ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

Development of observation operators for GPS slant delays

Reima Eresmaa and Juha-Pekka Luntama
Finnish Meteorological Institute

Outline

1) Introduction

Ground-based GPS meteorology

2) Data assimilation for Numerical Weather Prediction (NWP)

Concept of observation operator

3) Modelling of GPS Slant Delay (SD) observations

Observation operator

Validation aspects

4) Data assimilation of SD observations into an NWP system

5) Applicability for space weather

6) Conclusions

Introduction

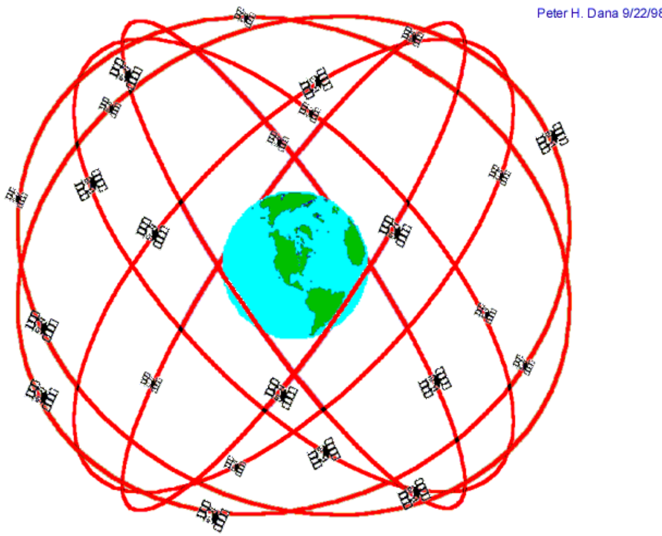
Positioning with the Global Positioning System (GPS)

The navigation signals are modulated on two microwave frequencies

The travel times of the signals are interpreted as *distance measurements*

The receiver coordinates are solved on the basis of the distance measurements, using methods of linear algebra

The contributing effects include e.g. *ionospheric* and *tropospheric delays*



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

Introduction

Tropospheric delay

The tropospheric delay Δ^T affects GPS code and carrier phase measurements and it rises from *the refraction in the neutral atmosphere*

$$\Delta^T = \int_s (n-1)ds = 10^{-6} \int_s N ds$$

The tropospheric delay

- accounts for several meters in the distance measurement
- can be estimated as a by-product of geodetic processing
- can be considered as *an observation of atmospheric humidity*

Introduction

GPS as a meteorological observing system

Advantages

- *dense observing networks* can be built and maintained at low cost
- *temporal resolution* of measurements is good
- quality of observations is *independent of weather*

Disadvantages

- observations are subject to *heavy preprocessing*
- *observation error statistics* are complicated
- *vertical resolution* is poor

Data assimilation for NWP

3D-Var cost function

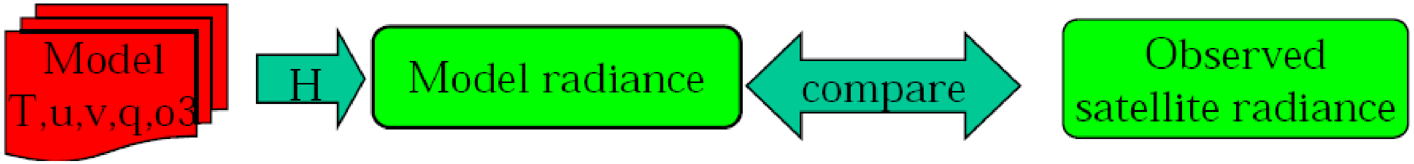
Three-dimensional variational data assimilation searches the model state *x* that *minimizes the cost function*

$$J(\mathbf{x}) = \underbrace{\frac{1}{2}(\mathbf{x}-\mathbf{x^b})^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x^b})}_{J_b} + \underbrace{\frac{1}{2}(H\mathbf{x}-\mathbf{y})^T\mathbf{R}^{-1}(H\mathbf{x}-\mathbf{y})}_{J_o}$$

x	analysed model state
x_b	background field (e.g. short-term forecast)
y	observations (pressure, temperature, wind, humidity, etc)
H	observation operator
B, R	background and observation error covariance matrices

Data assimilation for NWP

Concept of observation operator



Observation operator *H* is a functional model for expressing the model state *x* in the observation space

- The observing locations do not coincide with the model grid points
- The observed quantities often differ from the modelled ones

The observation operator *can be non-linear* and it *can make use of several model variables*

Observation modelling allows use of a wide range of observation types

Data assimilation for NWP

Role of the error covariances

Statistical characteristics of the information sources play an essential role in the data assimilation procedure:

- Background and observation *error variances* together determine the weight given to each observation
- *Background error correlation* spreads the observational information in horizontal and vertical and accounts for the dynamical balance constraints
- *Observation error correlation* is related with the weighting, but is often neglected in case of the conventional observation types

Modelling of GPS Slant Delay (SD) observations

SD in terms of meteorological quantities

Observation operators for tropospheric delays *integrate the model refractivity* as determined by pressure, temperature and humidity fields

$$\Delta^T = \int_s (n-1)ds = 10^{-6} \int_s N ds$$

$$N = k_1 \frac{p_d}{T} Z_d^{-1} + k_2 \frac{e}{T} Z_w^{-1} + k_3 \frac{e}{T^2} Z_w^{-1}$$

s	signal path	p_d	partial pressure of dry air
n	refractive index	T	temperature
N	$10^6(n\text{-}1)$, refractivity	e	water vapour partial pressure
k_1, k_2, k_3	empirical coefficients	Z_d, Z_w	compressibility factors

Modelling of GPS Slant Delay (SD) observations

SD observation operator in the High Resolution Limited Area Model

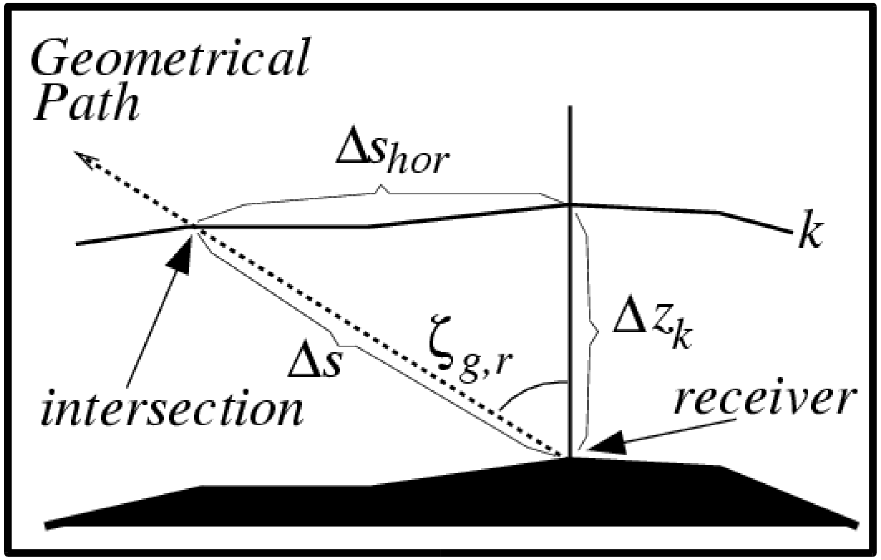
Determination of the signal path from the observation geometry

- the satellite azimuth and zenith angles
- an explicit correction for the effect of refractive bending

Interpolation of $ln\ p_s$, T and q from the model grid to the intersections

Determination of refractivity at the intersections

Integration of refractivity along the signal path



Modelling of GPS Slant Delay (SD) observations

Validation in terms of numerical reliability

Model levels	*SD at $\zeta=0^o$*	*SD at $\zeta=80^o$*
31	**242.98 cm**	**1346.64 cm**
61	**242.95 cm**	**1346.56 cm**
121	**242.95 cm**	**1346.57 cm**
481	**242.95 cm**	**1346.57 cm**
1921	**242.95 cm**	**1346.55 cm**

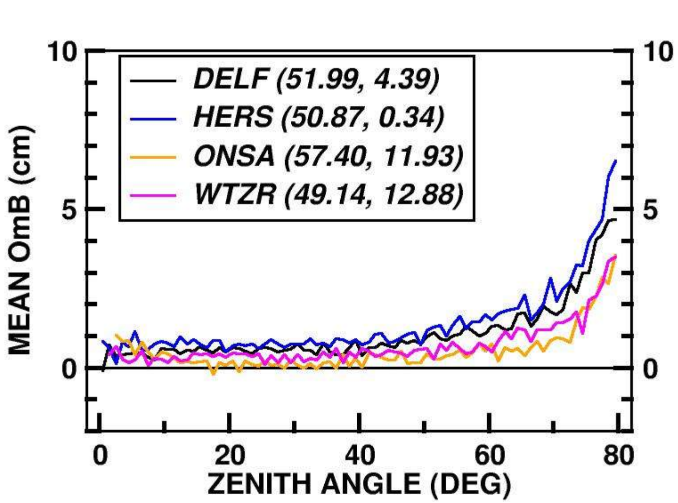
Table shows the modelled SD, at two satellite zenith angles, as a function of the number of NWP model levels in vertical, i.e. NWP model vertical resolution

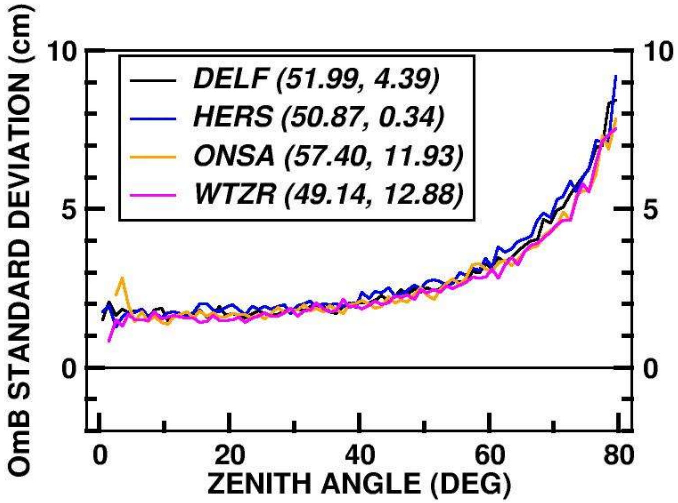
SD modelling is practically independent on the details of discretization of the model atmosphere in vertical

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

Modelling of GPS Slant Delay (SD) observations

Observation minus Background (OmB) -statistics





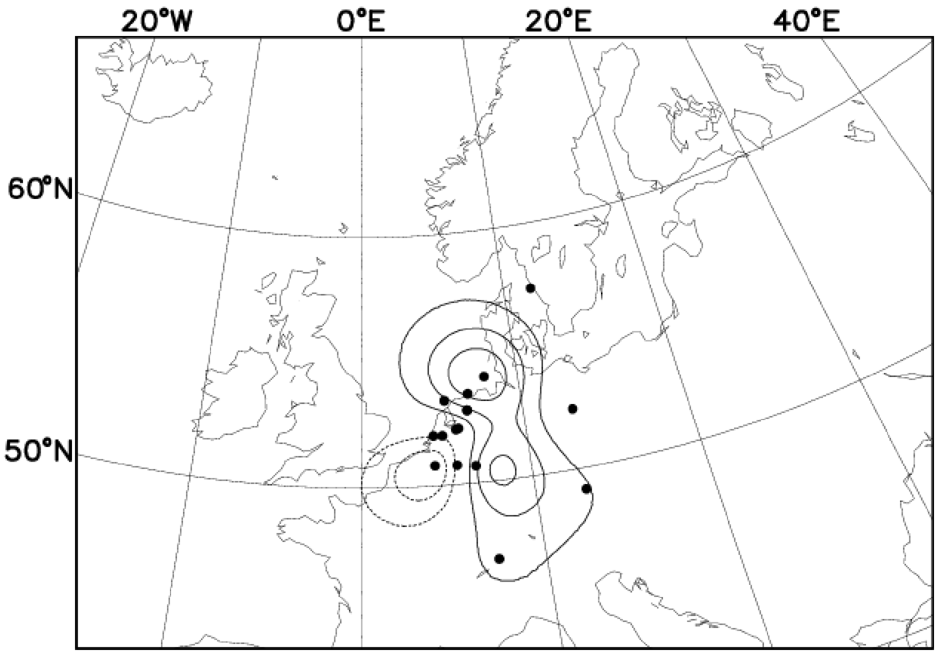
Statistics for a data set consisting of 360 000 SD observations

The modelled STD is systematically lower than the observed, especially at large zenith angles; this can be an indicator of incorrect modelling algorithm

Data assimilation of SD observations

Analysis impact of specific humidity at approx. 770 hPa level

- The SD observations are assimilated into a limited area NWP system *in a single meteorological case*
- The analysis impact from the SD observations is at a reasonable level when compared with the impacts from other observing systems
- It is likely that *observation error correlation* of SD *cannot be neglected*



Applicability for space weather

In principle, no obstacles are seen for application of variational data assimilation for ionospheric modelling

The main concern is whether or not there is a suitable ionospheric forecast model available

Further issues include e.g. *recognization of the available observation types*, *coding of the observation operators*, *evaluating the error statistics* and *implementation of observation quality control*

NWP community has developed methodology for the tasks listed above

—> Using the same methodology in space weather applications would potentially make the effort easier and reduce mistakes

Conclusions

Observation modelling allows exploitation of the GPS SD observations in the meteorological data assimilation procedure

The validation of the observation operators relies on the OmB -statistics

Similar methodology can potentially be applied to ground-based GPS observations of ionospheric delay or TEC (Total Electron Content)

Also other types of ionospheric observations can potentially be assimilated together with the GPS observations

Prerequisites for an efficient use of the data assimilation tools are a good forecast model and observation operators for all observation types

Correct error characterization is vital for succesful data assimilation

Some further reading

Bevis, M and coauthors, 1992: GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *J. Geophys. Res.*, **97**(D14), 15787—15801.

Eresmaa, R and H Järvinen, 2006: An observation operator for ground-based GPS slant delays. *Tellus*, **58A**(1), 131—140.

Kalnay, E, 2003: *Atmospheric modeling, data assimilation and predictability.* Cambridge University Press, 341pp.

Undén, P and coauthors, 2002: *HIRLAM-5 Scientific documentation.* Available from HIRLAM-5 Project, c/o Per Undén, SMHI, S-60176, Norrköping, Sweden. 144pp.