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CAN SPACEBORNE SYNTHETIC APERTURE RADAR BE USEFUL FOR THE MAPPING OF IONOSPHERIC DISTURBANCES IN THE ARTIC REGION?

ABSTRACT

In this work we study the potential of C-band SAR images to map ionosphere disturbances in the Arctic region. This region is a unique region for ionosphere studies due to the characteristics of the geomagnetic field. In particular, we focus on the SAR interferometry technique as means to measure the temporal variation of propagation delay in correspondence of ionosphere disturbances. This technique provides maps of propagation delay differences between the acquisition dates of the two coherent SAR images needed to estimate the propagation delay over the study area. The high spatial resolution of C-band SAR images, in the order of 25 meters could contribute to the study of spatial distribution of ionosphere disturbances. Digisondes, VLF/ELF receivers and the EISCAT radars in the available in the Arctic region provide the time of ionosphere disturbances due to the solar activity, monitored by the ACE satellite. This allows to select the SAR images to process to map the ionosphere disturbances. The typical spatial coverage and acquisition times of Sentinel-1 images over the Arctic region are reported. A numerical analysis is carried out to estimate the expected ionosphere propagation delay in Sentinel-1 interferograms and so the potential of SAR interferometry to map the effects of ionosphere disturbances.

KEYWORDS: Synthetic Aperture Radar (SAR), SAR interferometry, Ionosphere, Propagation delay, Total Electron Content (TEC), Arctic

INTRODUCTION

The last two decades have witnessed an astonishing development of Synthetic Aperture Radar (SAR) applications mainly in the C-band thanks to the regular acquisition plans and easy access of the European Space Agency (ESA) missions, Envisat/ASAR from 2002 up to 2012 and Sentinel-1 starting from 2014 and, in the Canadian Space Agency with the Radarsat-2 mission starting from 2007. The availability of a huge amount of C-band SAR images has spurred the use of SAR interferometry (InSAR) as a new space geodesy technique for the mapping of terrain displacements with a high spatial resolution and coverage, and a sub-centimeter precision of displacement measurements. The interferometric processing of time series of SAR images acquired over the same area, using the same acquisition geometry has demonstrated the concept of SAR interferometry as a new tool for the study of tectonics, landslides, subsidences, volcano and the measurements of displacements due to human activity as works in urban areas, water and oil pumping. All these applications pointed out the need to mitigate effects to due propagation in the atmosphere, mainly intended as temporal variations of propagation caused by the changes in the spatial variation of water vapor in troposphere. Recently, is has been recognized as SAR

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interferometry can also become a tool for mapping of the high resolution of water vapor in atmosphere giving rise the development of the so-called SAR meteorology. This recent concept has mainly benefited from the availability of Sentinel-1 images characterized by a mean temporal baseline of six days, depending on the geographical location, a spatial resolution of about 25 meters and an even increased spatial coverage up to the scale of country size. In all above InSAR applications of C-band SAR images, the propagation delay in ionosphere was neglected due to both smaller delay in the C-band with respect to the L-band. However, the larger spatial coverage of Sentinel-1 pointed out the need to correct for ionospheric propagation delay even in C-band [Mateus et al., 2017]. Even if delay can be considered a second order correction in SAR interferograms, it becomes useful when providing precise maps of water vapor in atmosphere. The Total Electrom Content (TEC) maps made available by ionosphere community were used to computed the propagation delays at the acquisition times of the two SAR images used to generate the interferogram.

In any case, Sentinel-1 images were not used so far for studies on ionosphere. The only papers on the detection of ionospheric effects in SAR images were based on the L-band SAR images [Meyer, 2011; Gomba, De Zan, 2017]. In particular, it was found that the propagation delay in atmosphere affects both the interferometric phase and the target position in SAR amplitude images. Furthermore more, specific effect as the Faraday rotation were detected in fully polarimetric SAR images (e.g. see the recent paper [Li et al., 2018] and reference therein). However, current L-band SAR missions do not have a regular acquisition plan as Sentinel-1 and this limits their use for systematic studies on ionosphere.

The aim of this paper is to investigate the potential of Sentinel-1 image as a new tool for the study of ionosphere phenomena, with emphasis on disturbances which lead to significant variations of TEC and an important impact on space geodesy application of both SAR and Global Navigation Satellite Systems (GNSS). The Arctic regions is chosen as study area it is characterized by significant ionosphere disturbances. Furthermore, Sentinel-1 has a very short revisiting time over this area, o a few days, due its polar orbit.

MATERIALS AND METHODS OF RESEARCH

IONOSPHERE PROPERTIES AND DATA OVER THE STUDY AREA

The spatial and temporal structure of ionosphere are primarily induced by the intensity of the solar radiation, electron density altitude distribution and geomagnetic field morphology. The solar radiation is the most important source in ionization processes which are shaping the temporal structure of the ionosphere. Charged particles and electromagnetic radiation are the two main contributions of solar radiation to the properties of ionosphere. Although their influences vary spatially in terms of geographical location and altitude, we can generally speak about daytime and nighttime ionosphere.

This vertical structure of ionosphere depends on the electron density vertical distribution and it depends on the day period. During daytime, the ionosphere is divided in three layers: F, E and D. The electron density is the largest in F-region while it attains a minimal value in the D-region. In the nighttime the lowest layers of ionosphere dissipate their electron density due to decrease of incoming solar radiation and, consequently, have a lower ionization. Significant differences in ionosphere are also observed moving from the equator toward the polar regions. These changes are due to morphology of the geomagnetic field, consequently, the ionosphere can be divided in equatorial, middle-latitude and polar ionosphere.

The knowledge of all these variations is important not only to describe the quiet ionosphere but also to study the influences of different geophysical and astrophysical events and processes on local plasma characteristics which can be quasi-permanent, periodical and sudden in time. For example, the influence of X-radiation on D-region perturbation is more important than on the upper ionosphere[1], while entering and penetration of charged particles depend on the geomagnetic field and their influence is the most important at polar region.

In this paper we focus on the polar ionosphere above the Arctic and near Arctic regions. Their geophysical locations characterized by morphology of the magnetic field which allows more intensive charge particle penetration to the lowest ionospheric altitudes makes very interesting research of the charged particles effect on changes in the physical and chemical characteristics of this area. Bearing in mind the role of the ionosphere in the propagation of electromagnetic waves, this task is also of significant importance for practical applications.

Fig. 1 shows the location of different stations deployed in Arctic and near-Arctic regions for ionosphere observations. In particular, we are interested in TEC measurements.

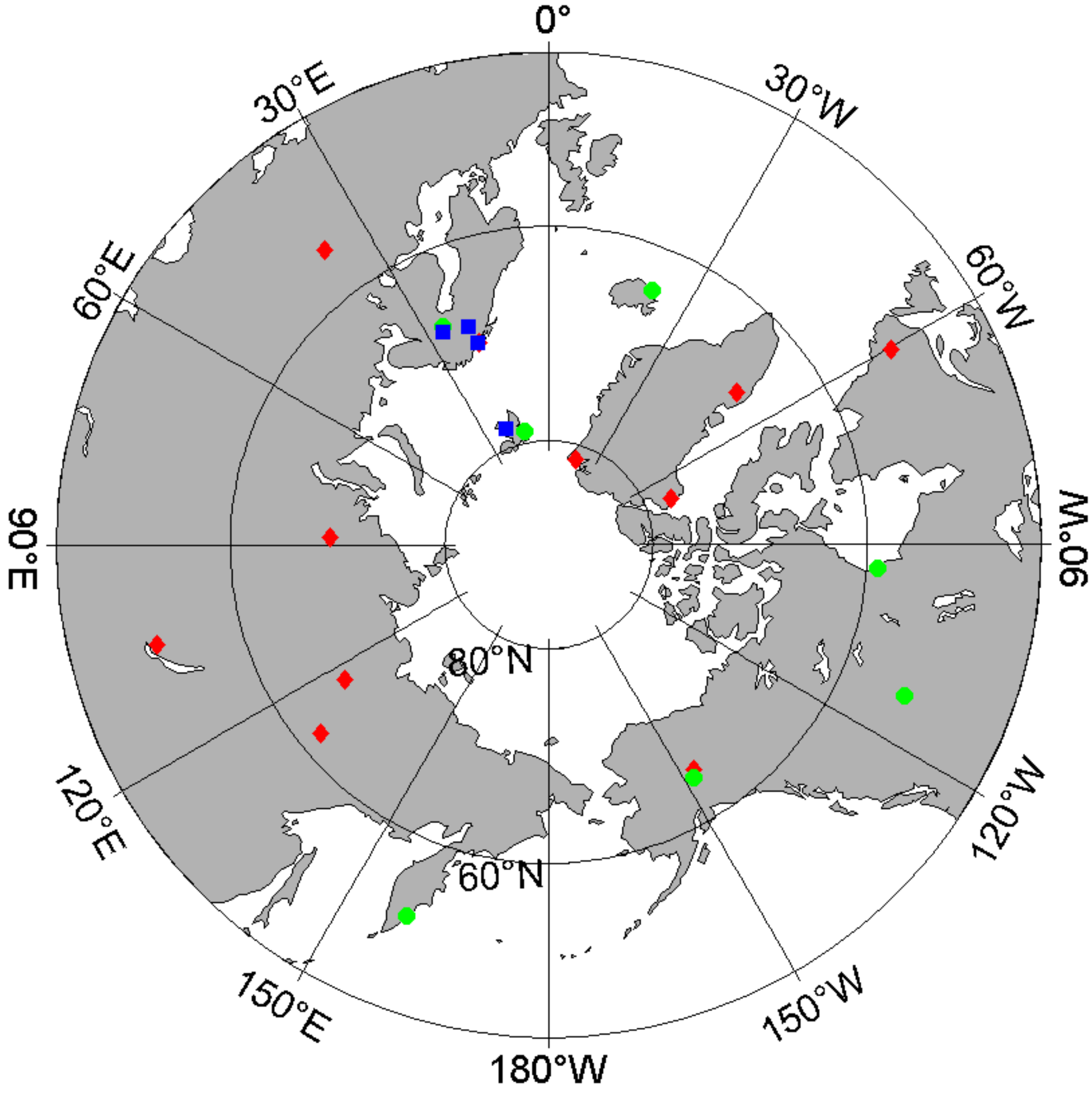


Fig. 1. Location of digisondes stations (red diamonds), EISCAT radar (blue square), VLF/ELF receivers (green circle) over the Arctic region

[1] *Todorović Drakul M., Čadež V.M., Bajčetić J., Blagojević D., Nina A*. Behaviour of electron contentin the ionospheric D-region during solar X-ray flares. Serbian Astronomical Journal, 2016. V. 193. P. 11–18. DOI: 10.2298/SAJ160404006T

In fact, the high temporal sampling of the point-like measurements can help to detect TEC variations induced by the impact of charged particles impact and select the most suitable Sentinel-1 images for the mapping of these effects at a much high spatial resolution.

SAR INTERFEROMETRY: BASICS

Synthetic Aperture Radar (SAR) interferometry relies on the processing of two SAR images of the same scene acquired by two spatially and/or temporally separated antennas. Many spaceborne SAR mission provide useful data for SAR interferometry applications. Usually, the satellite passes over the same area with a revisiting time giving the spatial baseline of the interferometric couple of SAR images, named master and slave, respectively. The distance between the two satellite orbits at the moment of SAR acquisitions is called spatial baseline. Both baselines affect the quality of the interferometric processing. In fact, the SAR interferogram, consisting in the phase image resulting from the processing of an interferometric pair of SAR images, is characterized by the interferometric coherence, depending on the scattering properties of the scene (e.g. vegetated areas are less coherent of urban areas) and temporal and spatial baseline (large baselines reduced the interferometric coherence) [Massonnet, 2018].

For each pair of coherent SAR images, the interferometric phase is computed as follows:

$$\Delta\varphi_{1,2} = \text{atan}\left\{ S_2 \cdot conj(S_1) \right\} \tag{1}$$

where S_1 and S_2 are the two coherent complex-values SAR images acquired at times t_1 and t_2, respectively.

The main application of SAR interferometry has been the measurement of terrain displacements. The Line-of-Sight (LoS) displacement $D_{1,2}$ of a point P in the scene, occurred in the time interval [t_1, t_2] is related to the interferometric phase $\Delta\varphi_{1,2}$ by the relationship:

$$D_{1,2} = \frac{\lambda}{4\pi}\Delta\varphi_{1,2} \tag{2}$$

where λ is the radar wavelength. The precision of displacement measurements depends on the accuracy of phase measurements and it can be a fraction of millimeter, if artifacts due to phase propagation in atmosphere are identified and corrected. However, if we use interferometric SAR images with a temporal baseline of a few days and we can neglect terrain displacements within this time interval, or we can model them and estimate their phase contribution to interferometric phase, the equation (2) provides the temporal change of propagation delay in atmosphere, between the acquisition times t_1 and t_2 [1,2].

RESULTS OF RESEARCH AND DISCUSSION, FINDINGS

In this section we present a few results about estimation of variations in SAR signal delay before and during the time interval when an increase of charged particles entering in the atmosphere is observed on 31st May 2018 as recorded by ACE satellite[3]. According to the TEC time evolutions derived from data recorded by ionosondes located in Thromsо (Norway), Moscow (Russia) and Eielson (Alaska) before and during increasing of charge particles entering in the atmosphere[4] we can see that TEC variations were significant for the first and third stations while

[1] *Mateus P., Nico G., Tomé R., Catalao J., Miranda P.M.A.* Experimental study on the atmospheric delay based on GPS, SAR interferometry, and numerical weather model data. IEEE Transactions on Geoscience and Remote Sensing, 2013. V. 51. No 1. P. 6–11. DOI: 10.1109/TGRS.2012.2200901

[2] *Mateus P., Miranda P.M.A., Nico G., Catalao J., Pinto P., Tomé R.* Assimilating InSAR maps of water vapor to improve heavy rainfall forecasts: a case study with successive storms. Journal of Geophysical Research: Atmospheres, 2018. V. 123. No 7. P. 3341–3355. DOI: 10.1002/2017JD027472

[3] See the URL ftp://sohoftp.nascom.nasa.gov/sdb/goes/ace/daily/20180531_ace_swepam_1m.txt

[4] Digisonde data are available at the URL http://giro.uml.edu/didbase/scaled.php

the Moscow station which was in the considered time period in night time did not detect TEC changes. In our analysis we estimated that TEC increases from about 5 to 20 TECU (it reaches about 37 TECU but in a short time period) above Thromso and from 5 to 9 TECU above Eielson.

Can the current Sentinel-1 acquisitions provide a coverage and temporal sampling to map the ionosphere disturbance locally detected by the ionosondes? Figures 2 and 3 try to answer this question. In particular, figure 2 shows the footprints of Sentinel-1 images over the Arctic region, emphasizing ascending and descending orbits. The corresponding acquisition times, measured with respect a reference image, are reported in figure 3. It is worth noting that mean revisiting time of Sentinel-1 images over Europe is of six days. This figure can increase over other geographical areas. Nevertheless, in correspondence of polar regions, the different orbits cross each other and the revisiting time over those regions is much smaller than six days. In particular, the analysis of figure 3 shows that the ionosphere disturbances over the whole Arctic can be sampled in time frequently during one day.

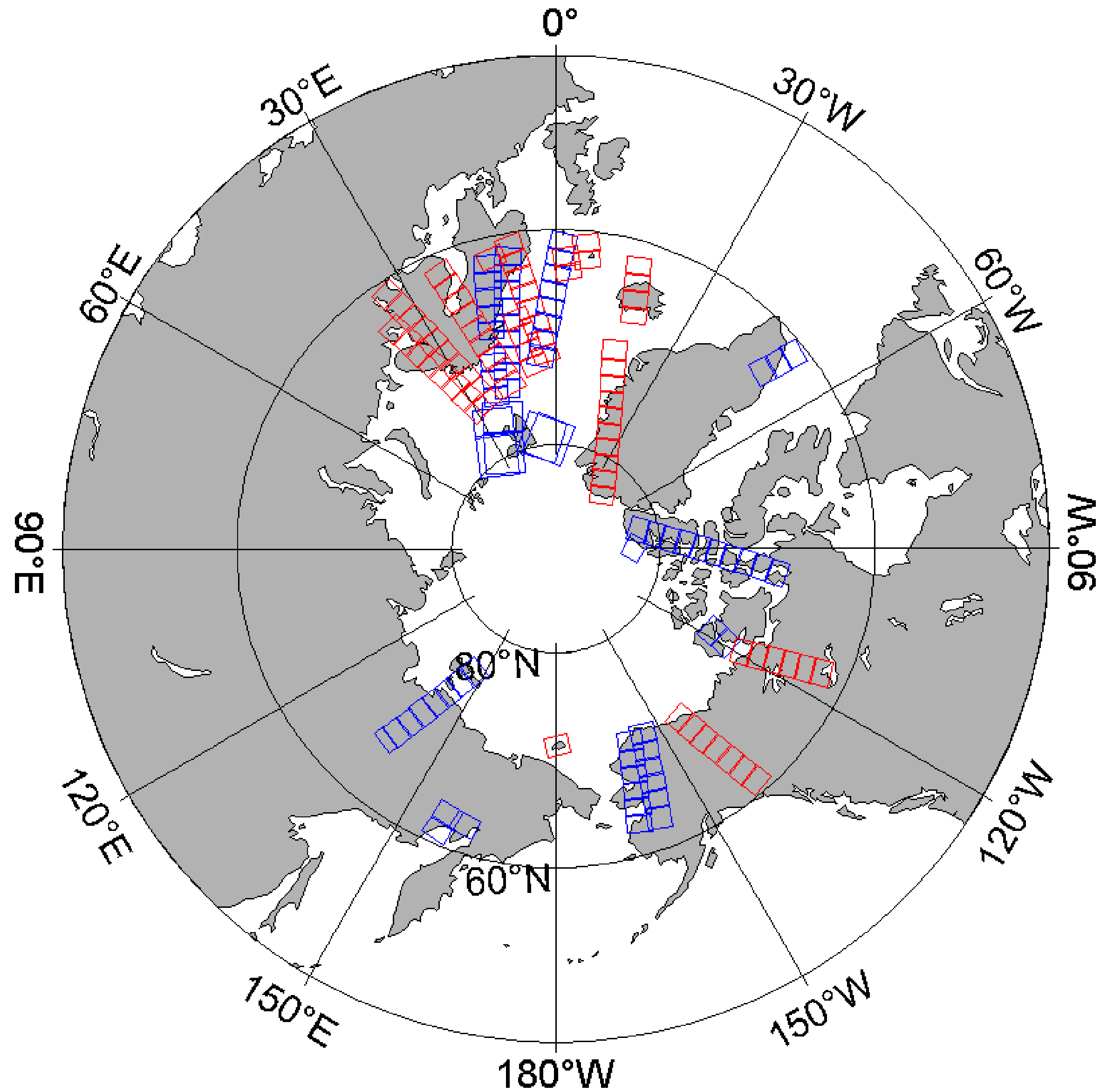
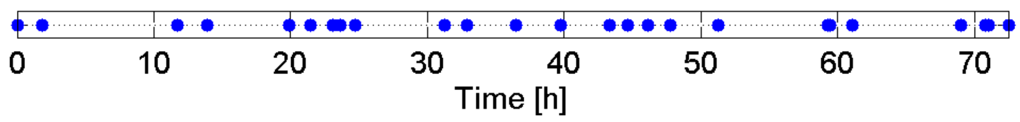


Fig. 2. Footprint of Sentinel-1 images over the Arctic region.
Ascending and descending passages are plot in red and blue, respectively



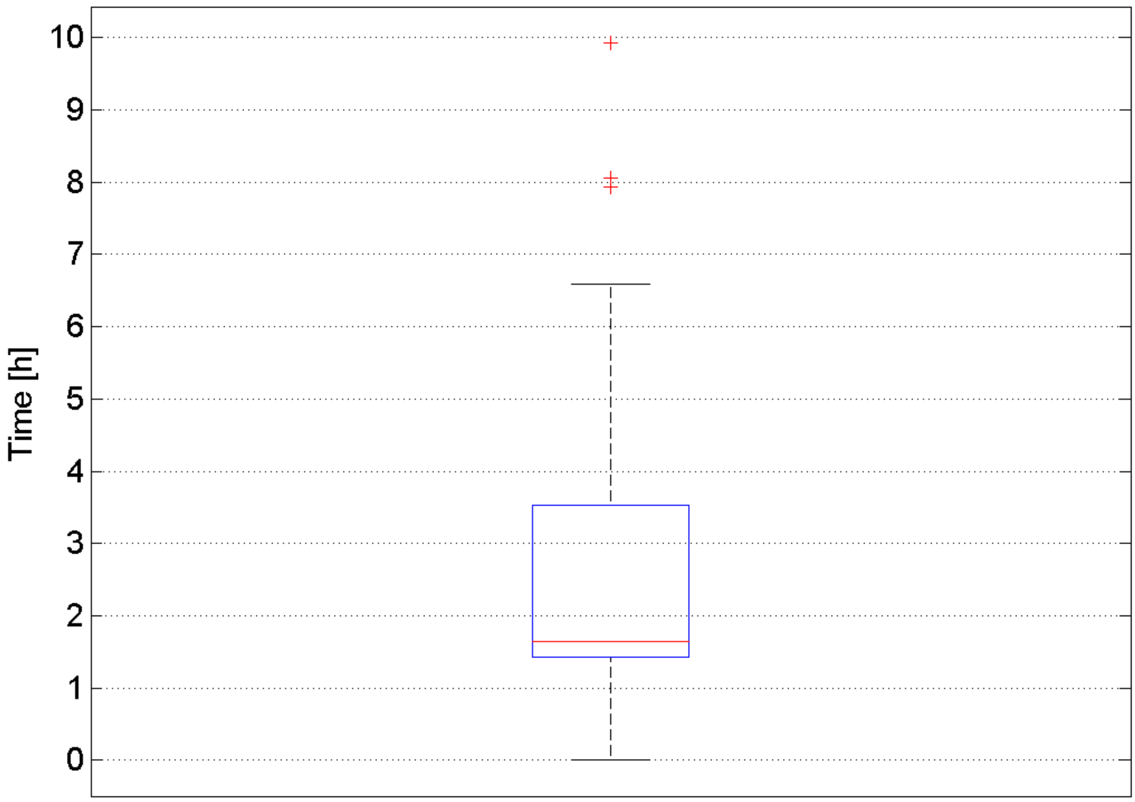


Fig. 3. Acquisition times of Sentinel-1 images over the Arctic region during a 4-day time interval:
(top) Relative acquisition times, in hours, with respect to the first Sentinel-1 acquistion;
(bottom) Boxplot of time intervals, in hours, between the different acquisitions

A second question concerns the Sentinel-1 interferograms to detect the typical TEC variations observed during an ionosphere disturbance and so to provide high resolution maps of them to complement the spatially coarse information provided traditional techniques currently used. Figure 4 displays the propagation delay it would be measured in the C-band at the frequency of Sentinel-1 SAR in the case of TEC measured at the stations of Thromsо and Eielson before and during ionosphere disturbances on 31st May 2018. The propagation delay is computed as a function of the SAR look angles. The difference between the propagation delay before and during the ionosphere disturbance gives the signal that it should be measured in Sentinel-1 interferograms in order to detected and map the ionosphere disturbance. It can be observed that the disturbances over the Thromsо and Eielson stations would give a difference in the propagation delay larger than 270 mm and 72 mm, respectively. In the case of Thromsо station, the change in the propagation delay would give rise up to about five fringes in a Sentinel-1 interferogram able to catch the maximum of the ionosphere disturbance. In the case of the Eielson station, the maximum number of fringes in a Sentinel-1 interferogram which map the peak of the disturbance would be of about one fringe and a half. In both cases, the disturbance would be detectable in a Sentinel-1 interferogram. However, it is worth noting that the acquisition times of the master and slave images used to produce the interferogram are of key point as it is required that one of the two images be acquired during the maximum of ionosphere disturbance.

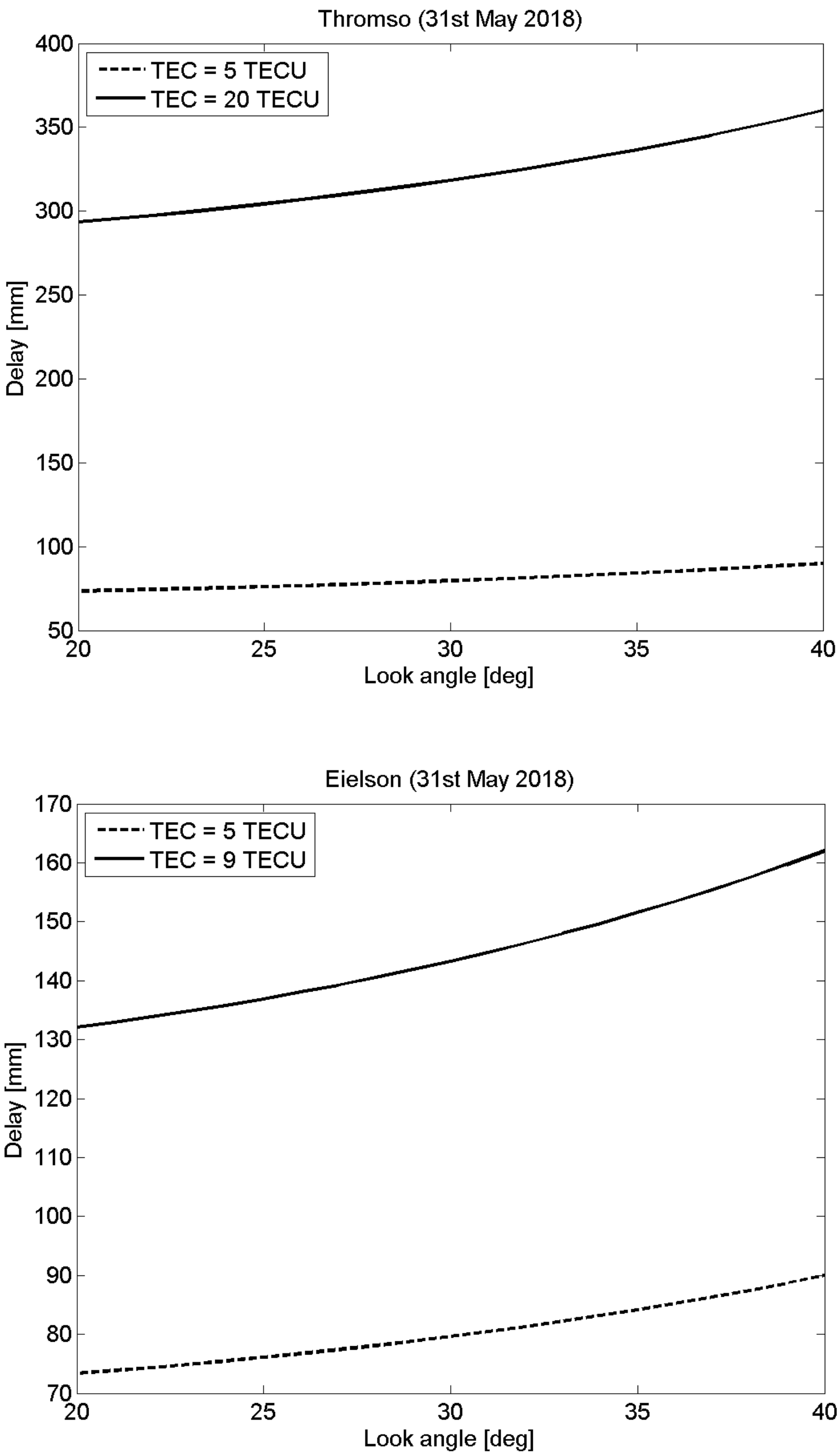


Fig. 4. Temporal change of propagation delay before and during the ionosphere disturbance observed on 31st May 2018 over the Arctic regions:
(top) Thromso (Norway);
(bottom) Eielson (Alaska)

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