SWIPPA - Space Weather Impact on Precise Positioning Applications of GNSS

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ABSTRACT

SWIPPA (Space Weather Impact on Precise Positioning Applications of GNSS) is a project, initiated by the German Aerospace Centre (DLR), aiming at establishing a specific Space Weather (SW) service for improving current Global Navigation Satellite System (GNSS) applications. This project is considered a substantial part of the preparations for future European Space Weather Programme and GALILEO services.

1. INTRODUCTION

It is now well recognised that the SW-induced effects, such as the ionosphere-plasmasphere system disturbances, can cause various technological problems [1,2,3]. Such problems include: range errors, rapid phase and amplitude fluctuations (radio scintillations) of satellite signals, etc., all leading to pronounced signal degradation, degradation in the system performance, its accuracy and reliability. Apart from the increased risk of using the affected systems, the signal degradations due to SW-induced ionospheric perturbations and corresponding data losses can also have a purely financial dimension. It is important to mention that not only the large companies are affected, but small- and medium-size business enterprises too. With the future advancement of technology, the above-mentioned risks and financial losses will certainly increase unless swift measures are taken in advance.

2. EXPERIENCED PROBLEMS

There are several problems currently experienced by the users of GNSS.

2.1 Fixing time for positioning

Since the trans-ionospheric propagation errors are a major source of positioning errors in satellite navigation, the positioning users of satellite navigation systems have to apply appropriate mitigation techniques such as: corrections based on dual frequency techniques, model-assisted corrections, local and/or global augmentation systems. Signal degradations due to SW-induced ionospheric perturbations and corresponding data losses can reach a significant economical value for companies using satellite navigation systems.

For example, *Allsat GmbH network+services* (*Allsat*) is an enterprise which services include the installation and support of reference networks based upon the GNSS technology. Since 1999 *Allsat* continually extends the *ascos*-service of the industrial giant company Ruhrgas AG. Users can dial in the service via cellular phone (GSM). With the help of the transmitted GNSS corrections a positioning with an accuracy of a few centimetres is quite achievable.

One very important factor determining the performance of any *ascos*-service is time required to solve the phase ambiguities. Therefore the behaviour of the error budget occurring by GNSS positioning plays an important role. Practical observations fit entirely with the theoretical statements, i.e. the correct ionosphere modelling represents a challenge for precise positioning.

The variability of the ionosphere has obviously an important impact on the determination of the phase ambiguities within the *ascos*-service. Due to enforcing problems in winter 2000/2001 *Allsat* has installed the so-called *Testrover* in order to analyse the process of fixing the ambiguities.

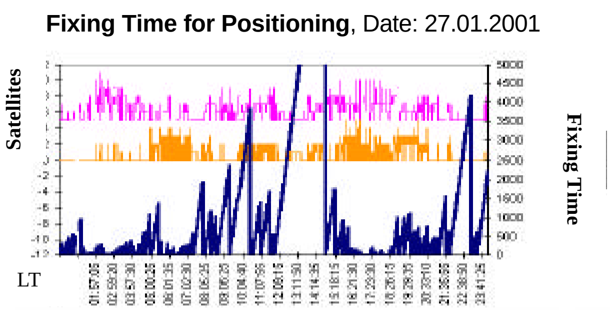

Fig.1 Time (solid line, ref. to the right-hand axis) required to fix ambiguities, presented as a function of local time (horizontal axis) and number of available GPS and GLONASS satellites (ref. to the left-hand axis).

The picture shows a typical behaviour. Mainly around noon the problems occur: the time required to fix ambiguities is quite large and sometimes it is even impossible to get a fixed solution. During such periods, it is very difficult to model the error influences and consequently the user cannot receive a precise positioning in a short time.

Nowcast and forecast of the disturbances would mean a great profit not only for *Allsat* as operator of the *ascos*-service but for other customers and the GNSS community as well. At present, *Allsat* alone has more than 150 registered network users who may benefit from an improved service involving SW information.

2.2 Strong phase fluctuations and scintillations

The phase fluctuations and amplitude scintillations are caused by the refractive and diffractive scatter due to ionospheric plasma-density irregularities, especially at equatorial and auroral-to-polar latitudes. These are small to medium-scale irregularities in the ionosphere-plasmasphere system. As **Fig.2** illustrates, small-scale irregularities lead to different signals at the reference station and the user site, i.e. the correction message transmitted from the GNSS reference network centre to the user in the field is definitely wrong.

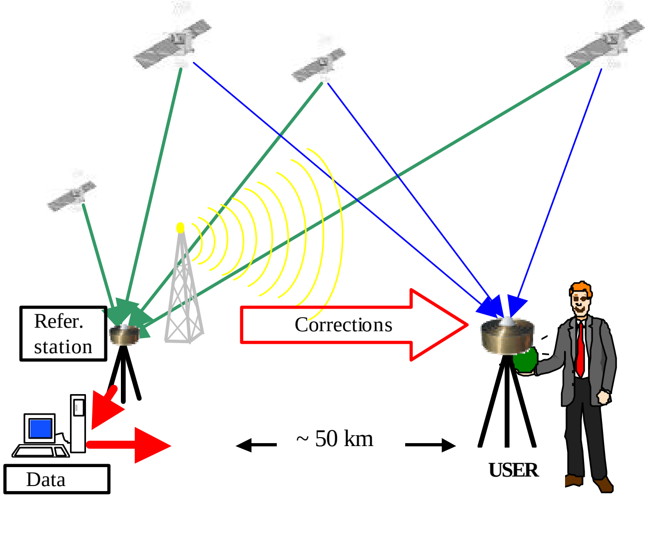

Fig.2 Small-scale ionosphere irregularities lead to different signals at the refer. centre and user; corrections are wrong

The strong phase fluctuations of TEC, observed during the storm on 6 April 2000, were in the order of $40\times10^{16}m^{-2}$ (6.50 m on L1 GPS frequency) which caused serious problems not only in precise positioning but in navigation too [3,4]. During this event, over Europe(exactly the area of interest), strong phase fluctuations have been detected by the GPS/GLONASS receivers operated by *Allsat* and DLR/IKN.

3. THE IONOSPHERE DOSSIER

The ionosphere plasma, whose density peaks around the altitude of 300 km, is a dispersive and also - due to the presence of the geomagnetic field - anisotropic propagation medium for the radio waves. The ionospheric plasma interacts with the trans-ionospheric radio waves and modifies wave parameters such as amplitude, phase and polarisation from the VHF up to the C-band frequency range.

The travel time delay of transionospheric navigation signals is in the first-order approximation directly proportional to the Total Electron Content (TEC) of the ionosphere and amounts up to 60 m for GPS signals [5]. Strong gradients in the horizontal TEC structure as well as small scale structures of the ionospheric plasma may seriously complicate or even prevent the resolution of phase ambiguities in precise geodetic or surveying networks. Principally, in reference networks, the ionospheric corrections degrade with increasing spatial decorrelation of propagation terms, in particular in the course of severe ionospheric storms, as mentioned before.

Whereas medium scale variations in time and space, such as Traveling Ionospheric Disturbances (TIDs), impact mainly the reference networks, local small-scale irregularities can cause radio scintillations, thus inducing severe signal degradation and even loss of lock in the receiver.

Out of the very broad spectrum of ionospheric propagation effects, the following principal conditions stand out and should be considered in a service:

- *'Regular' ionospheric behaviour*: accounts for the biggest component of the ionospheric delay and represents the main dependencies of the ionospheric delay, such as the local time, season, geomagnetic coordinates, solar and geomagnetic activities.
- *Large-scale ionosphere perturbations*: regional impact due to ionosphere storms, night-time enhancements, mid-latitude trough, low-latitude crest etc.
- *Ionospheric phase fluctuations, TID's and scintillations*: local impact of small scale ionospheric irregularities, their temporal and spatial behaviour.

How strong the ionosphere ionisation reacts to space-weather events is demonstrated in **Fig.3**. It shows also a strong correlation between some space-weather environment parameters (measured onboard geostationary satellites) and the Total Electron Content (TEC), which is permanently monitored by DLR for the polar and European regions. The observed correlation can be successfully used in the frame of the proposed solutions discussed next.

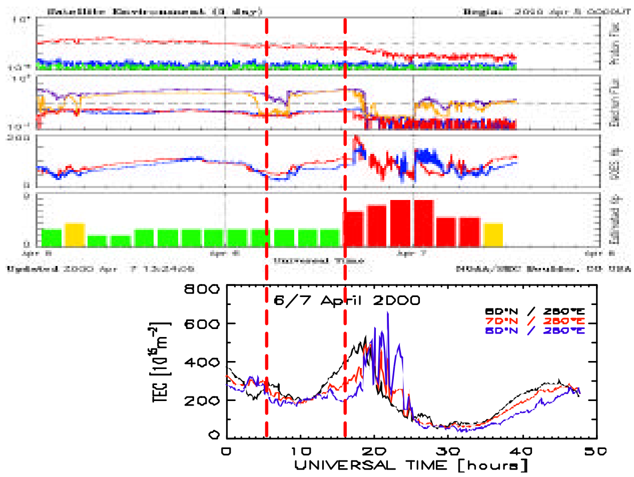

Fig.3 Correlation between SW and TEC polar observations.

4. PROPOSED SOLUTION

The SWIPPA proposal focuses on the direct and combined use of relevant ionosphere-plasmasphere system observations and available space-weather information in the operational GPS reference networks for the purposes of precise and reliable positioning. The proposed solution is in the development of a real-time monitoring system including nowcast and forecast services available to the designated users.

The DLR Institute of Communications and Navigation (DLR/IKN) Neustrelitz has a long-term experience in the detailed monitoring, analysing and studying ionospheric perturbations and ionospheric propagation errors based on both ground- and space-borne GPS measurements. Over the years, various advanced techniques and algorithms have been successfully developed and used to extract crucial information about the Earth's ionosphere and plasmasphere. Major activities are also related to GPS and GLONASS monitoring and validation, ionosphere monitoring by ground and space based methods and development of simulation tools.

4.1 TEC maps generation

Since 1995 DLR/IKN has been operating a new system for regularly processing data and producing maps of the integrated ionospheric electron content (TEC) over the European region based on GPS measurements by the International GPS Service (IGS). Extension of the monitored region is under current development. The 30s data of GPS stations of the European IGS network allow the determination of slant TEC values along numerous satellite-receiver links over the European area with high time resolution. The instrumental biases are separated from the observations by assuming a second-order polynomial approximation for TEC variations over the observing GPS ground station. Both TEC and the instrumental satellite-receiver biases are estimated simultaneously by a Kalman filter run over 24 hours. The slant TEC data are then mapped to the vertical by applying a mapping function which is based on a single layer approximation at h_{sp}=400km. Finally, the observed TEC data are combined with a regional TEC model (Neustrelitz TEC Model - NTCM) in a way that the map provides measured values near measuring points and model values at regions without measurements. The advantage of this procedure is that (in case of a low number of measurements) it delivers reasonable ionospheric corrections which can be provided to users to enhance accuracy and integrity of positioning. The existing large database, containing data from all solar/geomagnetic conditions, is an optimal background for the validation of all types of ionospheric correction especially at highly disturbed ionospheric conditions where other measurement techniques (e.g. ionosondes) are limited. As an example, **Fig.4** shows hourly TEC maps of the monitored region over several hours. Since the travel time delay of trans-ionospheric navigation signals is in the first order approximation, directly proportional to the Total Electron Content (TEC) of the ionosphere, the above TEC maps produced in DLR/IKN on a routine basis, provide directly the ionosphere induced propagation error in navigation signals. **Fig.4** provides an example for the ionosphere-induced vertical delay on the L1 frequency of GPS over Europe in the morning hours on January 2, 2002. According to these maps, a single frequency user located in the southern part of Europe has to consider an ionosphere induced range error of more than 25m at an elevation angle of 10°, whereas a user in higher latitudes has to take into account a propagation error of less than 15m under equivalent geometrical conditions. The maps are constantly being appreciated by many scientific and technical users worldwide. In year 2000 the TEC monitoring system was extended by the generation of TEC maps of the northern polar ionosphere. Such polar maps show coupling processes with the magnetosphere and the solar wind through the cusp region [4]. Therefore, this type of information is very valuable to detect the beginning of ionospheric perturbations. Since ionosphere-thermosphere perturbation processes propagate towards lower latitudes, these maps are also helpful to predict perturbation processes at middle latitudes. As for the European area, TEC maps are generated by combining actual measurements with the regional model NTCMP of the ionosphere over the northern high-latitude region ($\phi > 50°$). Besides TEC grid values the archive includes also bias estimations for all links between GPS satellites and the European IGS stations. The computed European TEC maps (comparable to WAAS and ESTB ionospheric correction maps) cover a region of 32.5°N to 70°N in latitude and –20° to 60° E in longitude. The measurements have a routine time resolution of 10 minutes. Former verification studies by independent data sources (EISCAT, ionosondes) have shown that the absolute errors of the estimated TEC values are less than about 2-3 TECU [1,5]. Furthermore, DLR/IKN has developed the software modules for deriving ionospheric grid errors in the EGNOS Testbed (ESTB) in real time. The corresponding propagation error maps (GIVE), for the ECAC area, are presented immediately on the DLR web page. The TEC maps and carrier phase data are used to derive additional information that is assumed to be helpful for the users. As expected, these data are strongly correlated with solar and geomagnetic parameters such as solar wind speed and Kp [2,6].

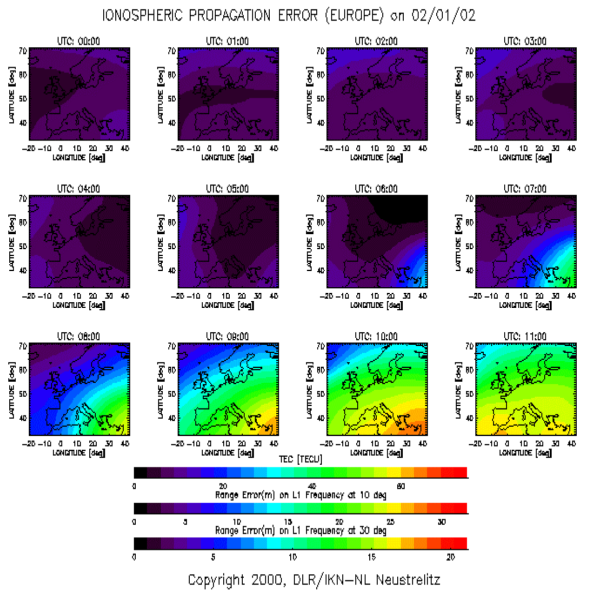

Fig.4 Hourly maps of vertical Ionospheric Propagation Error.

4.2 Operational data processing system

DLR/IKN is involved in the German CHAMP satellite project since the beginning of the Phase-A study in 1997 with several work packages related to the use of GPS radio occultation measurements onboard CHAMP for atmosphere ionosphere sounding and corresponding applications in meteorology and space weather. According to their responsibility, the DLR/IKN team developed the required retrieval and simulation software as well as the data processing system for ionospheric radio occultation (IRO) data analysis up to level 3 data products.

Taking into account the operational requirements of space weather applications, the ionosphere data products have to be available within 3 hours after each data block release from the satellite. A corresponding dynamically configurable processing system has been developed in DLR in the preparatory phase of the CHAMP mission [7]. After data reception in the DLR Remote Sensing Data Centre – Neustrelitz, the GPS data are automatically checked and pre-processed by the implemented software. If the controlling subsystem indicates the availability of all data needed for a certain data product, the corresponding generation module is started immediately. Supplementary data, such as orbits and fiducial network data, are provided by the GeoForschungsZentrum Potsdam. The modular structure enables high flexibility if retrieval modules should be modified or replaced in the course of the CHAMP mission or if supplementary data should be included to improve the products. At present, the IRO processing system provides three official data products that will be available for the scientific community and space weather customers after finishing the validation phase. These products can be briefly described as: original IRO/GPS data, relative TEC data along radio occultation links and vertical electron density profiles. The required orbit information for GPS and CHAMP satellites is provided by the IGS analysis center of the GeoForschungsZentrum in Potsdam.

4.3 Forecast of space environment characteristics

In addition to the now-cast data discussed in the previous sections, a short-term prediction of TEC, based on regular and reliable GPS measurements, would also be very helpful to improve the surveying practice. Various approaches have been used to predict / forecast the ionospheric characteristics, and TEC in particular: empirical, theoretical, neural networks, etc. New, auto- and cross-correlation procedures have been recently developed by DLR for predicting both the critical frequency and the TEC, strongly relating the short-term forecast to present and future geomagnetic activity [8]. Preliminary results of these methods/procedures have been already tested and reported for the one-dimensional case when forecasting is performed at a given location based on GPS measurements of the total electron content and on solar and geomagnetic activity indices. If such a prediction is made at several locations in a given region, then instantaneous maps of the forecast can be constructed covering the region of interest. The short-term forecast method is capable of delivering a forecast up to 24 hours ahead based on a prediction of the 'quite-time behaviour' of TEC and a sub-sequent correction on the relative deviations of the measured TEC from its median (quiet-time) values. These deviations, if large enough, are related to the perturbations induced by the eventual geomagnetic storm developing at the same time. This method relies on the long GPS TEC time-series data acquired at DLR/IKN. The research and development activities continue.

5. SUMMARY

The SWIPPA project focuses on the concrete use of SW information in the operational Global Positioning System (GPS) reference networks for the purposes of precise and reliable positioning. Several data products are offered to the designated users, research institutions, and general public. These products, based on information of the actual and predicted state of the ionosphere, will provide the users only with space weather information their really need for their tasks.

Present GPS and future GALILEO system customers will be provided with warnings, now-casts and forecast of the ionospheric status in order to deliver a precise and secure positioning service and to reduce the operation/production/business costs. Another major task of the project activities is to provide relevant information and support to the SWENET (the European Space Weather Network) community on a regular basis.

The benefits of the proposed SW service will be evaluated and recommendations for service improving will be given. There will be a huge and growing market for precise positioning and navigation applications in the near future in particular when GALILEO becomes operational in 2008. Since the perturbed ionosphere affects also other advanced technological systems using trans-ionospheric radio waves, the established service should be helpful also to them as well.

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