COST Action – CA15211 "ElectroNet"

Application form for Short-Term Scientific Missions (STSM)

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2. HOST
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STSM PERIOD: **October 14- October 22**

Overall context and objectives of this STSM

Synthetic Aperture Radar (SAR) interferometry and GNSS are two space geodesy techniques which are used to measure map water vapor distribution in the atmosphere. In particular, since the start of Sentinel-1 acquisitions, SAR interferometry has demonstrated the usefulness of its high resolution water vapor maps to study extreme weather events. However, both SAR and GNSS estimate the water vapor distribution by means of the microwave propagation delay in the atmosphere, which includes also the delay in the ionosphere. Space weather can severely affect electric properties of the atmosphere, first of all the Total Electron Content (TEC) in the ionosphere. The correct modelling of ionospheric propagation delay in the case of disturbances due space weather phenomena like solar wind is crucial in the processing of interferometric SAR and GNSS signals in many Earth Observation applications, and it is relevant for positioning and remote sensing. Besides traditional space geodesy applications based on SAR and GNSS data, the use of interferometric SAR images in meteorology calls for a procedure disentangle signal delays due to different reasons (e.g. propagation in troposphere and ionosphere). The availability of GNSS receivers that can measure both phase delay and ionospheric scintillation will be used to estimate the local (even if still over large areas) temporal variations of Precipitable Water Vapour (PWV) and TEC. Sentinel-1 data will be used to generate high resolution maps of PWV which will be corrected for propagation delay in a disturbed ionosphere. The aim of this Short Term Mobility is to strengthen a research collaboration with the Geographical Institute Jovan Cvijić of the Serbian Academy of Sciences and Arts on the topics related to the influence of the perturbed ionospheric electric properties due to solar wind on the GNSS and SAR signals.

The work carried out during the STSM

The scientific activity carried out by *Giovanni Nico* during his STSM at the Geographical Institute Jovan Cviijić, Serbian Academy of Sciences and Arts, is described as follows

FIRST DAY

- Arrival to Belgrade, meet the host scientist, Milan Radovanović
- Welcome meeting at the Geographical Institute Jovan Cviijić
- Seminar at Geographical Institute Jovan Cviijić

At the welcome meeting participated also Milan Milenkovic and Milan Radovanović of the Geographical Institute Jovan Cviijić, Miljana Todorovic Drakul of the Department of Geodesy and Geoinformatics, Faculty of Civil Engineering, University of Belgrade. During this meeting it was decided to search for both recent large disturbances in the ionosphere (whatever the cause) and X-ray flares which could cause a change in TEC. The reason for this it has been to increase the probability to have Sentinel-1 images useful to measure the temporal change of TEC.

SECOND DAY

Meeting with Miljana Todorovic Drakul of the Department of Geodesy and Geoinformatics, Faculty of Civil Engineering, University of Belgrade, to discuss about recent disturbances in ionospheric electric properties. She described a disturbance in ionosphere occurred in 21st March 2014 over Serbia. The TEC vas about 50 TECU which twice the values usually measured in this geographical region. Figure 1 displays the TEC map over Serbia measured on 21st March 2014.

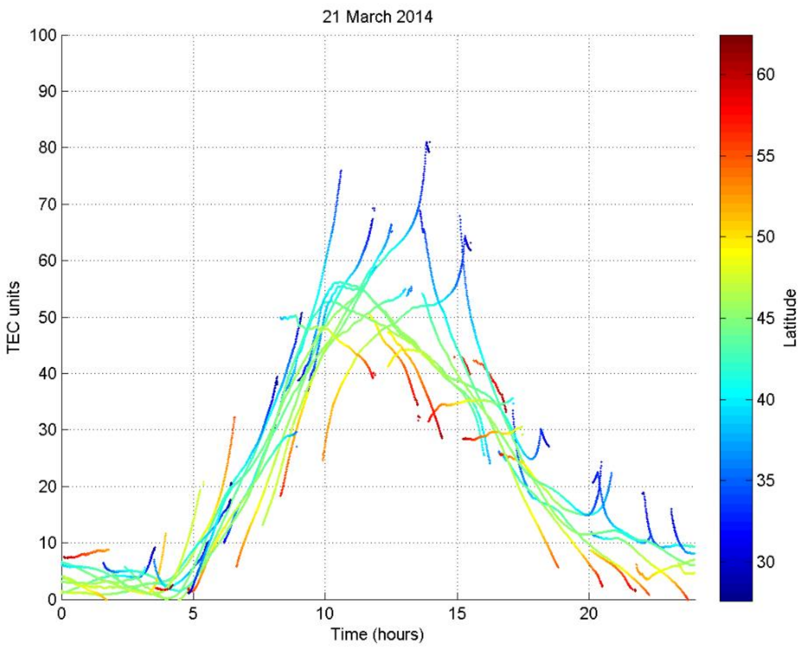


Figure 1: Map of TEC over Serbia during the ionosphere disturbances on 21st March 2014 (courtesy of Miljana Todorovic Drakul)

Besides this large disturbance, three more disturbances were found in 2019, on 17th March, 14th May and 5th August. In this days no significant X-ray flares were found.

Concerning X-ray flares, three flares were found on 6th, 7th and 10th September 2017 using GOES15 data and are reported in Figures 2, 3 and 4, respectively.

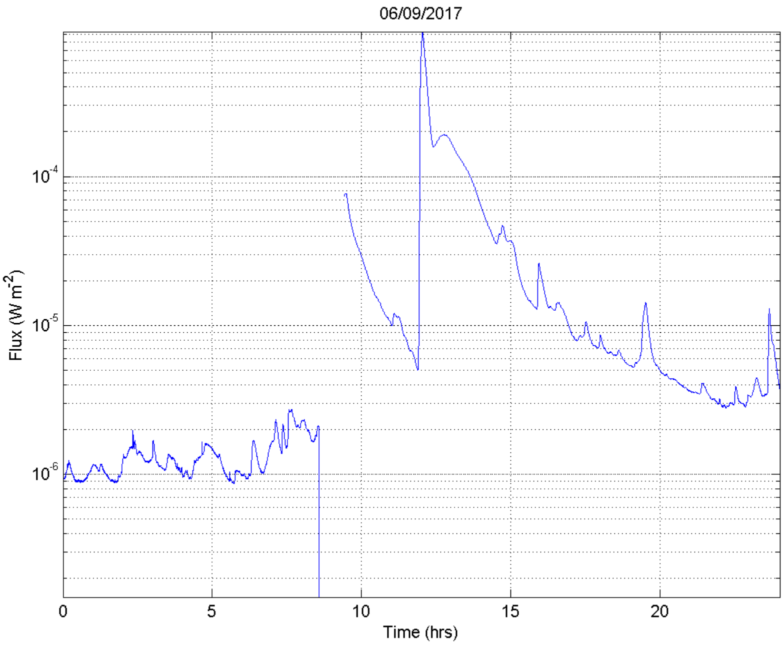


Figure 2: X-ray flares on 6th September 2017: 08:57 09:10 09:17 X2.2 S07W33 12673; 11:53 12:02 12:10 X9.3 S08W33 12673.

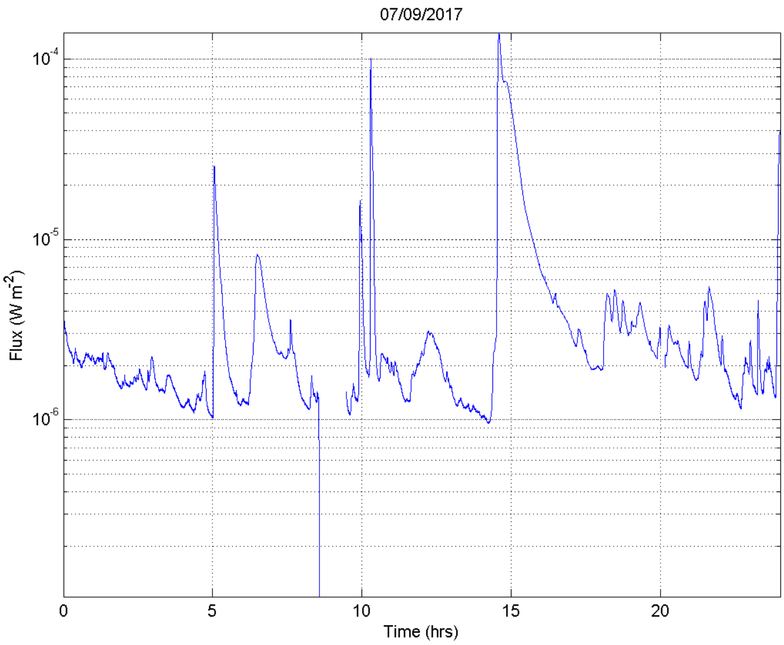


Figure 3: X-ray flares on 7th September 2017: 14:20 14:36 14:55 X1.3 S11W49 12673.

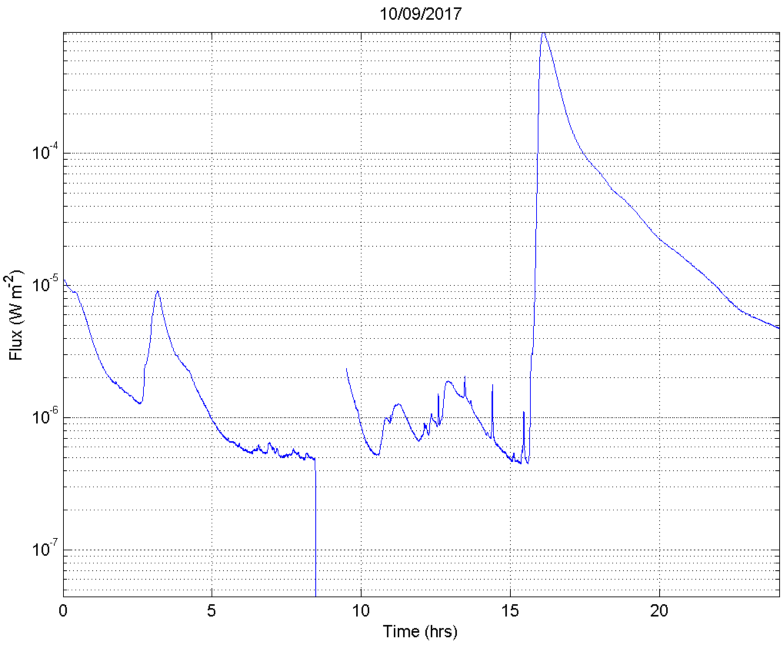


Figure 4: X-ray flares on 10th September 2017: 15:35 16:06 16:31 X8.2 12673.

Information about the location of GNSS permanent receivers and meteorological stations was also collected. GNSS data are useful for both the estimation of PWV and TEC while meteorological station are useful mainly for information about cumulated rainfall useful to compare with the assimilation of Sentinel-1 (and also GNSS) estimates of PWV in high resolution NWP models. This last point is not the main point of this STSM but it was discussed during my seminar on the first day at the Geographical Institute Jovan Cviijić as research topic to be developed in collaboration in the near future. Figure 5 and 6 show the location of GNSS permanent receivers and meteorological station, respectively.

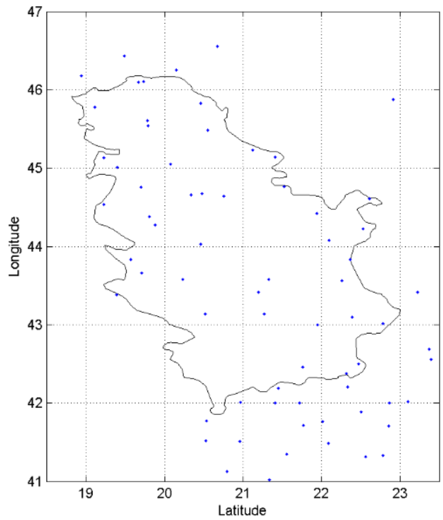


Figure 5: Location of permanent GNSS receivers over Serbia and nearby countries. Data are provided by the Republic Geodetic Authority of Serbia.

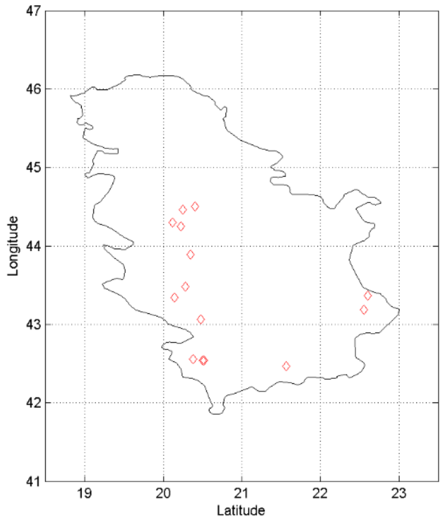


Figure 6: Location of meteorological station over Serbia. Data are provided by the Republic Hydrometeorological Service of Serbia.

Furthemore, a search was done on the Copernicus hub for Sentinel-1 data acquired over Serbia of interest for the study of the above ionosphere disturbances. To be of interest for this study, the acquisition dates of the two Sentinel-1 images used for generate a SAR interferogram should include the local ionosphere disturbance. To be better, the occurrence of the ionosphere disturbance should be as close as possible to the acquisition time of one of the two Sentinel-1 images of the interferometric couple to provide the larger phase variations. Unfortunately, Sentinel-1 images are not available for the larger disturbance on 21st March 2014 as it occurred a few days before the beginning of Sentinel-1 acquisitions. Table 1 summarizes the acquisition dates of Sentinel-1 images useful to study the ionosphere disturbances on 2019. For each acquisition, the acquisition time and orbit are provided. As far as the three days characterized by X-ray flares, it was verified that Sentinel-1 images were not acquired over Serbia on 6th, 7th and 10th September 2017. The closest available Sentinel-1 images were acquired on 5th September at 04:53 (orbit 51 descending) and 8th September at 16:24 (orbit 102 ascending). Figure 7 shows the footprints of Sentinel-1 images acquired over Serbia which will be used to study the TEC variation due to the large disturbance in ionosphere on 17th March, 14th May and 5th August 2019.

Table 1: Acquisition dates of Sentinel-1 images used to study ionosphere disturbances over Serbia.

Ionosphere disturbance	Sentinel-1 date acquisition	Orbit
17/03/2019	17/03/2019 @ 04:54	Descending 51
14/05/2019	14/05/2019 @17:34	Ascending 29
05/08/2019	05/08/2019 @ 16:25	Ascending 102

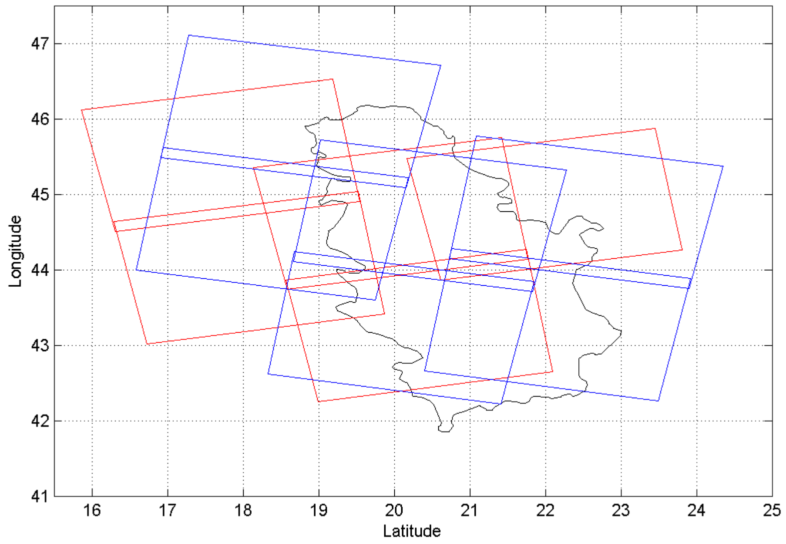
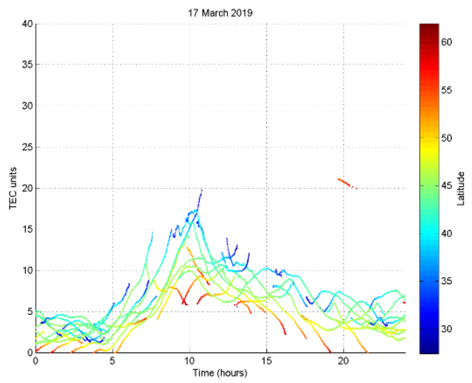


Figure 7: Footprint of Sentinel-1 images acquired over Serbia. Footprints in red and blue represents ascending and descending orbits, respectively.

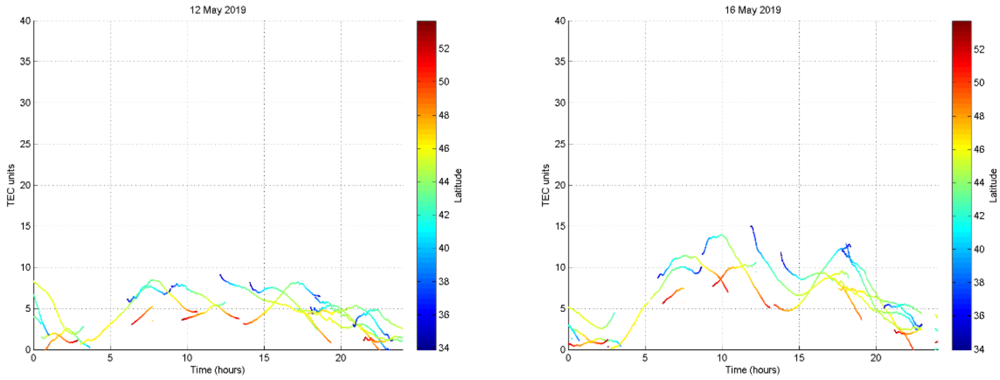
Interferometric couples of Sentinel-1 images acquired along the orbits listed in Table 1 have been downloaded. In particular, the images acquired at the acquisition times listed in Table 1, as well as those acquired six days before and after, along the same orbit, have been downloaded to increase the number of available interferograms.

THIRD AND FORTH DAYS

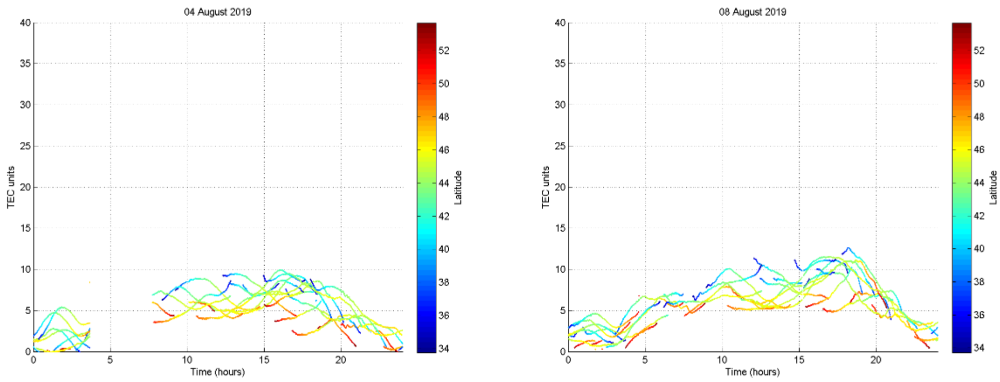
These two days have been devoted to the processing of GNSS data. Figure 8 summarizes the TEC values estimated on the day of ionosphere disturbances



Ionosphere disturbance on March 2019



Ionosphere disturbances on May 2019



Ionosphere disturbances on August 2019

Figure 8: TEC values estimated by GNSS data on the days characterized by ionosphere disturbances on 2019.

FIFTH AND SIXTH DAYS

These two days have been devoted to the processing of Sentinel-1 data. Three interferograms have been processed along the orbit 51 (descending), two along orbit 29 (ascending) and one along orbit 102 (ascending). Each interferogram has obtained by processing a reference image (master image) and a Sentinel-1 image (slave images) acquired with a temporal baseline of six days, which is the shortest temporal baseline corresponding to the revisiting time of Sentinel-1 along a given orbit, over Serbia.The phase of each interferogram contains contributions due to the temporal changes of propagation delay in both troposphere and ionosphere according to the following relationship

$$\Delta\varphi = \frac{4\pi}{\lambda} \cdot \int (N(s)^{slave} - N(s)^{master}) \cdot ds$$

where

$$N(s) = k_1 \frac{P_d}{T} + k_2 \frac{P_v}{T} + k_3 \frac{P_v}{T^2} + \left(1 - k_4 \frac{TEC}{f^2}\right)$$

where k_1 = 77.689 K hPa^{-1}, k_2 = 71.295 K hPa^{-1}, $k_3 = 3.755\times10^5$ K^2 hPa^{-1}, k_4 = 40.28 m^3 s^{-2}. So, after the modelling and correction of temporal changes of propagation delay due to changes in water vapour distribution, pressure and temperature, and assuming terrain displacements negligible in the short time interval of the revisiting time of six days, the phase of interferograms should contain the signal due to the temporal change of TEC between the acquisition times of slave and master Sentinel-1 images as

$$\Delta\varphi = \frac{4\pi k_4}{\lambda \cdot f^2} \cdot \Delta TEC.$$

SEVENTH, EIGTH AND NINTH DAYS

Data acquired in the first six days of the STSM, i.e. GNSS and Sentinel-1, were referring to large disturbances in the ionosphere. In fact, it has not be possible to find Sentinel-1 images acquired over Serbia, useful to study the TEC variations due the X-ray flares identified in 2017. The importance of relating this study to Serbia is due to the fact that it is needed to model and remove the phase delay due to temporal change in the troposphere and for this it is needed local information (GNSS data and meteorological stations useful to compare with Numerical Weather Prediction data). This part of the work is still on and we are conducting it using the WRF model. However, the experience of using Sentinel-1 images to map temporal changes of TEC due ionosphere disturbances can also be useful to study the effects of X-ray flares on ionosphere using Sentinel-1 data if useful images are found. In the last three days of the STSM we focused on the discussion of how to model the temporal change of TEC during a X-ray flare.

We discussed on the different methodologies to use GNSS and Sentinel-1 data processed in this STSM to model the ionospheric delay of microwave signals (both GNSS in L-band and Sentinel-1 images in C-band) based on matching changes of the observed very-low-frequency (VLF) signal (its amplitude and phase) with corresponding values resulting from simulations of the VLF signal propagation using the long-wave propagation capability (LWPC) numerical model developed by the Naval Ocean Systems Center, San Diego, USA according to the methodology published in a recent joint paper (Nina et al, IEEE Geoscience and Remote Sensing Letters, “GNSS and SAR Signal Delay in Perturbed Ionospheric D-Region During Solar X-Ray Flares”, 2019, doi: 10.1109/LGRS.2019.2941643).

We also discussed on the use of the relationship

$$\Delta TEC = 0.102 + 0.749 \frac{F}{10^{-4}}$$

published in the paper J.Y. Liu, C.H. Lin, Y.I. Chen, Y.C. Lin, T.W. Fang, C.H. Chen, Y.C. Chen, J.J. Hwang, “Solar flare signatures of the ionospheric GPS total electron content”, Journal of Geophysical Research, vol. 11, A05308, 2006, to model the temporal change of TEC using the X-radiation flux F will be measured by GOES15 data

We are now continuing the processing of data and modelling of ionosphere turbulence. We prepared the abstract “Space weather influences on SAR meteorology applications: review of ionospheric models and new mitigation tools for propagation delay due to solar high energy X-radiation” which has been submitted for approval to the special issue “GNSS and InSAR Meteorology”on the Journal Frontiers in Atmospheric Science.

Giovanni Nico

Appendix: Abstract sent to Frontiers in Earth Science, Atmospheric Science

Title: Space weather influences on SAR meteorology applications: review of ionospheric models and new mitigation tools for propagation delay due to solar high energy X-radiation

Authors: Aleksandra Nina, Giovanni Nico, Jelena Radović, Luca Č. Popovic, Pier Francesco Biagi, Andrea Andrisani

In this work we analyse different ionosphere models to model the microwave propagation delay in ionosphere and study the influences of space weather in SAR meteorology applications. This propagation delay depends on the 3D distribution of ionosphere refractivity. First, we give a review of models studying the higher ionosphere, both in quite and perturbed conditions. This part of ionosphere has the larger impact on both SAR and GNSS data. Many models have been developed to study TEC. We review the models, emphasizing their assumptions and capability to provide an accurate 3D distribution of electron density in ionosphere, and its temporal variations. Starting from this knowledge it is possible to model the propagation delay in ionosphere to be mitigated in SAR meteorology applications. However, there are few papers studying the D-region in the lower ionosphere. This region is usually characterized by a smaller contribution to the total propagation delay in ionosphere. However, in case of space weather phenomena such as X-ray flares, the D-region electron density is significantly increasing and can severely affect interferometric SAR data. Here we describe a procedure for improving the modelling of propagation delay in the ionosphere in SAR meteorology applications, during influence of high-energy radiations induced by solar X-ray flares. Namely, this radiation can significantly affect the lower ionosphere and induces an error in the estimation of the propagation delay due to the troposphere needed in SAR meteorology applications. The methodology for improving the modelling of ionosphere propagation delay in SAR meteorology, presented in this work, is based on X-ray flares observations by the GOES satellites. The intensity of X-radiation is used to model the 3D electron density in the D-region and compute the corresponding propagation delay in this ionosphere layer.