centre for Medium-Range Weather Forecasts (ECMWF) products using an Iterative Tropospheric Decomposition (ITD) model. This enables the reduction of the coupling effects of the troposphere turbulence and stratification and hence achieves equivalent performances over flat and mountainous terrains. GACOS comprises a range of notable features: (1) global coverage, (2) all-weather, all-time usability, (3) available with a maximum of two-day latency, and (4) indicators available to assess the model's performance and feasibility. In this paper, we demonstrate some successful applications of the GACOS online service to a variety of geophysical studies.

Key words: InSAR, atmospheric correction, GACOS, Earthquake, Volcano, landslide, city subsidence

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1 INTRODUCTION

Interferometric Synthetic Aperture Radar (InSAR) has experienced a tremendous development in the past two decades that enables us to map 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 2019 to 2025 (e.g., Sentinel-1C/D, Gaofen-3B/C, RADARSAT Constellation). Among all current missions, ESA's Sentinel-1 provides for the first-time global coverage images, systematically and frequently every 12 (one satellite) or six days (two satellites), freely available to the public, and therefore it is believed to have opened a new era for the InSAR community. The mission has a long duration, with future launches planned to extend the time series to at least 20 years. Since the launch of Sentinel-1A, a fruitful number of earth observation (EO) applications have been studied with very promising results (e.g., Feng et al., 2016; Lau et al., 2018; Shirzaei et al., 2017). As a result, more and more researchers have gathered to look at the Earth with unprecedented details from a SAR point of view, which in turn positively impacts future SAR missions.

InSAR phase measurements can be contaminated by several error sources such as orbital errors due to the inaccurate satellite state vectors, topographical errors introduced by the uncertainities in the external digital elevation model (DEM), unwrapping errors, atmospheric effects (i.e. ionospheric and tropospheric delays) and decorrelation errors (Massonnet and Feigl, 1998). The atmospheric effects represent one of the major error sources of InSAR which can mask actual displacements due to tectonic or volcanic deformation. It has become increasingly problematic recently, as the wider coverage, finer spatial-temporal resolution Sentinel-1 datasets, with precise orbital controls and free data distribution policies, fa-

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cilitate the studies of small amplitude ground deformation, over long time periods and across great spatial scales (e.g., Lau et al., 2018; Shirzaei et al., 2017).

One of the most popular approaches used to mitigate atmospheric effects on InSAR measurements is the phase-vs-topography correlation approach, which seeks to capture the spatial-temporal varitions of atmospheric water vapour and attempts to separate tropospheric delays from ground motion signals without any external information (e.g., Ferretti et al., 2001; Fruneau and Sarti, 2000; Hooper et al., 2004; Williams et al., 1998). This type of approach is straightforward to implement. However, the disadvantages are, firstly, there is inevitably a risk of removing actual ground motions, such as those induced by volcanic activities which may exert a similar topographic pattern with the stratified atmospheric delays. Secondly, the extraction of atmospheric delays from phases can be biased by ground motions or other error sources. Furthermore, it is sometimes impossible to quantify their performance.

Another type of atmospheric correction approach is to utilize external datasets such as, the space-based instruments include NASA's Moderate Resolution Imaging Spectroradiometer (MODIS, (e.g., Li et al., 2005, 2003) and ESA's Medium Resolution Imaging Spectrometer (MERIS, (e.g., Li et al., 2006, 2009)), ground-based instruments GPS and meteorological stations (e.g., Li et al., 2006a; Onn and Zebker, 2006; Xu et al., 2011; Yu et al., 2018) and weather models include the ECMWF Re-Analysis Interim (ERA-Interim, 6 hourly, 0.75 degree horizontal resolution, e.g., Doin et al., 2009; Jolivet et al., 2014) and the Weather Research and Forecasting model (WRF, e.g., Nico et al., 2011). However, these datasets can be limited by one or more of the following factors: (1) cloudy conditions; (2) the availability (and distribution) of GPS stations; (3) the low spatial resolution of the ERA-Interim model; and (4) the difficulties in quantifying their performance.

To overcome the abovementioned limitations, we developed the Generic Atmospheric Correction Online Service for InSAR (GACOS) and released it in the 2017 FRINGE workshop in Helsinki, Finland on 6 June 2017. In the GACOS online service, we attempted to address the following key questions: (1) how to account for the coupling effect of the tropospheric stratification and turbulence so as to best separate deformation and tropospheric signals? (2) how to deal with the low spatial-temporal resolutions of numerical weather models? (3) Is there any possibility to provide quality control indicators so that the users can decide when and where to use GACOS products? The overall aim of GACOS is to provide the InSAR community with precise and reliable atmospheric correction maps for free to enable InSAR researchers to extract small maginitude co-seismic offsets, landslide movements, and surface displacement velocities related to post-/inter-seismic slips, non-steady fault's slow slips, volcanic pumpings and ground water extractions.

2 GACOS SYSTEM DESCRIPTION

GACOS utilizes the operational high-resolution ECMWF data (0.125-degree grid, 137 vertical levels, 6-hour interval) and generates 90 m resolution atmospheric correction maps using the Iterative Tropospheric Decomposition (ITD) model (Yu et al., 2017), and overcomes the challenge to model the elevation-dependent tropospheric delays in the presence of tropospheric turbulence.

Specifically, modelled surface pressure, temperature and specific humidity from the model level operational high-resolution ECMWF product are used to calculate atmospheric delays at each 0.1-degree grid point (i.e. spacing of approximately 9-12 km), as described in Jolivet et al. (2011). The main procedure of ITD is to iteratively estimate the height scaling function and find the optimal exponential coefficients. It decouples the elevation and turbulent tropospheric delay components to retrieve high resolution tropospheric delay maps, with both the tropospheric stratification and turbulence being considered. Indicators describing the model's performance can then be derived to provide quality controls for subsequent automatic processing, and to give insights of the confidence level with which the generated atmospheric correction maps may be applied.

Since its release in June 2017, GACOS has received over 15,000 requests from all over the world, and attracted over 700 identical users for various different InSAR researches, such as tectonic or volcanic modelling, landslide and city subsidence monitoring. Given the convenience and global availability, it has rapidly responded to several large events such as the Maoxian Landslide (24 June 2017) and the Xinjiang earthquake (8 August 2017) by correcting SAR interferograms contaminated by serious atmospheric effects. The corrected inteferograms facilitated the detection of surface movements, and aided the rescue and recovery operations, which has been reported by over 20 social media and organizations.

3 APPLICATION CASE STUDIES

GACOS facilitates a variety of geophysical studies by providing InSAR atmospheric correction maps. In this section, we present some successful applications of GACOS in different scenarios.

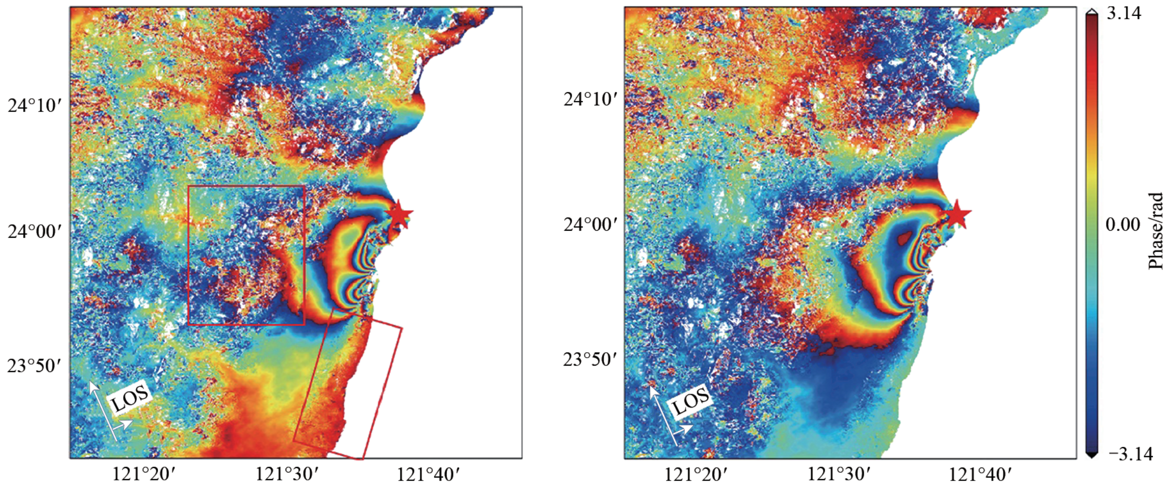
3.1 Earthquakes

Fig. 1 shows the co-seismic interferogram before and after the GACOS correction for the Mw 6.4 Hualian earthquake in Taiwan at 23:50 (UTC+8) on 6 February 2018. The west of the interferogram exhibits low coherence due to heavy vegetation. Obvious atmospheric signals can be observed along the coastal line south of the epicentre and over the west of the epicentre (red rectangle), where the phase fringes are distorted. After the GACOS correction, the fringes in the far field become continuous and smoother, allowing for better determination of earthquake source paramenters and slip distribution. It is clear in Fig. 1 that the GACOS correction can be applied on the whole interferogram without masking out the deforming area; in contrast, the phase-vs-topography correlation approach often works well in parts of the interfergram but introduces additional uncertainties in the remaining parts (Bekaert et al., 2015).

Fig. 2 shows a post-seismic interferogram for the 2016 Mw 7.8 Kaikoura earthquake in New Zealand. There are substantial post-seismic signals over the northeast coastal area (the red circle in Fig. 2(b)), which are completely masked by atmospheric effects (Fig. 2(a)). GACOS is able to remove most of the atmospheric disturbances, as well as the elevation dependent atmospheric delays over the mountainous areas (red rectangle). A collection of GACOS-corrected interferograms can then be used to retrieve the post-seismic signals in mm-level precision (Li et al., 2009).

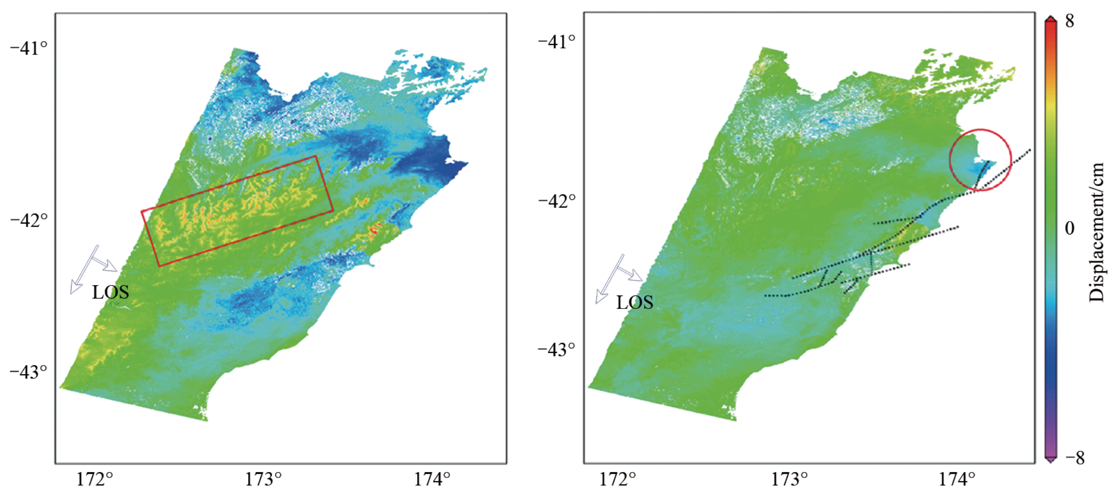
3.2 Volcanoes

Fig. 3 shows an interferogram acquired before the eruption of the Agung volcano on 21 November 2017. There are substantial atmospheric disturbances along the north coastal line which were likely caused by the complicated water vapour interactions between ocean and land bodies. GACOS captures these atmospheric delays and enables the removal of them from the original interferogram, resulting in a clean displacement map where the volcanic deformation signal stands out.



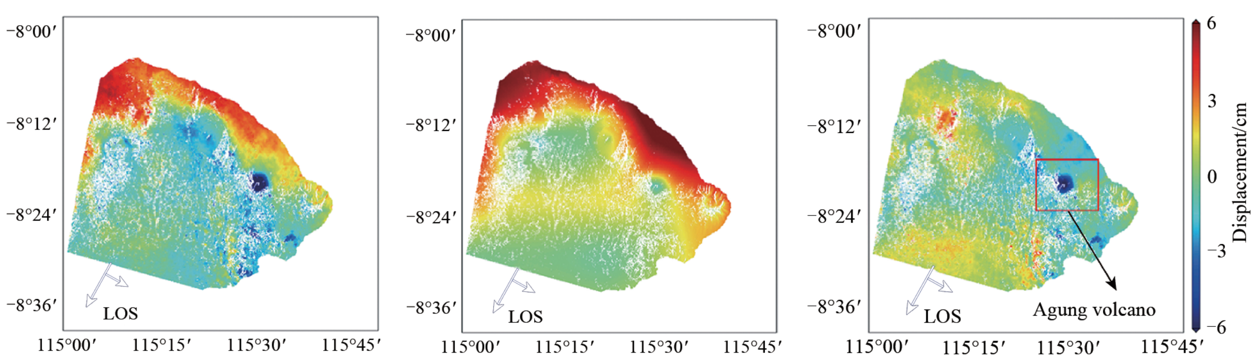
(a) Before GACOS correction (b) After GACOS correction

Fig. 1 Co-seismic Sentinel-1 interferograms (2018-02-03—2018-02-09) before and after the GACOS correction for the Mw 6.4 Hualian earthquake, Taiwan. The epicentre is denoted by a red star. Phases are unwrapped and rewrapped into $(-\pi, \pi)$ radians



(a) Before GACOS correction (b) After GACOS correction

Fig. 2 Post-seismic Sentinel-1 interferogram (2016-12-04—2016-12-16) after the Mw7.8 Kaikoura earthquake in New Zealand. The black dotted lines are mapped fault traces

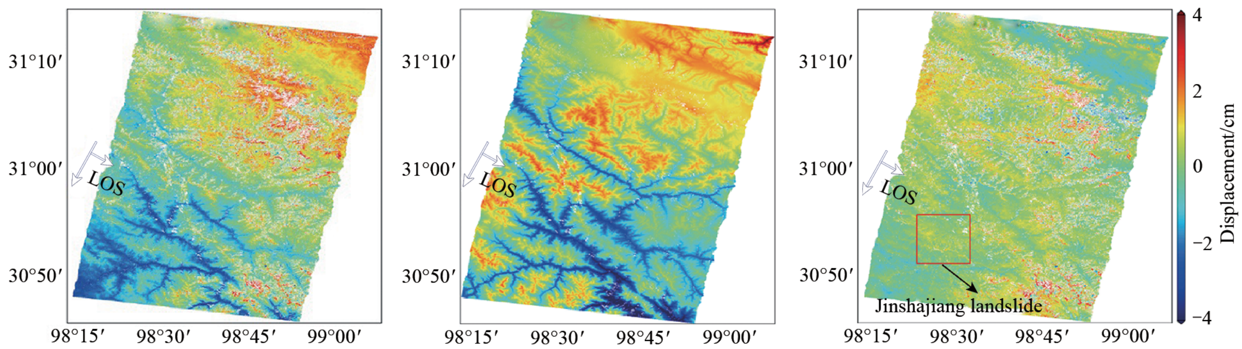


(a) Before GACOS correction (b) GACOS correction (c) After GACOS correction

Fig. 3 Sentinel-1 Interferograms (2017-08-28—2017-09-09) over Agung volcano before its eruption on 21 November 2017

3.3 Landslides

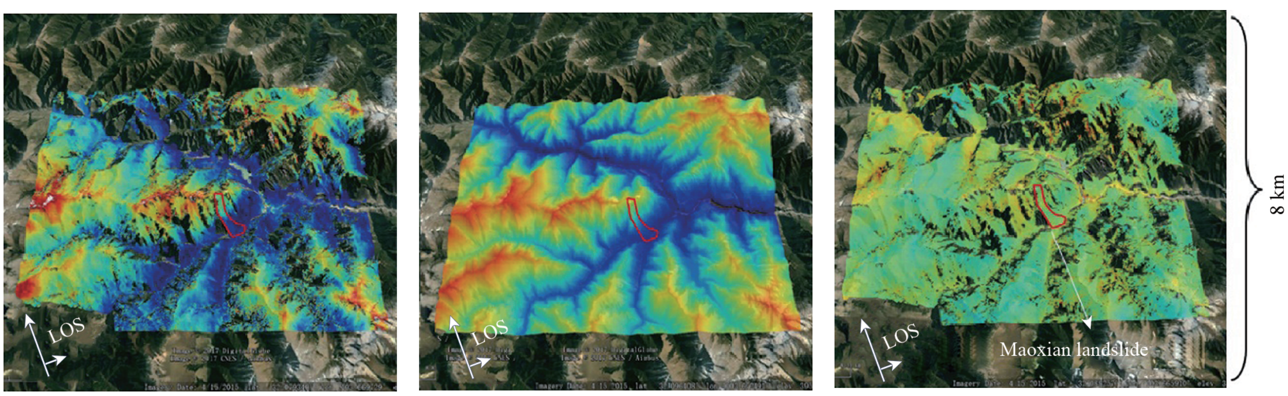
Fig. 4 shows a Sentinel-1 interferogram acquired before the failure of the Jinshanjiang landslide on 14 October 2018. The phase measurements are dominated by elevation-dependent atmospheric delays due to the steep topography, making it hard to distinguish small-magnitude ground movements, particularly along a deep slope. One of the major advantages of GACOS is to model the stratified atmospheric delays over mountainous areas, resulting in the corrected interferogram being less affected by elevation-dependent atmospheric errors and the actual ground displacements being identified easier.



(a) Before GACOS correction (b) GACOS correction (c) After GACOS correction

Fig. 4 Pre-event Sentinel-1 Interferogram (2018-09-21—2018-10-03) for the 2018 Jinshajiang landslide

Atmospheric delays can be substantial over a small spatial extent, particularly in mountainous areas with steep slopes. Fig. 5 shows an interferogram over the Maoxian landslide occurred on 24 June 2017. Obvious atmospheric errors can be observed over this small region (~ 8 km), with the GACOS correction being able to remove most of the elevation-dependent errors.



(a) Before GACOS correction (b) GACOS correction (c) After GACOS correction

Fig. 5 Sentinel-1 Interferogram (2017-01-31—2017-05-31) over the 2017 Maoxian landslide (circled red area).

3.4 City subsidence

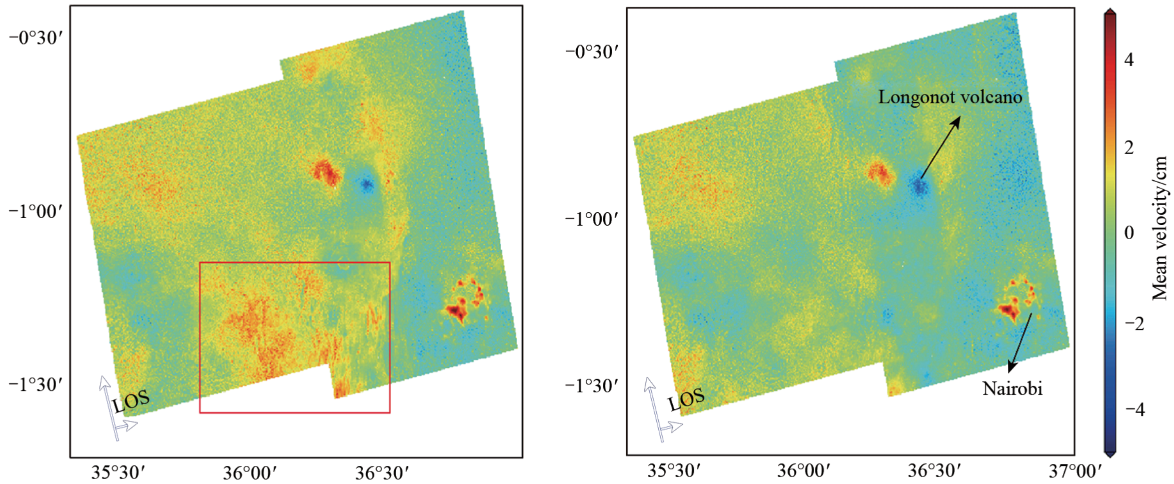
When resolving the mean velocity of city subsidence, atmospheric effects can be problematic, with its spatial-temporal correlation degrading the filter performance which is commonly used in time series analysis. After applying GACOS corrections to each interferogram in a time series, the spatial-temporal correlation of the atmospheric error can be reduced, resulting in an improved filter performance and a higher precision of velocity mapping. This can be seen in Fig. 6, where the mean velocity map retrieved from the GACOS corrected interferograms (Fig. 6(b)) is less noisy and free from long wavelength residuals (red rectangle).

3.5 Glacial movements

GACOS is also able to provide atmospheric correction maps over (near) polar regions to aid the studies of glacial movements. Fig. 7 shows an interferogram over the western Iceland where a dramatic improvement is observed after applying the GACOS correction. The glacial movement usually occurs along with a steep topography, resulting in dominating elevation-dependent signals. As a result, the GACOS correction, with modelled elevation-dependent atmospheric delays, is valuable when retrieving movements along different river channels and over coastal areas.

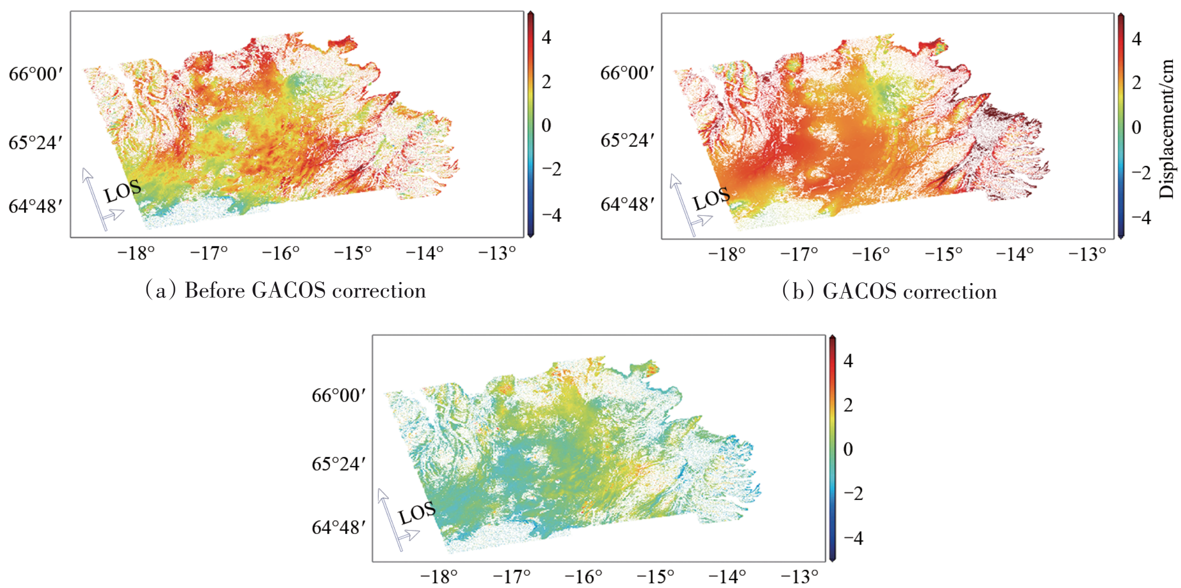
4 CONCLUSIONS

In this paper, we have demonstrated some successful applications of the GACOS online service, including the studies of earthquakes, volcanoes, landslides, city subsidence and glacial movements. GACOS is proven to be able to provide the InSAR community with reliable atmospheric correction maps that have (1) global coverage, (2) all-weather, all-time usability, (3) a short time delay of less than two days; (4) robust and easy implementation with quality control indicators. Being convenient and reliable, GACOS has become a popular toolbox, receiving over 30,000 requests from all over the world and attracting over 2000 identical users for a range of InSAR related researches. A wide spectrual of GACOS users from different research areas has provided constructive suggestions and feedback, resulting in an efficient operation of the system and inspirations for further developments.



(a) Before GACOS correction (b) After GACOS correction

Fig. 6 Mean velocity maps retrieved using InSAR time series stacking over Nairobi, Kenya



(a) Before GACOS correction (b) GACOS correction

(c) After GACOS correction

Fig. 7 Sentinel−1 Interferogram (20180115−20180127) over western Iceland, the GACOS atmospheric correction and the interferogram after the GACOS atmospheric correction

A new generation of GACOS is being tested, which is to utilize tropospheric delay products from the Global Positioning System (GPS) and to release an API system to allow the registered users to incorporate GACOS to their automatic data processing chains. These new features of GACOS are dedicated to further facilitate the study of small amplitude ground deformation over large spatial scales using long time series InSAR measurements, such as the identification of small magnitude co-seismic displacement over mountainous areas, the isolation of topographic related volcanic deformation and the retrieval of non-linear, time varying velocity fields.

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