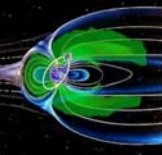
Space Weather Impact on Precise Positioniong Applications



First experience in operationally monitoring and assessing the space weather impact on GNSS positioning

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The Space Weather is defined as the set of all conditions -- on the Sun, and in the solar wind, magnetosphere, ionosphere and thermosphere systems -- that can influence the performance and reliability of ground-based and space-borne technological systems and can endanger human health and life. SWIPPA is a pilot project, jointly supported by the German Aerospace Centre (DLR) and the European Space Agency (ESA) via contract ESTEC-16952/02/NL/LvH, aiming at the establishment of a specific space weather service to improve various Global Navigation Satellite System (GNSS) applications. The main objectives of the SWIPPA project is to demonstrate technological, economic and social benefits of a targeted space weather service for the GNSS precise positioning tasks performed by the project consortium members, to help the Space Weather European Network partners, and to work towards raising the public awareness on the space weather importance.

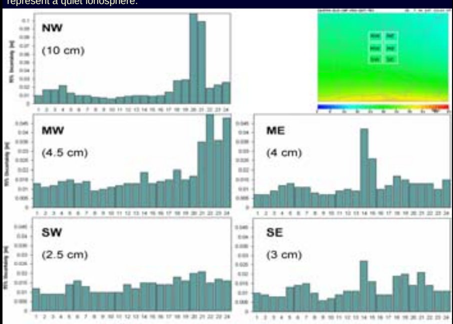
Service

This project provides specific space weather information to GNSS reference network operators in order to help them deliver a more reliable, precise and secure positioning service and to eventually reduce the operation, production, and other business costs. Another major task is to regularly provide relevant information and support to the Space Weather European Network (SWENET).

SWIPPA Data / Information Exchange System

Network Model Integrity

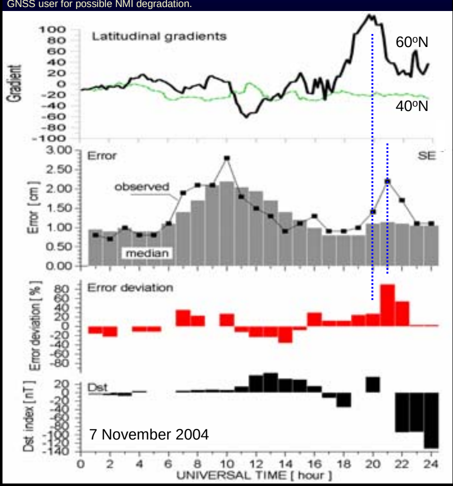
The Network Model Integrity module is used within the software of the *ascos satellite positioning services* reference network to describe the non-linear error in the generated data. The software determines the ionospheric influence on GNSS signals and then removes the linear parts of these effects by applying ionospheric and geometric corrections to the raw data. An associated problem is that, during periods of disturbed ionosphere, the ionospheric residuals cannot be considered as linear. The integrity module estimates the non-linear error in the generated data. The error itself is determined by omitting one station from the calculation of the ionospheric influence, and then the surrounding stations are employed to predict the ionospheric influence for the site of the omitted station. Finally, the predicted error is compared with the measured values and the ionospheric and geometric errors are shown separately. Recent experiences teach that it is hardly possible to obtain precise and accurate results while the error is larger than 8 cm. If the error is between 4 and 8 cm, the reference network user has to accept longer times to fix ambiguities. Smaller values represent a quiet ionosphere.



The NMI graphs show the remaining errors at different locations as estimated by the network model integrity on 25 July 2004. The remaining error of a single subnet is plotted with an average value. The plots of the different subnets are shown according to the area they cover in Germany (NW – North West, NE - North East, MW – Mid West, ME – Mid East, SW - South West, SE – South East). Around noon, higher-than-usual values are observed in the eastern areas ME and SE. Later, the influence is detected in the western areas NW, MW, and SW as well. As the ionosphere perturbations propagate from polar to lower latitudes, GNSS applications are also affected. However, the influence decreases at lower latitudes.

Early detection of disturbances

Demonstrated next is how SWIPPA products and services can help. By generating high-resolution maps of TEC spatial and temporal gradients, particularly at higher higher latitudes, ionospheric disturbances become. As the space weather / ionospheric disturbances lead to increase in the residual error (decreased NMI respectively), the TEC maps can be effectively used for alerting the GNSS user for possible NMI degradation.

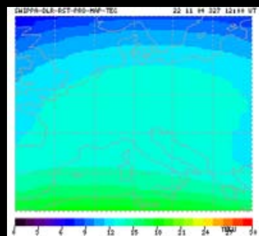


Products

Within the SWIPPA project, several near real time data products and services – such as TEC maps, TEC spatial and temporal gradient maps, cycle slip monitoring, space weather warnings, etc. -- are offered to the consortium members, designated users, and general public. These products and services are based on information of the actual and predicted state of the ionosphere-plasmasphere system and deliver only such type of space weather information which GNSS users need for the execution of their routine tasks [1,3].

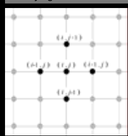
TEC

DLR operates a system for regularly processing ground based GPS data and producing maps of the integrated ionospheric electron content over the European region. Used are measurements from the *ascos* ground reference network and from other geodetic networks via BKG (Bundesamt für Kartografie und Geodesie). The 1sec GPS data allow the determination of slant TEC values along numerous satellite-receiver links over the European area with a high time resolution. The slant TEC data are then mapped onto the vertical axis by applying a mapping function which is based on the single layer approximation at hsp=400km. Finally, to produce regional TEC maps over Europe, the measured and calibrated TEC data are assimilated into the regional TEC model Neustrelitz TEC Model (NTCM2).



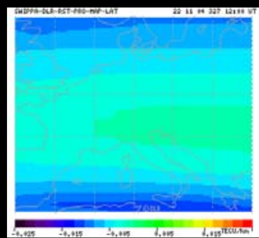
TEC gradients - latitude

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.



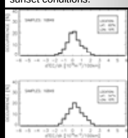
Gradients are calculated at each grid point (1 deg resolution) over Europe using the computational molecule (left side map).

Latitudinal (North-South) gradients (right side map) show how and how far the disturbances propagate toward lower latitudes.



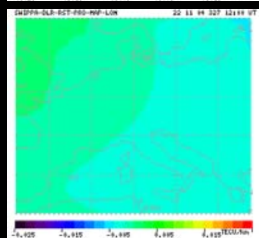
TEC gradients - longitude

Longitude (East-West) gradients (right side map) show how the disturbances move between different local-time sectors and can be helpful in the same way as the latitudinal gradients in particular under sunrise and sunset conditions.



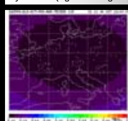
Severe ionospheric storms cause significant redistribution of plasma resulting in large longitudinal gradients which may also have a negative impact on positioning.

The left side figure shows gradient statistics for year 1995 (low solar activity).

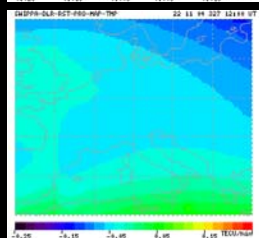


TEC gradients - time

Existence of strong temporal gradients indicates the development of highly dynamic processes in the ionosphere-plasmasphere system with a potential of degrading GNSS positioning/navigation. Temporal gradient maps can indicate regions with enhanced dynamics (right side figure).



Note:
In order to monitor the quality of the TEC mapping, a novel in-house procedure has been developed for practical estimation of the TEC calculation error (left side figure).

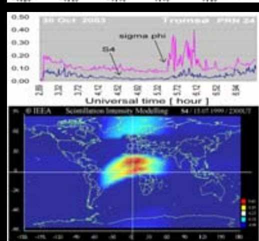


Scintillation Monitoring

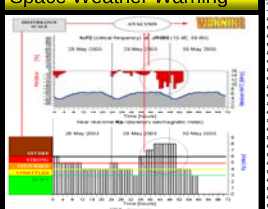
Phase scintillations are traditionally monitored by estimating the standard deviation of the power spectrum of detrended carrier phase of GNSS satellite signals. Amplitude scintillations are monitored via the S4 index. The S4 index value, normally calculated over a 60 second interval, is deduced from detrended signal intensity (actually, the received signal power) of GNSS satellite signals.

To better monitor the polar scintillation activities, DLR has installed a GPS receiver in Tromsoe (data analysed and processed at 50Hz sampling frequency) and started to produce estimates of S4 and Sigma-phi.

Additionally, the IEEA Global Ionospheric Scintillation Model (GISM) is used to provide estimates of the scintillation intensity [4].



Space Weather Warning

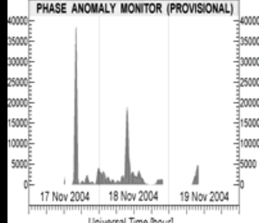



```
QUIET                    # Space Weather Conditions
12:32:11                 # Time(UT) of this SW cond. warning
22.11.2004               # Date(UT) of this SW cond. warning
---------1---------2---------3---------4---------5---------6---------7---------8
# Report prepared under the rules of the project SWIPPA
# Space Weather Impact on Precise Positioning Applications
#        http://www.kn.nz.dlr.de/swippa/index.htm
# and delivered by the
#        German Aerospace Centre (DLR)
#        Institute of Communications and Navigation (IKN)
#        Department of Navigation and Guidance Systems
#        D-17235 Neustrelitz, Germany
# Comments/Suggestions related to the SWIPPA service:
#        Stanimir.Stankov@dlr.de
#        Norbert.Jakowski@dlr.de
# Space weather conditions scale used:
#        SEVERE
#        STRONG
#        DISTURBED
#        UNSETTLED
#        QUIET
# Data sources used:
#        German Aerospace Center (DLR)
#        NOAA Space Environment Center
#        NOAA Satellite and Information Services
#        GeoForschungsZentrum - Potsdam
# END-OF-FILE
```

Cycle Slip Monitoring

The number of cycle slips or other phase anomalies is an important indicator of the GPS service quality. A cycle slip in a carrier phase L_i, denoted Δn_i, is defined as an integer discontinuing in the value of the corresponding bias b_i. Similarly, a cycle slip in dual frequency data is expressed as $(\Delta n_1, \Delta n_2) = (b_1' - b_1, b_2' - b_2)$, where b_1' and b_2' are the new values of the phase biases after the cycle slip. Because cycle slips can occur concurrently and differently on the L1 and L2 channels, non-zero values of Δn_1 and Δn_2 must be independently detectable.

Presented (right side figure) are results of preliminary estimation of cycle slips and/or phase anomalies.

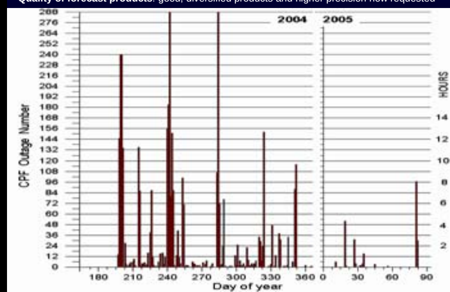


Benefit

Benefits of the SWIPPA space weather service have been evaluated by consortium users and ESA appointed companies as well. Presented here are the preliminary estimates together with recommendations for improving the service.

Evaluation of user satisfaction

- **Service reliability**: Central Processing Facility (CPF) outages, both scheduled and non-scheduled, decreased steadily during the project.
- **Spatial and temporal resolution**: higher and better than originally requested by the users
- **Quality of forecast products**: good, diversified products and higher precision now requested



- Increased awareness of space weather - related problems.
- Improved SAPOS-based positioning: Improved likelihood of successful measurements and consequent processing and imaging.
- Estimated €250 per day per surveying team saved during each major space weather event by avoiding re-initialisation procedure(s).
- Estimated €1500 per day saved during each major space weather event by avoiding repeated precise positioning measurements.

Prospective for service improvements

The experience gained by both, the developers and the users, during this pilot space weather project guarantees the rich prospective for service improvement and expansion:

- Develop new improved service to address a larger set of GNSS users
- Focus on forecast products;
- ALLSAT: spatial resolution less than 200 km; scintillations forecast needed
- SENSYS: forecast needed 12-24h ahead
- LVMV: forecast needed 3h ahead
- Improve the spatial and temporal resolution of the nowcast
- Improve the quality of the short-term ionospheric forecast
- Utilize space-based measurements for plasmasphere reconstruction
- Deliver new, more specific, products to be directly used in GNSS algorithms
- Extend current regional mapping towards local and global coverage
- Develop new improved service to attract a larger set of GNSS users
- Extension to non-European areas

Sustainability of service

- To maintain a space weather service like SWIPPA, the man power is estimated to be in the order of 2 persons per year.
- Funding already awarded by the Germane State Government of Mecklenburg for improving and expanding the service to include space-based observations in the monitoring.
- Additional national and international sources are being contacted for ensuring the long-term sustainability of the service.
- Expected also is that the market for GNSS based precise positioning and navigation applications will grow in future, particularly when GALILEO becomes operational.

Consortium

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Institute of Communications and Navigation,
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(http://www.kn.nz.dlr.de)

Allsat GmbH network+services,
Hannover, Germany
(http://www.allsat.de)

IEEA - Informatique Electromagnetisme Electronique Analyse numerique, Courbevoie, France
(http://www.ieea-fr.com)

SENSYS - Sensorik & Systemtechnologie GmbH,
Bad Saarow, Germany
(http://www.sensys.de)

LVMV - Land Surveying Office of Mecklenburg-Vorpommern,
Schwerin, Germany
(http://www.lverma-mv.de)

Swiss Reinsurance, Zurich, Switzerland
(http://www.swissre.com)

GeoForschungsZentrum (GFZ), Potsdam, Germany
(http://www.gfz-potsdam.de)

University of Applied Sciences – Neubrandenburg, Germany
(http://www.fh-nb.de)

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[2] Stankov, S.M., Jakowski, N., Wilken, V., Tsybulya, K. (2005): Generation and propagation of ionospheric disturbances studied by ground and space based GPS techniques. Paper No. A064/9B2. Proc. Ionospheric Effects Symposium, 3-5 May 2005, Alexandria VA, USA.

[3] Jakowski, N., Stankov, S.M., Klaehn, D., Schlueter, S., Beniguel, Y., Rueffer, J. (2004): Operational service for monitoring and evaluating the space weather impact on precise positioning. Proc. European Navigation Conference GNSS-2004, 16-19 May 2004, Rotterdam, The Netherlands.

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[5] Beniguel, Y. , Global ionospheric propagation model (GIM) - a propagation model for scintillations of transmitted signals. Radio Science, May-June 2002.

Website

http://www.kn.nz.dlr.de/swippa/index.htm

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