

TECHNICAL NOTE

Forecasting Space Weather in the Arctic Region (FORSWAR)

DL18: Executive Summary Report

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1 INTRODUCTION

This document has been prepared in the frame of the activity Forecasting Space Weather in the Arctic Region (FORSWAR) as part of the ESA ITT “Forecasting Space Weather Impacts on Navigation Systems in the Arctic (Greenland Area)” Expro+, Activity No. 1000026374 (ESA-star system). The ESA Contract No. is 4000131555/20/NL/AS. This document has been prepared by the University of Oslo (UiO), Universitat Politècnica de Catalunya (UPC), German Aerospace Center (DLR), University of Warmia and Mazury in Olsztyn (UWM).

This document entitled Executive Summary Report (ESR), according to the Statement of Work (SOW), shall concisely summarise the findings of the Contract. It shall be suitable for non-experts in the field and should also be appropriate for publication. For this reason, it shall not exceed five (5) pages of text and ten (10) pages in total (one thousand five hundred (1500) to three thousand (3000) words).

2 EXECUTIVE SUMMARY REPORT

This project has been conducted within the frame of the activity Forecasting Space Weather in the Arctic Region (FORSWAR) as part of the ESA ITT “Forecasting Space Weather Impacts on Navigation Systems in the Arctic (Greenland Area)” Expro+, Activity No. 1000026374 (ESA-star system).

Space Weather refers to solar processes as well as varying conditions in the solar wind, the Earth's magnetosphere, ionosphere and thermosphere that may affect space- and ground-based technological systems in their performance and reliability. The monitoring and forecasting of potential impacts on technological systems is significant, since space weather effects are observed in the degradation of spacecraft communications, performance, reliability, and lifetime. In addition, it leads to enhanced risks to human health on manned space missions. Predictions of the state of the ionosphere in the Arctic region provide significant contributions to avoid safety-critical situations (e.g. aviation, maritime), high costs of unsuccessful operations and safety of operations (e.g. surveys of offshore resources or precise positioning), and tourist industry.

The Arctic region is due to the open magnetic field lines especially exposed to Space Weather and the solar wind energy couples into the Earth system causing unique physical processes like the occurrence of aurora indicating energetic particle precipitation events. Though the aurora is a fantastic light phenomenon in the polar region, it gives rise to significant detrimental impact on Global Navigation Satellite System (GNSS) applications. Next to auroral particle precipitation, geomagnetic field perturbations often associated to ionospheric currents and electric fields are important components of space weather in this region. At high latitudes, islands of high-density plasma called polar cap patches are frequently observed. Strong density gradients near the edges of polar patches can disrupt the communication and navigation systems in the Arctic region. During very severe space weather events, when the solar wind compresses the Earth magnetic field, the physical processes which are normally restricted to the Polar Regions can dislocate towards lower latitudes. Such variations in electron density can greatly affect GNSS users who would benefit from an accurate prediction.

To address and potentially mitigate the adverse space weather effects on navigation systems, it is necessary to develop advanced space weather forecasting models that can predict the space weather conditions in both short (hours) and long-time domains (days or months). In the FORSWAR project, we have developed a new advanced space weather forecasting model for the satellite-based Positioning, Navigation and Timing (PNT) users in the Arctic region with a focus in the Greenland area. We have explored new techniques for the space weather forecasting and demonstrated their advantage over existing models. The final space weather product is a warning product that gives a readable map over the Arctic indicating weak, moderate and severe disturbances for the PNT applications for general users.

To achieve this goal, the project is divided into several main work packages. As a preparation phase of the project, we first collected GNSS data from Greenland Network of GNSS Stations (GNET) and other relevant datasets from International GNSS Service (IGS). In addition, we have made a comprehensive review of historical space weather threats and existing space weather services for PNT systems in the Arctic region and the Greenland area in particular. We have reviewed historical space weather threats in the Arctic area during the last two solar maxima (1998-2018). The space weather effects on navigation systems are particular significant during severe solar and geomagnetic storms. The space weather impacts on the

PNT application during the Halloween storms in 2003 and St. Patrick Day storm in 2015 have been extensively reviewed. Furthermore, we have analysed the GNSS data from selected Greenland stations covering different latitudes to demonstrate the longest possible time-extent of GNSS dataset (from as early as 1999). To reflect the variability and small-scale fluctuations of the ionosphere we derive rate of change of TEC index (ROTI) from the ground-based GNSS receivers. With the historical data over more than two solar cycles, we have developed a climatological model that is able to predict the ROTI climatology in the Greenland area. With observation data and proper prediction of the solar activity, geomagnetic disturbances and solar wind condition, the model has been run in 1965-2035, i.e., across 6 solar cycles. Due to the simplicity, the climatological model is able to make the long-term forecast as long as the solar wind data and solar radiation proxy are given.

On the other hand, we have also made a detailed review on existing real time space weather forecast and warning products. We have critically reviewed and assessed the existing real time space weather forecast/warning services and identified the most appropriate requirements for the advanced space weather forecast by considering both the customer's needs and the practicality of the product. This part of work is summarized in TN-1.2 Product Requirement Specification for Advanced Space Weather forecast for PNT in the Arctic region. The document furthermore contains a detailed view on existing services in the ESA SSA programme for GNSS users and contains the user needs gathered from existing roadmaps and past user surveys. The document is a major guideline during the development and implementation of the forecast model as it describes the product requirements and user needs. Finally, as a preparation phase of the development and validation plan, we have also defined use cases definition and validation methodology that are used in later phases of this project. This is basically to validate the space weather product by using diriment positioning techniques and in-situ data from Swarm satellites.

As the main activity of this project, we have explored three new methods for the development of the advanced space weather forecast/warning products. This part of work is largely based on data analysis and model development, and it is the central part of this project that lays foundations for the new forecasting service in the Arctic area. As a start point, we construct the ROTI maps over the Arctic region using all available GNSS data above 50° geographic latitude. To do this, the ROTI data are divided into arrays of 18×72, i.e., 45° to 90° in latitude and -180° to 180° in longitude, with a resolution of 2.5°×5°. The ROTI maps form the start point for exploring new space weather methods. The ROTI maps are smoothed using Gaussian filter to exclude extreme values. This is because the long-tail distribution of ROTI can severely affect the performance of machine learning algorithms. In total, three methods have been explored in detail, i.e., the method based on the gradient profiles of the ionosphere, Dynamic Time Warping (DTW), and Optical Flow Algorithm. At the end, the optical flow algorithm is selected for the implementation of the new space weather model (Monte-Moreno et al., 2021), and it is able to predict the space weather condition in terms of ROTI in the forecast horizons from 15 minutes to 3 hours.

The approach we follow to solve the problem is based on modelling the time variation of the ROTI distribution as if it was a pseudo-conservative flow in time scale of less than 3 hours (McGranaghan et al., 2018). This has the advantage that it does not require the creation of a historical database covering different space weather conditions. It is also not hindered by the fact that the ROTI has a long tail probability distribution in amplitude. The latter severely affects the performance of machine learning algorithms, which are based on averaging differences. Another advantage is that ROTI measurements generate maps that span the polar region and we are not restricted to measurements at a few stations. A further significant

advantage is that the introduction of changes in prediction horizons is immediate and does not require offline re-training, as in the case of machine learning systems. Finally, in the case of classification, i.e. detecting presence or absence of a level of ROTI greater than a threshold, the system does not need to resample the database to balance class proportions.

The final method that is used for the implementation is the Optical Flow forecast method. This method implements anisotropic continuous deformation, solving the problems related to the extremes of the map, and can deal with any number of independent ROTI regions. Note that the optical flow method does not include external data such as the solar activity, solar wind condition and geomagnetic indices. On one hand, the fact that no external data are used contributes to the simplicity and robustness of the method. This is very important for its potential 24/7 real-time implementation in the future. On the other hand, this issue can also introduce certain limitations in the final space weather model, i.e., lacking of information of external drivers may limit the performance during rapid progression in geomagnetic storms.

This space weather model has also been verified and validated using PNT applications and in-situ data from Swarm satellites. Since the GNSS positioning is especially prone to the state of the ionosphere, it can be successfully used as a validator of provided forecasting/warning products. We have defined the validation plan of the forecast/warning products over Greenland by means of GNSS positioning. We characterized the chosen mathematical models of positioning, presented the details of the processing strategy and described the experiment design. The validation plan calls for the usage, as the dataset, of GNSS observations collected by selected permanent GNSS stations of GNET during the adopted ionospheric disturbance periods, namely (#1) March 17, 2015 - St. Patrick Day storm in 2015; (#2) June 22 storm in 2015; and (#3) August 25-26 storm in 2018. Moreover, the observations collected during adjacent days of lower ionospheric activity were also processed to serve as benchmarks.

Three positioning models, which offer different accuracy of the solution, are used in the GNSS positioning validation, namely single point positioning (SPP) based on single frequency pseudoranges (SF SPP), as well as dual-frequency ionospheric-free linear combination (DF-IF-SPP); single-frequency ionospheric-free precise point positioning based on GRAPHIC linear combination of phase and code observations (SF-IF PPP); and a relative kinematic mode of positioning – RTK. The positioning is performed in kinematic (SPP, RTK) and static mode of positioning (PPP).

The validation plan assumes examination of the correlation between the existence of the ionospheric disturbances manifested by forecast ROTI maps of different forecast horizons and the performance of GNSS positioning in terms of the availability and accuracy of the solution.

We found a high correlation between the presence of the ionospheric disturbances expressed in the forecasted ROTIs and the deterioration of RTK positioning, in specific the float solution. We showed a significant deterioration of the accuracy of the float RTK positioning during the ionospheric disturbed periods that correlate with the forecasted ROTIs. Considering an accurate a priori position provided by the float RTK solution as the prerequisite of the successful ambiguity fixing, the aforementioned worsening in the ambiguity resolution domain is fully justified. We also showed a minor, but noticeable, impact of the ionospheric disturbances on the fixed solution accuracy of RTK positioning providing that the ambiguities were correctly resolved.

So far, the real-time GNSS data in Greenland is not available. We therefore implement the space weather product using post-processed (instead of real-time) data. Note that with extra resources, near real-time observations from 10-18 GNET stations can be available through Internet or Iridium satellites. However, this option will be left for the future. During the last phase of this project, we “operate” the space weather model for two months, i.e., September and October 2020. The operation period is defined as the time when the German research vessel Polarstern was in the Arctic. An overview of the space weather forecasts during the two months was reported. As the general space weather condition was relative quiet as a result of the present low solar activity, we further present an event during a recent geomagnetic storm during November 3-5, 2021. The storm event reveals that the space weather model cannot well predict the prompt increase of ROTI variations at the beginning of the magnetic storm due to a lack of information from external drivers. In the future, the incorporation of the solar wind data may mitigate this shortcoming.

We also consider the realistic issues during the real-time operation of such a space weather product. In the case of missing data, the predictions at certain area may not be usable. We have investigated this issue by comparing the predictions with 0, 5 and 10 stations from Greenland. As expected, if no GNSS data is available from Greenland, the forecasted ROTI is not useful at all. When no Greenland data is used, the predictions in Greenland area is almost 0. This is due to the fact that the space weather algorithm assumes the bins of missing data as 0, i.e., no activity. The predictions are still incorrect when the number of stations is increased to 5. When the number of Greenland stations is increased to 10, the forecasted ROTI is acceptable. We therefore conclude that the minimum number of the Greenland stations should be around 10. Fewer than 10 stations cannot give adequate space weather forecast. The space weather model show great capability in the predictions of Arctic ionospheric disturbances. However, there is still some limitation and future improvement is needed.

Finally, we have drafted the scientific roadmap for future development of the space weather product in the Arctic area for the future scientific and operational activities. We have related the current project within the ESA SWE network. The possibility of future operation in relation to the Expert Service Center Ionospheric Weather (I-ESC) is also discussed.

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