Pilot Project for Space Weather Applications

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

Prepared by
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and
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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 algoritms to validate GPS data products in an operating near-real-time end-to-end chain for processing of GPS data from telemetry to application**

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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 instrumentations, which may become an operational reality in just a few years time.**

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DMI Team

DMI Research and Development Division is prime contractor and provides Contracts Officer and the Project manager:
The Contract Officer is Director Anne Mette Jørgensen, tel: +45 39157450, fax +45 39157460, Email: amj@dmi.dk
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We gratefully acknowledge support received from:
Henrik Vedel, Per Høeg, Georg B. Larsen, and Martin B. Sørensen, DMI.

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TERMA Team

TERMA Space Division is subcontractor.
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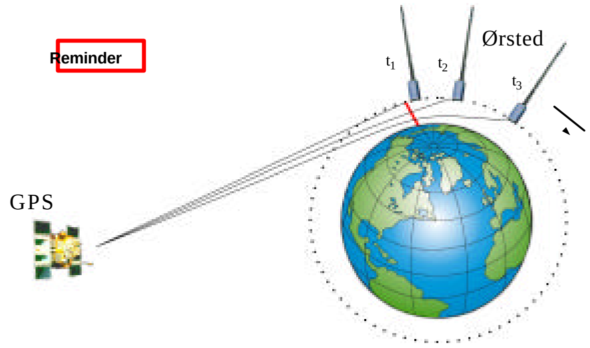
Project Team: Peter Hoffmeyer (Team leader)
Keld Schulz
Preben Bohn

We gratefully acknowledge support received from:
Peter Davidsen, Terma.

GPS Ionosphere and Atmosphere profiling

Reminder



Courtesy Hoeg et al.

GPS Ionosphere and Atmosphere profiling

Occultation Ray Geometry

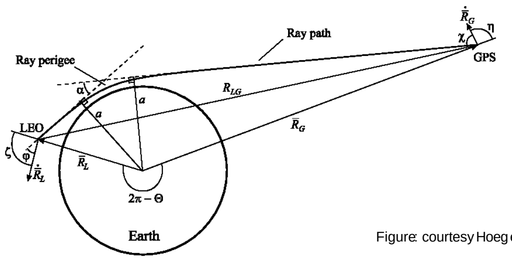


Figure: courtesy Hoeg et al.

The GPS satellittes transmit on two carrier-frequencies, L1: 1575.42 MHz, and L2: 1227.6 MHz. The carriers are modulated with code signals P1 og P2. The code signals identify the GPS satellittes and hold their precise time code.

GPS Ionosphere profiling

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

$$r = \frac{a}{\mu}$$

$$\Delta\Phi = \lambda^{-1}\left(\int \mu(s)\,ds - R_L\right)$$

$$\text{TEC} = \frac{f_1^2 f_2^2}{C(f_1^2 - f_2^2)}[L_1 - L_2]$$

$$\mu(r) = \exp\left[\pi^{-1}\int_r^{\infty}\frac{\alpha(\xi)}{\sqrt{\xi^2 - r^2}}\,d\xi\right]$$

$$\mu^2 = 1 - \left[\frac{f_p}{f}\right]^2$$

$$\alpha = \theta - \arccos\left(\frac{a}{R_L}\right) - \arccos\left(\frac{a}{R_G}\right)$$

$$\dot{L}_C + \dot{R}_{LG} - (\dot{R}_L \cos\phi(a) - \dot{R}_G \cos\chi(a)) = 0$$

$$N_e(a) = \frac{(1-\mu(a))\,f_1^2}{C}$$

GPS Atmosphere profiling

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

**) More elaborate methods are being developed*

Atmospheric Refractivity
$N=(m-1)\cdot 10^6$

$$N = k_1 \frac{P_d}{T} + k_2 \frac{P_w}{T^2} + k_3 \frac{P_w}{T}$$

$k_1 = 77.6$ K/hPa
$k_2 = 37.4\ 10^4$ K²/hPa
$k_3 = 70.40$ K/hPa

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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

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Atmospheric Regions

Lower Troposphere	(LT)	1000hPa to 500hPa	(Surface to 5km)
Higher Troposphere	(HT)	500 hPa to 100 hPa	(5km to 15km)
Lower Stratosphere	(LS)	100 hPa to 10hPa	(15km to 35km)
Higher Stratosphere/Mesosphere	(HS)	10hPa to 1hPa	(35km to 50km)

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WMO User Requirements for Globalal Numerical Weather Prediction

		Temperature	Specific Humidity	Surface Pressure
Horizontal Domain		Global	Global	Global
Horizontal Resolution [1]		50–500 km	50–250 km	50–250km
Vertical Domain		Sfc to 1 hPa	Sfc to 100 hPa	Sfc (msl)
Vertical Resolution [2]	LT	0.3–3 km	0.4–2 km	–
	HT	1–3 km	1–3 km	–
	LS	1–3 km	–	–
	HS	1–3 km	–	–
Time Resolution [3]		1–12 hrs	1–12 hrs	1–12hrs
RMS Accuracy [4]	LT	0.5–3 K	0.25–1 g/kg [5]	0.5–2 hPa
	HT	0.5–3 K	0.025–0.1 g/kg [5]	–
	LS	0.5–3 K	–	–
	HS	0.5–5 K	–	–
Timeliness		1–4 hrs	1–4 hrs	1–4hrs

Table 1. Generic User Requirements for global NWP
(Source: WMO TD No. 913, SAT-21, 28/9/1998)

From: GRAS Meteorology SAF Report, 2001 .

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Translation of WMO requirements to GPS Radio Occultation Measurements

		Temperature	Specific Humidity	Surface Pressure	Refractivity	Bending Angle
Horizontal Domain		Global	Global	Global	Global	Global
➢ Horizontal Sampling		100–1000km	100–1000km	100–1000km	100–1000km	100–1000km
Vertical Domain		Sfc–1 hPa	Sfc–100 hPa	Sfc (msl)	Sfc–1 hPa	Sfc–80 km
Vertical Sampling	LT	0.3–3km	0.4–2 km	–	0.3–3 km	2–5 Hz
	HT	1–3 km	1–3 km	–	1–3 km	
	LS	1–3 km	–	–	1–3 km	
	HS	1–3 km	–	–	1–3 km	
Time Window		1–12 hrs	1–12 hrs	1–12 hrs	1–12 hrs	1–12 hrs
RMS Accuracy [4]	LT	0.5–3 K	0.25–1 g/kg [5]	0.5–2 hPa	0.1–0.5%	1 µrad or 0.4% [7]
	HT	0.5–3 K	0.05–0.2g/kg [5]	–	0.1–0.2%	
	LS	0.5–3 K	–	–	0.1–0.2%	
	HS	0.5–5 K	–	–	0.2–2%	
➢ Timeliness		1–3 hrs	1–3 hrs	1–3 hrs	1–3 hrs	1–3 hrs

Table 4. RO User Requirements for global NWP

From: GRAS Meteorology SAF Report, 2001 .

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WMO User Requirements for Regional Numerical Weather Prediction

		Temperature	Specific Humidity	Surface Pressure
Horizontal Domain		Regional	Regional	Regional
➢ Horizontal Resolution [1]		10–500 km	10–100 km	10–250km
Vertical Domain		Sfc to 10 hPa	Sfc to 100 hPa	Sfc (msl)
Vertical Resolution [2]	LT	0.3–3 km	0.4–2 km	–
	HT	1–3 km	1–3 km	–
	LS	1–3 km	–	–
Time Resolution [3]		0.5–12 hrs	0.5–12 hrs	0.5–12hrs
RMS Accuracy [4]	LT	0.5–3 K	0.25–1 g/kg [5]	0.5–1 hPa
	HT	0.5–3 K	0.025–0.1 g/kg [5]	–
	LS	0.5–3 K	–	–
➢ Timeliness		0.5–2 hrs	0.5–2 hrs	0.5–2 hrs

Table 2. Generic User Requirements for regional NWP
(Source: WMO TD No. 913, SAT-21, 28/9/1998)

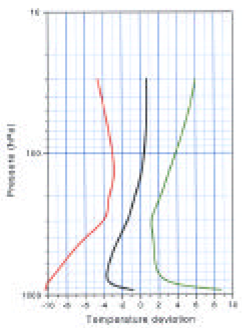
From: GRAS Meteorology SAF Report, 2001 .

Ørsted GPS Atmosphere Profiling

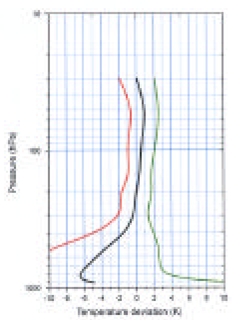
Comparison of GPS and ECMWF Temperature Profiles

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)



Ørsted



GPSMET

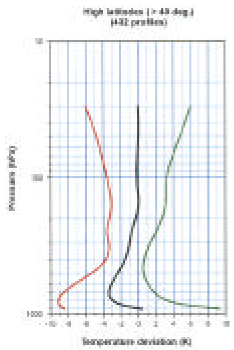
(AS:Anti-Spoofing , SA:Selective Availability)

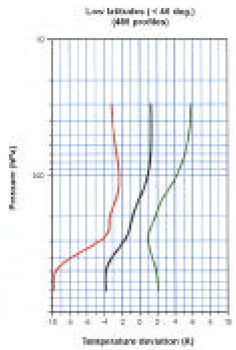
Courtesy Terma Climap Rep., 2000

Ørsted GPS Atmosphere Profiling

Comparison of GPS and ECMWF Temperature Profiles

Ørsted data comprise 956 occultations from 3.2 - 22.2.2000





Courtesy Terma Climap Rep., 2000

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The Most Important User Requirement for Numerical Weather Prediction:

Inclusion of GPS RO data in forecast models

MUST IMPROVE

Weather Prediction Results

Do they ?

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Well....

Reference: Bjarne Amstrup, Kristian S. Mogensen, and Xiang-Yu Huang: *Use of GPS observations in an optimum interpolation based data assimilation system*. DMI Scientific Report # 00-14, 2000.

Method: Use of geopotential profiles retrieved from GPS/MET occultation data 2-16 Feb 1997 in High Resolution Limited-Area Modelling (HIRLAM) Numerical Weather Prediction (NWP) model implemented at DMI. Model recalculations with and without GPS RO data.

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"*

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Yes !

Reference: Sean Healy, Adrian Jupp, and Christian Marquardt: *A forecast impact trial with CHAMP radio occultation measurements*. EGS/AGU Assembly April 2003. To appear in "Annales Geophysicae".

Method: Use of refractivity profiles retrieved from CHAMP occultation data 26 May-11 June 2001 in Met Office "New Dynamics" 1D-VAR Numerical Weather Prediction (NWP) model. No RO data below 4 km of altitude included. Model calculations run with and without GPS RO data. Model results compared with radiosonde observations.

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."*

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Concluding remarks on "Users Requirements":

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

Such reservations comprises 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
- Scintillationsrelated 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, spatiallyinhomogenous and temporally varying ionospheric electron densitydistributions enhance thevariance of the observables and increase the uncertaintyon the actual signal path.
- Scintillations in signal amplitude or phase may produce erronous samples and/or cause loss of GPS satellite tracking for shorter or longer intervals

Space Weather Impact on GPS Profiling

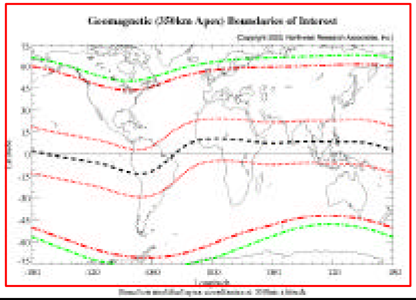
Space Weather effects are related to events like:

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

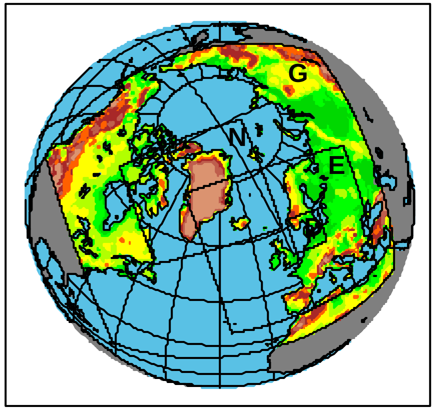
Space Weather Impact on GPS Profiling

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

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



Space Weather Impact on GPS Profiling



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 multi-path and scintillation effects are anticipated.

ESA GPS Space Weather Pilot Project

Work Plan

W e 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'

W e 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

ESA GPS Space Weather Pilot Project

Work Plan

- The Ørsted TurboRogue GPS data collection shall be intensified in order to collect a large pool of data with SA turned off (AS still in effect)
- For the GPS data collected the irregularities which could be the result of adverse Space Weather conditions shall be studies, 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.

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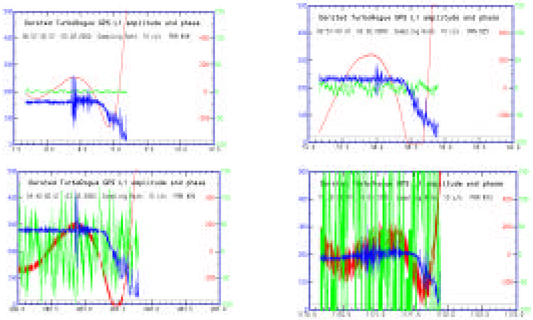
RO Data Quality control



Blue trace indicate 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.

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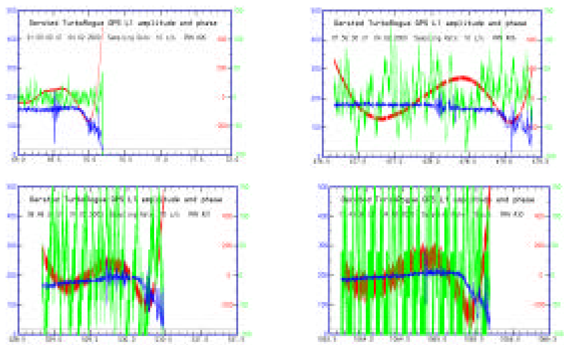
RO Data Quality control



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DMI

Work Plan

• 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.

ESA GPS Space Weather Pilot Project

DMI

Work Plan

• If systematic patterns are found at the data analysis outlined above then they, if appropriate, should be converted into data processing code to provide 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.

ESA GPS Space Weather Pilot Project

DMI

Work Plan. Conclusions

• The validity of the NRT data product: bending angle, refractivity, or 'dry' temperature profile, shall be examined with the procedure outlined above.

• The usefulness of the GPS data products shall be evaluated taking the Ørsted TurboRogue deficiencies and the sparsity of occultations into account considering that both of these limitations will change substantially in the near future with the upcoming fleets of GPS-LEO satellites.

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DMI

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