Validation of Near-real-time GPS Occultation Data Products for Meteorological Services

Prepared by
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ESA GPS Space Weather Pilot Project

Terma A/S and the Danish Meteorological Institute (DMI) conduct this pilot project for Space Weather applications. The basic objectives for the project are the following:

- Identify and describe Space Weather conditions which can adversely affect the quality and reliability of atmospheric profiling data acquired through GPS occultation measurements.
- Define characteristics indicative of poor GPS data quality resulting from adverse Space Weather effects.
- Devise algorithms to validate GPS data products in an operating near-real-time end-to-end chain for processing of GPS data from telemetry to application.

Project Structure

- TERMA Space Division is the basic service provider by managing the satellite and the processing of telemetry data to provide the GPS occultation data products in a useful form for the meteorological services.
- The DMI shall be the main service user. The institute shall identify the specifications for quality-controlled occultation data products to be of use in its operational numerical weather prediction (NWP) models.
- DMI shall provide analyses of GPS observations in order to identify Space Weather effects in the GPS data and shall devise quality control procedures to be used in the data processing routines for validating the GPS data products for operational uses.
- The evaluation of the overall usefulness of GPS occultation data from LEO satellites shall take into account the sparseness of presently available satellites equipped with GPS receivers and the limitations on their performance in relation to the anticipated fleet of such satellites equipped with more advanced GPS instruments, which may become an operational reality in just a few years time.
The GPS satellites transmit on two carrier-frequencies, L1: 1575.42 MHz, and L2: 1227.6 MHz. The carriers are modulated with code signals P1 and P2. The code signals identify the GPS satellites and hold their precise time code.

Sequence of Steps in Calculations of Electron Density Profiles at Occultations

- Observations of phase delays for L1 and L2
- Calculation of Total Electron Density (TEC)
- Calculation of bending angle profile
- Inversion of bending angles using the Abel transform
- Retrieval of the electron density profile

\[ \Delta \Phi = \lambda^{-1} \left[ \int \frac{\mu(s)ds}{R_e} - R_e \right] \]
\[ TEC = \frac{f_1^2}{f_2^2} \left[ \frac{L_1}{L_2} - 1 \right] \]
\[ \mu = \exp \left[ - \pi \frac{f_1^2}{L_2} \right] \]
\[ \alpha = \theta - \arccos \left( \frac{a}{R_e} \right) - \arccos \left( \frac{a}{R_0} \right) \]
\[ \mu = 1 - \left( \frac{f_2}{f_1} \right)^2 \]
\[ N_e(a) = \frac{1 - \mu(a)}{C} \]
Sequence of Steps in Calculations of Atmospheric Profiles at Occultations

- Derivation of frequency independent ionosphere-corrected phase delay
- Calculation of bending angle profile
- Inversion of bending angles using the Abel transform
- Retrieval of refractivity profile
- Relating refractivity to temperature, pressure and humidity

Atmospheric Refractivity

\[ N = \frac{k_1 P}{T} + \frac{k_2 P^2}{T^2} + \frac{k_3 P^3}{T^3} \]

- \( k_1 = 77.6 \text{ K}/\text{hPa} \)
- \( k_2 = 37.4 \times 10^4 \text{ K}^2/\text{hPa} \)
- \( k_3 = 70.40 \text{ K}/\text{hPa} \)

USER REQUIREMENT CATEGORIES

- **Timeliness**
  - Comply with WMO requirements on latency
- **Accuracy**
  - Comply with WMO requirements on RMS accuracy
- **Resolution**
  - Comply with WMO requirements on vertical and horizontal resolutions
- **Altitude and Regional Coverage**
  - GPS data must provide adequate altitudinal and regional coverage
- **Reliability**
  - Potential failure risks must be identified and assessed

Atmospheric Regions

- **Lower Troposphere** (LT): 100 hPa to 500 hPa (Surface to 5 km)
- **Higher Troposphere** (HT): 500 hPa to 100 hPa (5 km to 15 km)
- **Lower Stratosphere** (LS): 100 hPa to 10 hPa (15 km to 55 km)
- **Higher Stratosphere/Mesosphere** (HS): 10 hPa to 1 hPa (55 km to 50 km)

**WMO User Requirements for Global Numerical Weather Prediction**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Specific Humidity</th>
<th>Surface Pressure</th>
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<tbody>
<tr>
<td>Horizontal Domain</td>
<td>Global</td>
<td>Global</td>
</tr>
<tr>
<td>Vertical Domain</td>
<td>SS: to 1 hPa</td>
<td>SS: to 10 hPa</td>
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<tr>
<td>Resolution</td>
<td>LT</td>
<td>0.3-3 km</td>
</tr>
<tr>
<td>LS</td>
<td>1-3 km</td>
<td>1-5 km</td>
</tr>
<tr>
<td>HS</td>
<td>1-3 km</td>
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<tr>
<td>Time Resolution</td>
<td>LT</td>
<td>1-12 hrs</td>
</tr>
<tr>
<td>HT</td>
<td>0.5-3 km</td>
<td>0.25-1 g/kg</td>
</tr>
<tr>
<td>LS</td>
<td>0.5-3 km</td>
<td>0.025-0.1 g/kg</td>
</tr>
<tr>
<td>HS</td>
<td>0.5-5 km</td>
<td>--</td>
</tr>
<tr>
<td>Time Invasion</td>
<td>LT</td>
<td>1-4 hrs</td>
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</table>

Source: GRAS Meteorology SAF Report, 2001
Translation of WMO requirements to GPS Radio Occultation Measurements

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Specific Humidity</th>
<th>Surface Pressure</th>
<th>Refractivity</th>
<th>Scattering Angle</th>
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<tr>
<td>Horizontal Scintillation</td>
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<td>100-100 km</td>
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<td>Vertical Scintillation</td>
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<td>HV</td>
<td>LH</td>
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<td>Time Window</td>
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<td>0.5-2 km</td>
<td>0.3-1 km</td>
<td>0.3-1 km</td>
</tr>
</tbody>
</table>

Table 4: R0 User Requirements for global NWP.


Ørsted GPS Atmosphere Profiling

Comparison of GPS and ECMWF Temperature Profiles

Ørsted data comprise 956 occultations from 3.2 - 22.2.2000 (AS and SA on).
GPSMET data comprise ~2000 occultations from 1997 (AS and SA off).

Comparison of GPS and ECMWF Temperature Profiles

Ørsted data comprise 956 occultations from 3.2 - 22.2.2000.

Table 2: Generic User Requirements for regional NWP
(Source: WMO TD No. 911, SAT 21, 26/01/1998)

The Most Important User Requirement for Numerical Weather Prediction:

Inclusion of GPS RO data in forecast models

**MUST IMPROVE**

Weather Prediction Results

Do they?


Result: The impact from GPS RO data was neutral when averaged over the whole period but varies considerably on a daily basis.

Authors note: "It should be stressed that quality control plays an important role in the error statistics"


Result: The impact from GPS RO data was positive and gave 0.2% improvements when averaged over the whole period. Largest impact in the southern hemisphere.

Authors note: "Given the small number of observations the results are very encouraging and support the case for assimilating RO measurements in NWP operationally.”

Concluding remarks on “Users Requirements”:

It seems of vital importance for the usefulness of GPS RO observations in NWP models that potential error sources are removed before assimilation of RO data in forecast models.

Such reservations comprise low-altitude effects related to tropospheric propagation problems relating to effects from high and irregularly distributed water vapor content and from multipath propagation due to ground scatter.

However, it is also most likely that the corresponding precautions must be taken to exclude adverse Space Weather effects.
Space Weather Impact on GPS Profiling

Space Weather influences GPS profiling mainly through ionospheric effects like:

- Inaccurate Ionospheric Correction of Signal Phase
- Scintillations related to Ionospheric Propagation

- An inherent error source arises from the path splitting for the L1 and L2 signals due to differences in bending angles at their different frequencies. This problem is particularly serious in regions with high electron densities.
- Asymmetric, spatially inhomogeneous and temporally varying ionospheric electron density distributions enhance the variance of the observables and increase the uncertainty on the actual signal path.
- Scintillations in signal amplitude or phase may produce erroneous samples and/or cause loss of GPS satellite tracking for shorter or longer intervals.

Space Weather Impact on GPS Profiling

Space Weather effects are related to events like:

- Solar X-ray flares
- Solar Wind Enhancements
- Geomagnetic Storms
- Auroral Substorms

Adverse effects on Atmospheric profiling from Ionospheric density enhancements or strong gradients are particularly important in these regions:

- Equatorial electron density maximum (dayside)
- Midlatitude electron density 'Through' region
- Auroral Oval
- Polar Cusp region

DMI-HIRLAM

The operational system consists of four nested models named "G", "N", "E" and "D".

DMI-HIRLAM region "G" comprises northern auroral and cusp regions where severe multipath and scintillation effects are anticipated.
We shall build on the experiences gained from the CLIMAP project (1997-2000)

Noting that this project
- terminated at an early phase of Ørsted operations
- terminated GPS data collection before ‘Selective Availability’ (SA) was turned off
- never came around to investigate possible Space Weather effects
- never came to operate GPS data processing in ‘Near-Real-Time’

We plan to use
- the overall GPS data processing scheme developed for the CLIMAP project
- the methodologies and codes developed for CLIMAP modified with recent techniques
- the experiences gained in the operation of the Ørsted satellite and its GPS receiver
- data collected after SA turn-off on 2 May 2000 for evaluation of Space Weather effects

The Ørsted TurboRogue GPS data collection shall be intensified in order to collect a large pool of data with SA turned off (SA still in effect)

For the GPS data collected the irregularities which could be the result of adverse Space Weather conditions shall be studied, e.g.,
- The occurrences of data samples to be excluded according to CLIMAP data discrimination criteria shall be registered
- Amplitude scintillation index shall be calculated currently
- Phase variance index shall be calculated currently

These ‘irregularity’ indicators shall be grouped statistically according to geophysical location and space weather conditions looking for systematic patterns.

Blue trace indicates GPS L1 signal amplitude. Red trace shows difference between L1 signal phase and cubic fit over total sequence. Green trace shows phase difference between L1 signal and running cubic fit over 3 s.
• The available Ørsted TurboRogue GPS data sets shall be processed to retrieve atmospheric profile parameters, e.g., ‘dry’ temperature profile or simply bending angle.

• The corresponding parameters shall be derived from the ECMWF or DMI-HIRLAM analysis operational model for appropriate times and locations.

• The differences between the atmospheric parameters based respectively on GPS data and on ECMWF/HIRLAM shall be grouped statistically according to geophysical location and space weather conditions looking for systematic patterns.

• If systematic patterns are found at the data analysis outlined above then they, if appropriate should be converted into data processing code to provided data selection or data discrimination criteria to be imposed on near-real-time data.

• The steps missing in the CLIMAP procedures to accomplish a functioning near-real-time (NRT) GPS data processing system shall be taken.

• The NRT data product, bending angle, refractivity, or ‘dry’ temperature profile shall be transmitted to the DMI meteorological research section. The amount of data and their latency shall be recorded.

Distribution of Radiosondes. If GPS profiling proves accurate and reliable then the number of radiosonde launches can be substantially reduced. The operation of radiosonde balloon launches is a major cost factor for Meteorological Services.