Assessing the Impact of TEC Fluctuations on ALOS-PALSAR Images

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Keywords: Ionosphere, SAR, InSAR, Total Electron Content, GNSS, Mid-latitude Ionosphere.

Abstract: Trans-ionospheric waves experience delay proportional to the Total Electron Content (TEC), being the number of free electrons present along a satellite-receiver ray path. TEC is a highly variable quantity, influenced by different helio-geophysical parameters, such as solar activity, season, time of the day, etc. Such large variability may lead to TEC spatial and temporal fluctuations over different scales, affecting the quality of the Synthetic Aperture Radar (SAR) signals and, in turn, limiting further developments of interferometric techniques, such as InSAR (Interferometric SAR). In the specific, the need of catching qualitative and quantitative correspondences between TEC fluctuations and InSAR image streaks is a key point to drive the development of future mitigation techniques to improve the quality of the SAR imaging. In this paper calibrated TEC values, derived from the RINEX data provided by the RING (Rete Integrata Nazionale GPS) network of GPS receivers, are analysed to assess the ionosphere conditions during the ALOS (Advanced Land Observing Satellite) – PALSAR (Phased Array type L-band Synthetic Aperture Radar) passages over central Italy.

1 INTRODUCTION

The InSAR is among the most used techniques for geophysical applications, because it is able to provide high-resolution imaging, independently on all tropospheric weather conditions (Bürgmann et al., 2000). SAR signals emitted by ALOS-PALSAR in L-band frequency range cross the bulk of the ionosphere, because they are emitted at about 700km altitude, i.e. in the topside ionosphere. By consequence, such signals experience changes in their phase and group velocity induced by the ionosphere. Changes are proportional to the distribution of free electrons encountered during their travel from SAR satellite to ground and back. The InSAR technique extracts the position and/or the displacement of a surface by calculating the phase difference between two SAR images acquired in different days, but at the same local time and on the same geometrical area (Ferretti et al., 2007).

Thus, to ensure the performance of the InSAR imaging and to assess the ionospheric impact on it, the status of the ionosphere in both passages must be taken into account, as it is known to be responsible of the appearance of streaks on SAR co-registration images. In the specific, the shift of the co-registration is proportional to the ionospheric TEC gradients. (Chen & Zebker, 2014).

TEC can be obtained by means of GNSS dual frequency receivers located at ground. GNSS slant TEC (STEC) is defined as the total number of free electrons within a cylinder with a cross section of 1 m^2 and height equal to the signal ray path, from satellite to ground (in the GNSS case). STEC is then a measure of the integrated electron density Ne according to the formula:

Spogli L., MusicÃš E., Cesaroni C., Boncori J., Franceschi G. and Seu R.
Assessing the Impact of TEC Fluctuations on ALOS-PALSAR Images.
DOI: 10.5220/0006226700150021
In *Proceedings of the Fifth International Conference on Telecommunications and Remote Sensing (ICTRS 2016)*, pages 15-21
ISBN: 978-989-758-200-4

$$STEC = \int Ne(s)\, ds, \qquad (1).$$

where s is the ray path of the satellite-receiver link. Being GNSS satellites located at an altitude of about 20200 km, TEC measured with suitable ground receivers provides information also above the ALOS altitudes. However, the contribution to TEC of the ionosphere above 700 km is of few %'s (Kelley, 2009).

TEC is a highly variable quantity influenced by different helio-geophysical parameters such as the solar activity, the season and the time of the day. This must be taken into account when considering the ionospheric conditions of the days to which the images obtained by InSAR techniques refer. Many researches about ionospheric effects on SAR have been carried out, most of which are based on numerical simulations, use of global ionospheric models like WBMOD (Meyer & Agram, 2015) or large-scale interpolated ionospheric maps that do not have the spatial resolution needed for InSAR (Hanssen, 2001). Currently, only few studies investigated the relationship between ionospheric variability and SAR/InSAR imaging by means of independent measurements (like GNSS) and, in general, a final word has not been told about the ionospheric influence on real SAR images (Zhu el al 2016). For this reason, high-resolution determination of TEC and of its spatial-temporal fluctuations is needed. In this work, we show the preliminary results obtained by comparing ALOS-PALSAR images of central Italy and TEC measurements obtained by means of the Rete Integrata Nazionale GPS (RING, http://ring.gm.ingv.it/) network of GNSS receivers, managed by the Istituto Nazionale di Geofisica e Vulcanologia (Italy).

The paper is organized as follows: section 2 presents the ALOS-PALSAR and GNSS data and how they have been treated to obtain the results, discussed in section 3. Then, conclusions are provided in section 4.

2 DATA AND METHODS

2.1 ALOS-PALSAR

InSAR is an imaging technique that evaluates the pixel-to-pixel phase difference between two SAR images, acquired over the same area, to produce an interferogram. In this work, two SAR images (a "master" and a "slave") are acquired with a single receiver in two different epochs with almost the same incidence angle and on the same area, i.e. in the so called "repeat-pass interferometry mode". Since the orbital positons of the two SAR passages are slightly different, it is necessary to coregistrate the master and slave images, with the accuracy of sub-pixel, to calculate the phase difference of two corresponding pixels and, then, obtaining high quality InSAR images. In the present work, we concentrate on the results of the co-registration, without looking at the final InSAR product (interpherometric phase), with the aim to minimize the tropospheric error affecting phase measurements (Hassen, 2001) and to focus on the ionospheric contribution only.

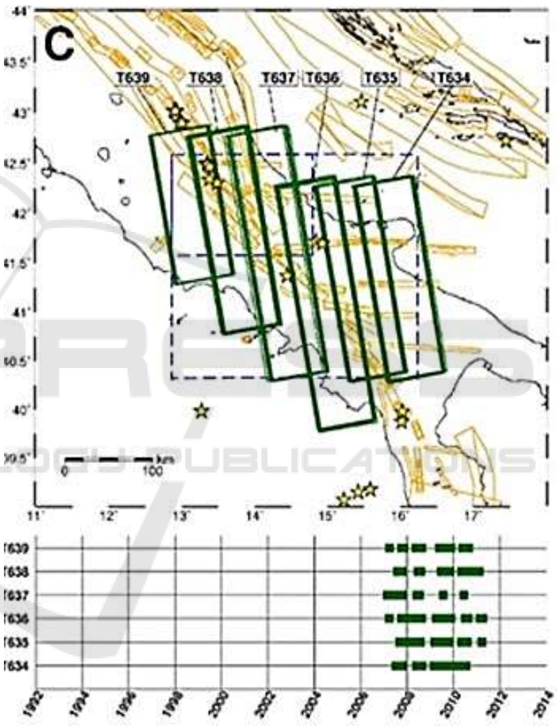

Figure 1: ALOS ascending tracks over central Italy

We consider the azimuth shifts obtained by the coregistration of three images acquired by ALOS-PALSAR over Italy. The observed area is that covered by the ground track 638 of ALOS, which is located over central Italy. Shifts are estimated by using the Multiple Aperture InSAR (MAI) method. The MAI method, based on split-beam InSAR processing, is able to extract along-track displacements from InSAR data more efficiently than the pixel amplitude correlation (Bechor & Zebker 2006).

2.2 GNSS

As mentioned before, GNSS signals passing through the ionosphere experience transmission delay proportional to TEC. Starting from RINEX data, dual frequencies GNSS receivers are able to calculate TEC along the slant path, according to the following formula:

$$STEC = \frac{1}{40.3}\left(\frac{L1^2 L2^2}{L2^2 - L1^2}\right)(P_2 - P_1) - \varepsilon, \qquad (2)$$

where $L1$ (1575.42 MHz) and $L2$ (1227.60 MHz) are the two frequencies of the signal transmitted, $P1$ and $P2$ are the corresponding pseudoranges and ε represents the biases induced by the receiver, satellite, multipath etc. In order to minimize the biases, it is necessary calibrate the STEC (Cesaroni et al., 2015a).

To such scope, the GOPI calibration software (http://seemala.blogspot.it/2011/04/rinex-gps-tec-program-version-22.html) has been used. The GOPI software provides TEC values projected to the vertical, under the assumption that the ionosphere can be represented by a single, thin, ionized layer located at 350 km (Mannucci et al., 1998) that is suitable for a quiet mid-latitude ionosphere. Hereafter, we refer to calibrated and verticalized TEC as TECcal. The projection to the vertical allows having TEC values not dependent on the position of the GNSS receivers at ground. Since ALOS ascending passages of T638 over the area of interest occurred during night, it is reasonable to assume that a mid-latitude ionosphere in the nighttime is “frozen”, i.e. not meaningfully changing, during a time interval of 5 minutes around the two passages of ALOS.

To find the portion of the ionosphere crossed by the SAR signal, some geometrical consideration are here reported and sketched in figure 2.

The distance D between the point P at ground and the projection of the point P_i (which is the intersection of the SAR signal and the ionosphere) at ground is approximately given by H_i*tan (α) (Reuveni et al 2015), where the look angle, α, is related to the incidence angle, θ, through the following formula:

$$\alpha = \sin^{-1}\left(\frac{Re}{Re+Hs}\sin\theta\right); \qquad (3)$$

In which Re is the Earth’s radius and H_i is the altitude of the thin layer approximated ionosphere.

Then, to highlight the difference (if any) between the ionospheric features in correspondence with the two ALOS passages, maps of TECcal values have been considered. To obtain a fine representation of the ionospheric features as derived from regional TEC maps, it is necessary to have a very dense GNSS network. To the scope, the RING geodetic network has been selected, being composed by more than 100 receiver spread all over the Italian territory (Figure 3). TECcal maps boundaries have been defined to correspond to the SAR images boundaries, following the geometry described in Figure 2.

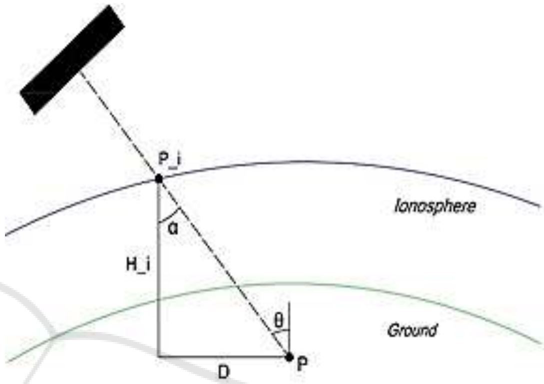

Figure 2: Ionosphere crossed by SAR signal. P_i is the intersection between the SAR signal and the ionosphere, D is the distance between the point P at ground and the projection of the point P_i on the ground, α and θ are respectively the look angle and the incidence angle, H_i is the altitude of the thin layer ionosphere.

Figure 3: Location of the GPS stations of the RING network

In such maps, TECcal are calculated at each IPP (Ionospheric Pierce Point) for every satellite in view by each receiver over a 5-minute interval (frozen ionosphere) centred in the time of the track. TECcal are then interpolated with the natural neighbour method (Sibson, 1981). Such interpolation technique has been selected according to Cesaroni (2015b) and to Foster and Evans (2008), in which the authors demonstrate that the natural neighbour interpolation is the best choice when regional TEC maps are considered. To avoid border effect due to the interpolation, maps have been calculated all over Italy and, then, restricted to fit the SAR image boundaries, as mentioned before. To evaluate the TECcal differences between the two passages, the values of the maps that correspond to the master and slave days are subtracted and a map of difference (ΔTECcal) is produced.

3 RESULTS AND DISCUSSION

The variations of the ionosphere between the different passes of the SAR cause an azimuth shift between the positions of the pixels of the master and slave image. This effect, also known as "azimuth streaks", influences the optimal coregistration of the interferometric pair (Gray et al., 2000).

In this work, we concentrate on 3 ALOS-PALSAR images of central Italy, whose master/slave dates and parameters are summarized in Table 1. For each coregistred image, azimuth shifts have been determined and reported in figures 4 to 6.

Table 1: Images and relative parameters used in this work, where θm and θs are respectively the incidence angle of the master and the slave image, Bt stands for the temporal baseline and Bp stands for perpendicular baseline.

Image #	1	2	3
Master	01/07/2007	01/07/2007	16/08/2007
θm (°)	38.7191	38.7191	38.7395
Slave	16/08/2007	01/10/2007	01/10/2007
θs (°)	38.7395	38.7223	38.7223
Bt(days)	46	92	46
Bp (m)	279.9401	539.2134	259.2523

In all three cases, the shift varies from -3 m to 3 m. By comparing such figures, a strong similarity between image #1 (fig. 4) and #2 (fig. 6) can be noticed. In particular, a similar pattern of the shift are present, but with opposite sign. The sign shift is because the day 16 August 2007 is used as slave in figure 4, while in figure 6 it is used as master.

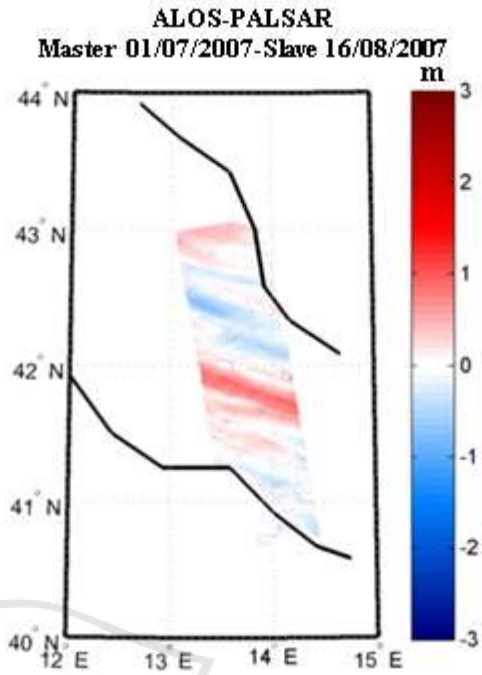

Figure 4: Shift obtained by coregistration of the master (01/07/2007) and slave (16/08/2007) images

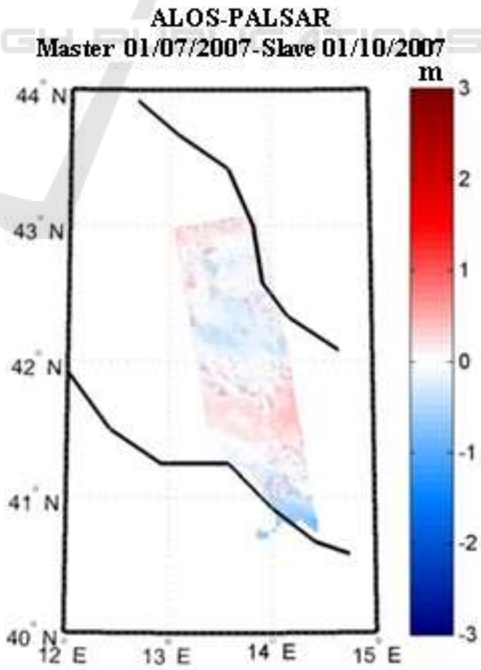

Figure 5: Shift obtained by coregistration of the master (01/07/2007) and slave (01/10/2007) images

By looking closely to the red strike located at around 41.8°N in figure 4 (or the corresponding blue strike in figure 6), it is possible to note that it divides into 3 smaller sub-strikes.

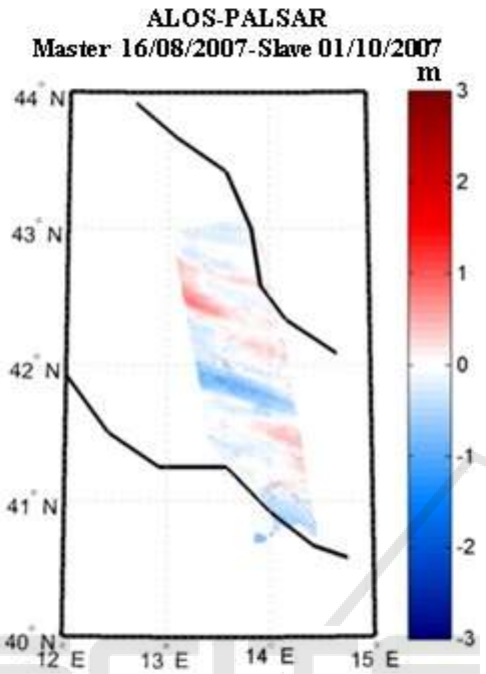

Figure 6: Shift obtained by coregistration of the master (16/08/2007) and slave (01/10/2007) images

In Figure 5, the streaks are broader and less structured than those in Figures 4 and 6. In the case of Figure 5, 4 large streaks can be identified:

- a positive shift around 43°N,
- a negative shift between 41.7°N and 42.8°N,
- a positive shift between 41.5°N and 41.7°N,
- a negative shift between 40.7°N and 41.5°N.

Since the SAR image of the 16 August is used both in Figures 4 and 6 but not in Figure 5, the ionosphere in 16 august 2007 seems to be the principal responsible for the streaks appearance. According to Dst (Figure 7) and Kp (not shown) indices, 16 August 2007 can be considered quiet from the geomagnetic point of view (red box of middle panel). Also 1 July 2007 (red box, top panel of Figure 7) and 1 October 2007 (red box, bottom panel of Figure 7) can be considered quiet.

In Figures 8 to 10, the ΔTECcal maps corresponding to the images #1 to #3, respectively, are reported. All maps presents structures of ΔTECcal, that are likely responsible for the presence of streaks in the ALOS-PALSAR images.

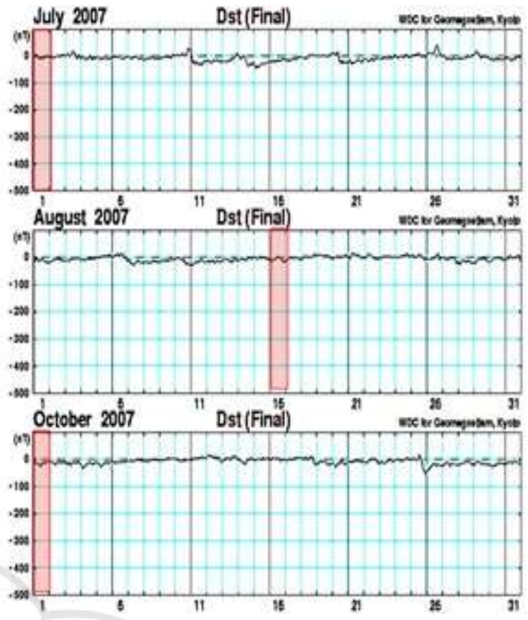

Figure 7: Dst index of July, August and October 2007. (http://wdc.kugi.kyoto-u.ac.jp/dst_final/). Days of the images are highlighted in athe red boxes

We remind that, to highlight the correspondence between azimuth streaks and gradients of ΔTECcal, the ionosphere maps are fitted on SAR area, according to the method described in Section 2.2. By comparing ΔTECcal behaviour in the figures, we can see that the ΔTECcal values show largely different patterns among the three days, reinforcing the idea on how variable can be the ionospheric conditions in different days, even if at mid latitudes. Figures 8-10 show patterns of ΔTECcal characterized by large ΔTECcal gradients mainly in the N-NW direction of all over the maps, and, in particular, gradients of 1-2 TECu in the latitudinal range between 42.2°N and 41.5°N, where the strikes, highlighted in figures 4-6, are present. This confirm how variation of few TECu's and below have a great impact on the SAR imaging.It is important to note that ΔTECcal map in figure 8 is obtained by differencing TEC data acquired in the same season, while the maps in Figure 9 and 10 have been obtained by differencing summer and fall data.

Considering that the geospace conditions can be considered quiet for all the 3 days, the seasonal variation seems to be a key point in understanding the impact of the ionosphere on the streaks appearance in the analysed case.

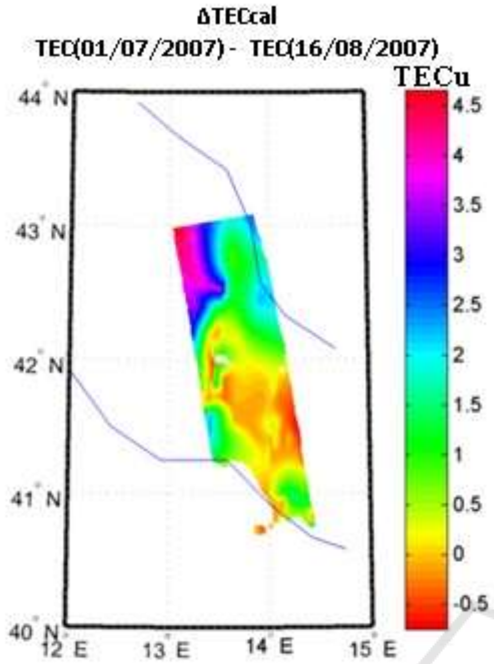

Figure 8: ΔTECcal maps (01/07/2007-16/08/2007) The color bar shows the differences of the ΔTECcal values in TECu

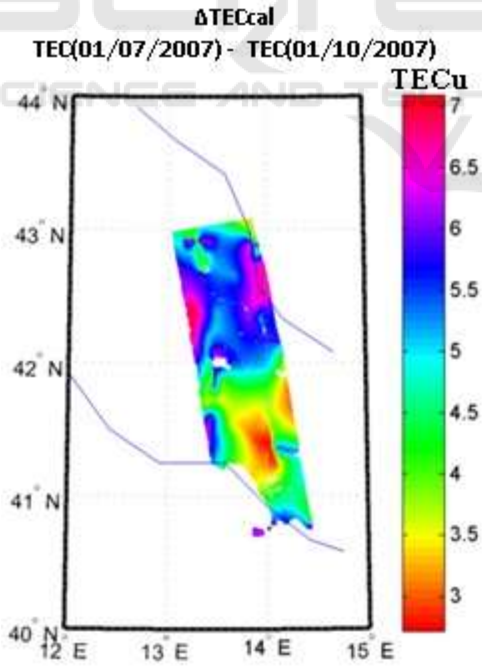

Figure 9: ΔTECcal maps (01/07/2007-01/10/2007) The color bar shows the differences of the ΔTECcal values in TECu.

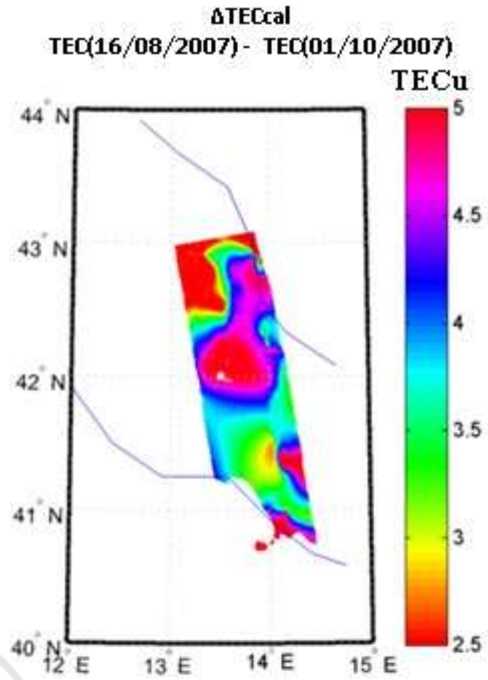

Figure 10: ΔTECcal maps (16/08/2007-01/10/2007) The color bar shows the differences of the ΔTECcal values in TECu

The spatial scale of the identified ΔTECcal gradients has been reached thanks to the fine spatial density of the GNSS receivers at ground. Such resolution is not reachable with the standard, global, ionospheric models commonly used.

4 CONCLUSIONS

TEC fluctuation can significantly affect InSAR applications. To investigate these ionospheric effects on ALOS-PALSAR images, we analysed 3 maps of azimuth shift and 3 maps of TEC differences (ΔTECcal) over central Italy.

The InSAR images present meaningful streaks, with shift ranging from -3 m to 3 m.

The ΔTECcal maps were obtained by:

- using dual frequency GPS data of the RING network,
- assuming that the ionosphere is a thin layer located at an altitude of 350 km above the Earth's surface,
- processing the GPS data with a calibration technique to reduce the errors introduced by satellite receiver biases

– interpolating the data with natural neighbour interpolation

In order to show the condition of the ionosphere in terms of TEC fluctuation in correspondence with the coregisistration of two L-band SAR images (Fig. 4-6), the maps of ΔTECcal were projected on the same area. Results indicate how variations below 1-2 TECu observed with ΔTECcal provides the appearance of streaks. The map (Fig. 9) in which

- the maximum value of ΔTECcal is larger than those of the other 2 maps
- the gradient are less and smaller than those in Figures 8 and 10

corresponds to the case with less strikes.

Furthermore, the results show that the 16 August 2007 seems to be the principal responsible for the streaks appearance.

These case study suggests how variations of few TECUs can affect considerably ALOS-PALSAR images. Further refinement of the work will aim at compensating for the seasonal variation, aiming at catching finer ionospheric effects and different geospace conditions and geographical sectors will be investigated. A comparison between the results with the TEC mapping here shown and common ionospheric models (like GIM, WBMOD) is currently ongoing. Future refinement of the work will aim at quantitatively assess the impact of TEC fluctuation on L-band SAR, by evaluating the TEC gradient along the azimuth direction. Effect of the zonal and meridional ΔTECcal gradients will be also investigated.

ACKNOWLEDGEMENTS

ALOS PALSAR data were provided by the European Space Agency through Category-1 Proposal 26350. Authors are grateful to Dr. Antonio Avallone for his support with RING data.

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