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The Concept of the TRANSMIT Prototype –Network Based Service for Mitigation of Ionospheric Threats to GNSS

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1. Introduction

Global Navigation Satellite Systems (GNSS) are a crucial component in countless modern systems, e.g. in telecommunication, navigation, remote sensing and precision timing. The main threat to the reliable and safe operation of GNSS is the variable propagation conditions encountered by GNSS signals as they pass through the Earth's upper atmosphere (the ionosphere).

The ionospheric plasma can be perturbed by severe space weather conditions due to varying solar and geomagnetic activities. These perturbations come at a wide range of spatial and temporal scales as observed by ground based and space-borne instruments. The perturbations lead to formation of irregularities and disturbances in the ionosphere which can strongly affect the performance of GNSS positioning, by degrading its accuracy, reliability and availability. The scintillation phenomenon characterized by sudden signal fluctuations, for example, may cause GNSS operational outages.

Therefore it is important to assess the threat that space weather can pose to GNSS as well as estimate the strongest possible influence of the ionosphere. Enhanced research activities in this field are desired for the mitigation of the ionospheric impact on GNSS.

The European Commission FP7 funded project Training Research and Applications Network to Support the Mitigation of Ionospheric Threats (TRANSMIT) focuses on bringing together young researchers to undertake the aforementioned challenges for ionospheric impacts on GNSS. The research sub-projects under TRANSMIT aim to provide awareness of current ionospheric threats and improved solutions for the mitigation of ionospheric impacts for users of GNSS and related services and applications.

To highlight the research results of the TRANSMIT project, a prototype of a service is being designed and implemented for access via the internet. The TRANSMIT prototype can be considered as a milestone for the establishment of a Pan-European network for Ionospheric Perturbation Detection and Monitoring (IPDM) in the upcoming years (Jakowski et al., 2008).

In this paper we present an overview of the prototype service and the integration of the research results from TRANSMIT's sub-projects. The concept of data network over the project's partner institutions will be illustrated for optimal operation of the final product.

2. The TRANSMIT prototype

The TRANSMIT prototype is a web-based demonstrator and consists of three processors (called TRANSMIT processors) addressing six applications. The processors have been developed by the TRANSMIT research fellows exploiting the varied expertise in the project's partner institutions. TRANSMIT processors are designed to be able to exchange their outcomes and use them as inputs to other related applications via the prototype network. The design of data flow in the prototype system is characterized as a cross-institutional network approach. The main concept of the prototype network is to clearly divide the functions of the partner institutions. The user portal and demonstration, data archive and processor applications are hosted by different institutions distributed over Europe. The data flow design in the TRANSMIT prototype service is shown in Figure 1. The demonstration portal, denoted as institution C in the middle of the figure, receives queries sent by the users. The user queries can be parameter input or selection of particular ionospheric event that will be used in the processor applications.

Once the users define parameters and store them in the prototype portal, the prototype data transfer is triggered by requesting processing on the selected processor. The transfer of the parameters is forwarded directly to the processor hosting institutes denoted as B. The processor parses the parameters and determines whether it computes locally or requests the necessary data from the data archive hosting institute A. The processing time until the delivery of results of the applications varies among the processors. The variation of computation time will be estimated from less than one minute to a few hours. When a user selects a quick processing application, the results can be displayed on the prototype portal directly after the processing. Other processors with longer processing time require post-sending service. In this case the results will be accessible, for example, by implementing an email notification function.

Figure 1 also implies an advantage of this data transfer design for future application and project. The element blocks that form the network system for database and applications (A and B) can be renewable and replaceable. The new data archive, new processor hosting institutes or redesigned output from the existing processor will be easily integrated to be a part of the prototype system. For the TRANSMIT project, this flexibility would provide the young researchers opportunity to present their most recent result to the scientific and industrial community related to GNSS services. This functionality will be a key component in the

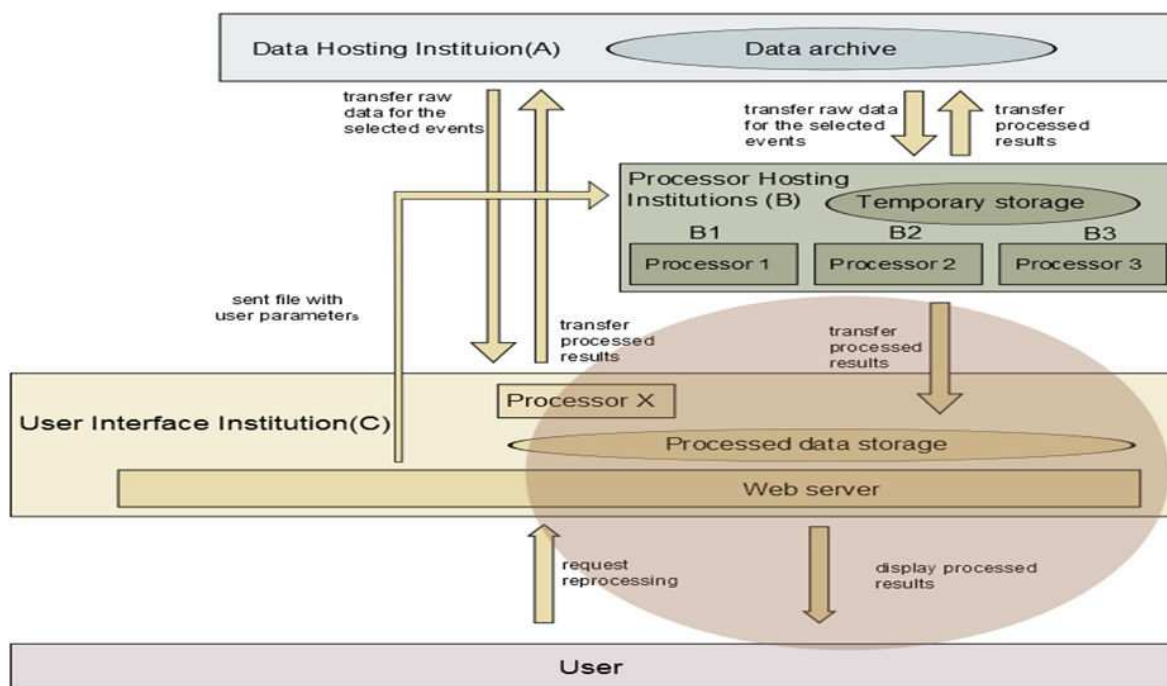


Figure 1. Schematic diagram of TRANSMIT prototype network and the modelled data flow

fundamental data management design for professional services involving multiple research organization such as the IPDM network.

3. TRANSMIT prototype processors

3.1. Processor 1: Scintillation index prediction by a Spline model

Small scale irregularities in the ionospheric plasma may cause fluctuations of the signal strength of radio waves e.g., GNSS signals. The S4 Index is a measure to describe the amount of amplitude variation in the received GNSS signals. This index is calculated by the standard deviation of the signal power received on the ground normalized to the average signal power. The S4 index is considered to reflect on the influence of radio wave scattering by electrons on the received signals. Therefore it is important to predict event of scintillation in terms of electron density in the Ionosphere. There have been numerous efforts made to model scintillation mechanisms, including measurement based statistical method and theoretical model using phase screening approach (Rino, 1979). The first TRANSMIT processor aims at developing an S4 index (and TEC value) prediction model over the European high to middle latitude regions. The advantage of this modelling is to combine the ground based measurements with in-situ (directly observed) plasma parameters by spacecraft orbiting over the concerned region. In this version of the model, the Dynamic Explorer 2 (DE2) satellite is selected as in-situ reference. The DE2 data provides local information of plasma parameters in the ionosphere including electron density and its fluctuation levels.

The developed model will be expressed with an analytical cubic B-Spline function that is derived from time, position, season and solar activity levels (Kp and solar flux value F10.7) as input parameters. The contribution from satellite measurements comes through a phase screening model to calculate S4. A correction method in propagation geometry is introduced for these regions (Priyadarshi & Wernik, 2013). Combining these inputs of ionospheric plasma parameters, the spline model gives a map of the predicted S4 values in geographical coordinates. This model will be compared to the observed S4 values from the receivers from arctic and middle latitudes. The measurement of scintillation is provided by stations from Spitsbergen, northern Norway, to Warsaw in Poland. The results will be visualized by 2D color-coded mapping of S4 or turbulence strength parameters. An example under a quiet geomagnetic condition is shown in Figure 2. The horizontal and vertical axes for the plot have been chosen to be magnetic local time and invariant latitude of the spacecraft. This comparison of the model and observation will give a convincing conclusion of modelling the scintillation over the European region. An advantage of using this model is that it may predict scintillation values which has good match with corresponding local plasma density even in the area that is not covered by the spacecraft. Thus the TRANSMIT processor 1 provides users a trustable tool to visualize scintillation estimate from the concerned solar activity level and geomagnetic conditions.

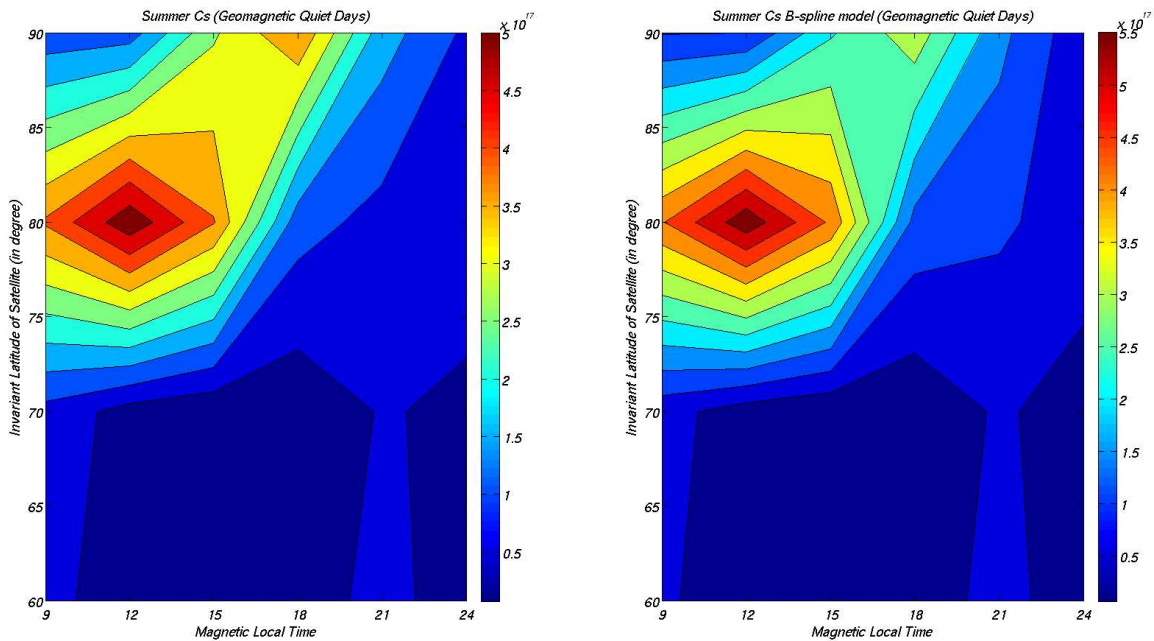


Figure 2. Example output from processor 1. Observation (left) and B spline model (right) result for turbulence strength parameters in quiet condition.

3.2. Processor 2: Improved tracking architecture and positioning error mitigation

As described in section 1, the radio signals from GNSS satellite can experience unexpected fluctuations in amplitude and phase when traveling through ionospheric irregularities. These

unfavourable conditions may lead to errors in positioning application services. This can be a critical issue especially in absolute GNSS positioning solutions such as Precise Point Positioning (PPP), where a high level of accuracy is expected from the estimated coordinates. While the first TRANSMIT processor aims to model the S4 scintillation index from observed plasma parameters, the second processor investigates and mitigates the effects of ionospheric disturbances at receiver and positioning level. The focus is on the following research topics: i) investigate the effect of mitigation techniques on the accuracy of positioning applications. ii) design a robust receiver architecture that will be able to cope with different scintillation and radio frequency interference scenarios..

The effect of the application of the mitigation technique in the positioning accuracy of a GNSS receiver is shown in Figure 3. The variation in the receiver position accuracy computed with an improved stochastic model based mitigation technique is plotted during a scintillation event day. Here the three components of the positioning error in north, east and height are coloured in blue, green and red respectively. A couple of scintillation events have been observed on this day. The performance of the mitigation implementation is proven to be able to reduce the positioning error from the ground truth in comparison with the conventional results, i.e. when no mitigation technique is applied. The convergence time of the positioning error during the scintillation event is improved by this mitigation technique. This would be particularly evident for the height component when compared to non-mitigated results.

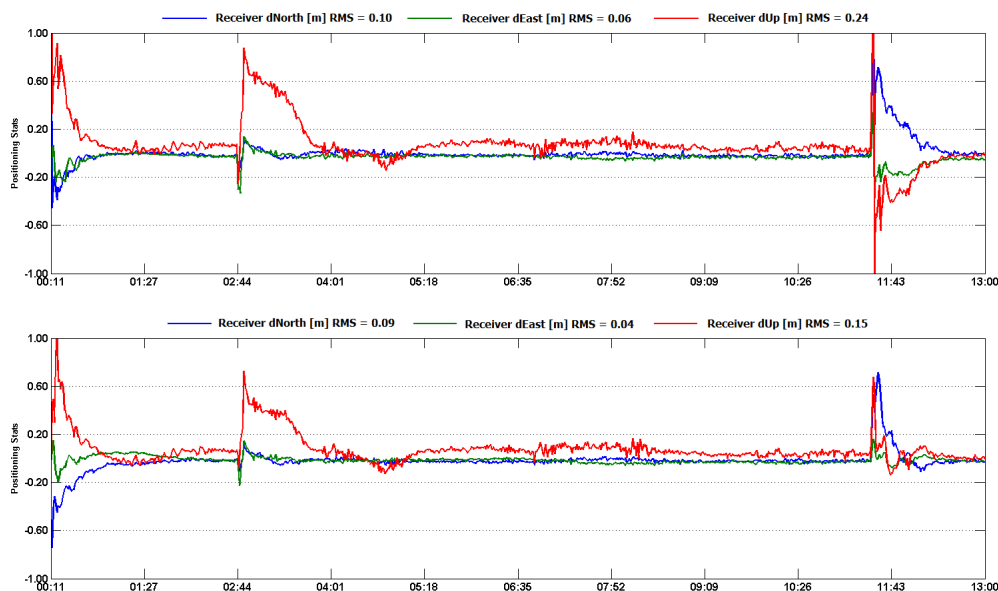


Figure 3. (top) The variation of PPP positioning error computed by TRANSMIT processor 2 without mitigation technique. (bottom) The same as the top but the mitigation technique is applied.

Processor 2 also deals with the design and implementation of a robust GNSS tracking architecture under different scintillation and radio frequency interference scenarios. It will output the performance of the receiver tracking scheme as well as characterization of the scintillation level according to the user's scenario specification. The designed scheme of the robust receiver

features an adaptive Kalman filter based Phase Locked Loop (PLL) for GPS and Galileo signals. The software receiver implemented with this scheme is able to evaluate scintillation levels and use them to adapt the PLL loop filter. The parameters for scintillation detection are derived from the carrier phase spectrum with a dedicated algorithm. The algorithm has been examined by using real data from the receivers set in middle latitude regions. In simulation, the performance of the proposed architecture can be tested with different scenarios: scintillation and a combination of scintillation and various levels of other types of interference. Results of the comparison between our tracking scheme and a traditional fixed bandwidth PLL will be demonstrated for both the GPS L1 and Galileo E1 signals. This comparative performance study is made in terms of the following output parameters: C/N0, phase lock indicator and phase jitter. The algorithm implemented in the software receiver has been validated using the Septentrio PolaRxS scintillation monitor receiver as benchmark.

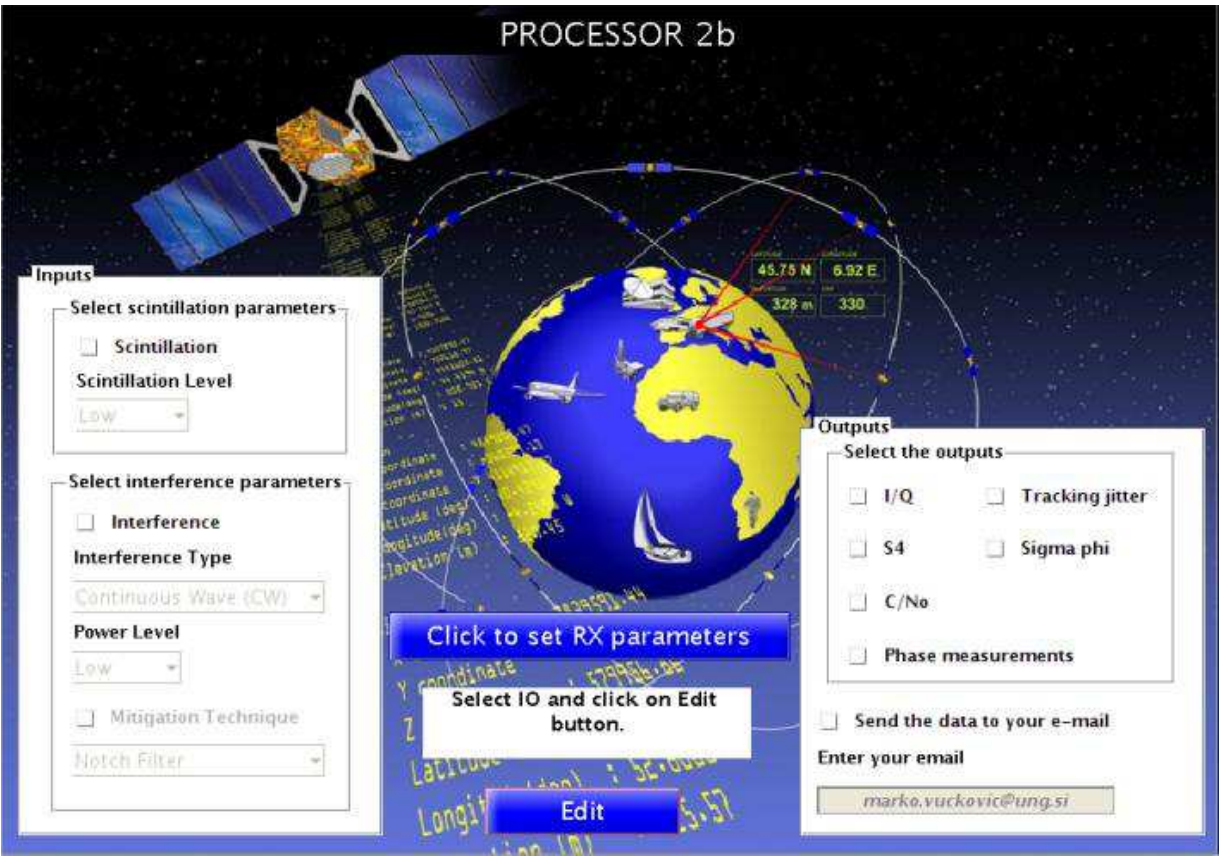


Figure 4. A showcase interface for input and output parameters selection of TRANSMIT Processor 2 for robust receiver architecture.

On the graphical interface of TRANSMIT processor 2, the user can determine their specific scenarios, which will be used to affect the receiver performance. Figure 4 shows an example interface for showcasing the results. Once the scenario is defined, the processor will provide the related outputs in Matlab format, defining the performance of the receiver tracking scheme and characterizing the scintillation level. The PLL application is designed to provide pseudo-

range and phase measurements. These improved pseudo-range and phase measurements will be used as input in the PPP application.

3.3. Processor 3: Ionospheric models and applications

Prediction of potential scintillation event and other threats from our space environment has a crucial role for GNSS users in practical applications. Therefore modelling the ionosphere is an important approach for mitigation of ionospheric threats. The purpose of the third TRANSMIT processor is to provide a new insight on existing ionospheric models. The starting point of this approach is to develop a new TEC prediction model with a data assimilation technique. Next, we make a comparative study of some widely used models, including our developed model, with a measurement database of global network of GNSS stations. Finally, as an application of the modeling approach, this processor demonstrates the error caused by the assumption residing in a common modeling method in Radio Occultation remote sensing for ionospheric research. The three applications forming the processor are designed to exchange outputs and inputs (See element B in the Figure 1).

The TEC model developed in TRANSMIT processor 3 employs computerized ionospheric tomography (CIT) and integrated Slant TEC measurements to estimate ionospheric electron density (Mitchell & Spencer, 2003). The main additions to the work by previous authors are a regularization technique using wavelet and physics based models. This approach will solve the major undermined problems in ionospheric reconstruction that lack of data is the source of instability in numerical results. It is expected that this method can improve the imaging quality of the tomography as well as enabling short-term ionospheric forecasting

The second output of TRANSMIT processor 3 is a world map of the most suitable ionospheric model that fits observational data. To make a reasonable observation-based recommendation among the selected models, we use the CODE (Center for Orbit Determination in Europe) as the reference database. From this international GNSS service database, TRANSMIT processor 3 takes electron density data input from more than 200 stations (Hugentobler et. al., 2008). For the prototype service, we have selected the following four ionospheric models: Klobuchar model (Klobuchar, 1987), International Reference Ionosphere 2012 (IRI2012, <http://iri.gsfc.nasa.gov>), NeQuick2 (Nava et. al., 2008) and Neustrelitz TEC Model (NTCM, Jakowski et. al., 2010). The result of the comparison will be displayed in the form of global maps indicating the best fit model for a given user input of month of year, hour of day and observed solar radio flux (SF). At the current stage of development, computation of data from year 2010 to 2012 is ready to use for output.

Ionospheric models can be used as a reference to create electron density maps for Radio Occultation (RO) remote sensing. The observational “real” and modeled ionosphere often show asymmetrical configuration of plasmas. For the standard inversion technique for RO, however, it is often assumed that the distribution of electrons is spherically symmetric in the ionosphere, which can be an effective and trustable assumption when the horizontal gradient of electron density is not significant. Such a condition can be satisfied typically in low solar activity conditions and a non-disturbed ionosphere. This assumption, however, may cause an untruthful retrieval of electron density when the spatial variation of plasma concentration is

not negligible (Shaikh, et. al., 2014). In this case, the ionosphere is not spherical and should be treated as an asymmetrical distribution of plasma. The error that can be caused by this assumption will be demonstrated as the third output of TRANSMIT processor 3. Figure 5 illustrates the process for this application. The user of the processor can select specific geographical locations (star symbols) in the global map to view a plot showing expected electron density retrieval from the used models. The computed errors caused by the symmetry assumption are displayed against the aforementioned background models.

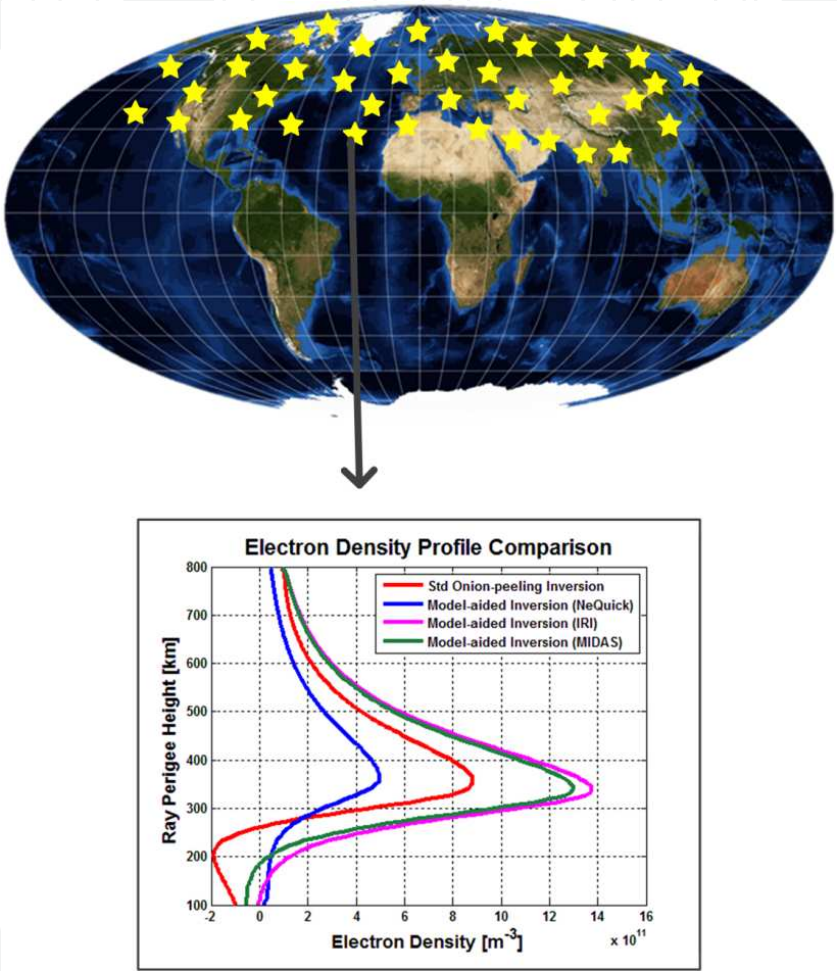


Figure 5. The procedure of location selection (star symbol) and electron density retrieval in the Processor 3 output.

4. Conclusions and future work

We presented the concept of the TRANSMIT prototype network and its application output from the processors for mitigation of ionospheric effects on GNSS. The processors in the prototype service will provide users awareness of current threats from the ionosphere. The data flow in the proposed cross institutional network design gives the TRASNMIT prototype simplicity and flexibility to present research result to the users. TRANSMIT prototype outputs

are diverse and involve different scientific and engineering disciplines. The design of the final product should include an optimal interface for users with various interests related to GNSS based services. The processing time and the delivery method will need to be carefully estimated for each processor application result. A post-sending service such as email notification, for example, must be considered for time consuming processing applications. Establishment of data transfer within multiple institutions needs to be done under a coordinated and integrated scheme. When these challenges are overcome, the prototype service can be regarded as a milestone to evaluate the proposed IPDM network model in the real world. The TRANSMIT prototype has also other types of challenges as it has a cross disciplinary nature. The original purpose of the project is expected to be best achieved when scientists and engineers involved work together beyond their ordinary disciplines.

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