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Use of ground-based GNSS measurements in data assimilation

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Outline

1) Introduction

GNSS positioning*

Tropospheric delay

2) GNSS as a meteorological observing system

Meteorological observations

3) Observation modelling and error statistics

Zenith Delays

Slant Delays

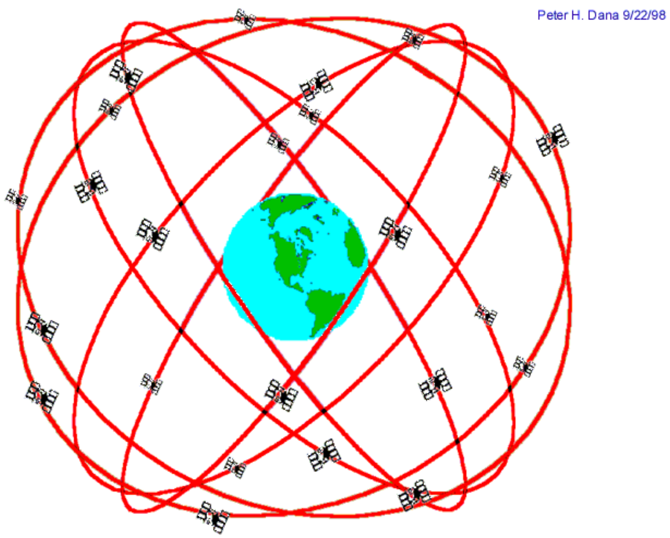
*) Global Navigation Satellite System

Introduction

Global Navigation Satellite Systems

The most accurate positioning applications utilize navigation satellite systems

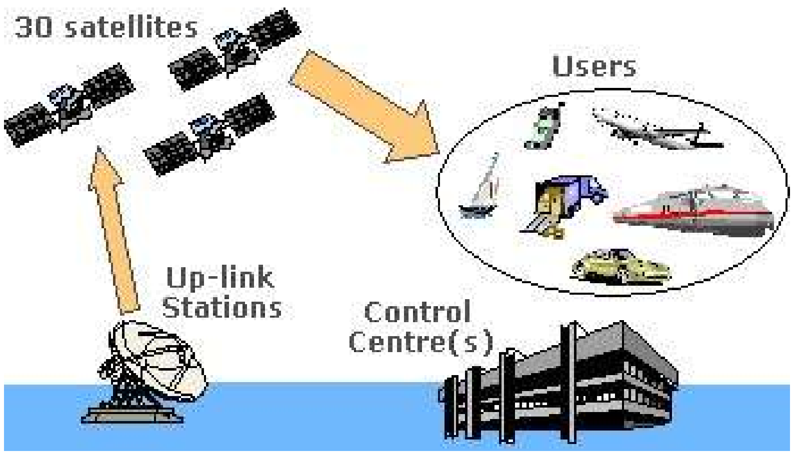
- GPS (Global Positioning System)
- GLONASS (Globalnaja Navigatsionnaja Sputnikovaja Sistema)
- Galileo



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

Introduction

GNSS positioning



Navigation satellites broadcast signals modulated on two microwave frequencies

Travel times of the electromagnetic signals are interpreted as distance measurements

The distance measurements are utilized by linear algebra to determine the receiver coordinates

Introduction

GNSS observation equation

GNSS positioning is based on solving the unknown parameters of observation equation

$$\Phi = \frac{1}{\lambda}\varrho + \frac{c}{\lambda}(\delta_R - \delta^S) + N_i + \Delta^T + \Delta^I$$

Φ	carrier phase
λ	wavelength
ϱ	distance
c	speed of light
δ_R	receiver clock error
δ^S	satellite clock error
N_i	integer ambiguity
Δ^T	**tropospheric refraction**
Δ^I	ionospheric refraction

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Introduction

Tropospheric delay

The tropospheric delay Δ^T is a consequence of the decrease of the microwave propagation speed in the neutral atmosphere

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

The tropospheric delay

- appears as increase in the measured distance
- can be estimated as a by-product of geodetic processing
- is an integral of refractivity N along the signal path s through the atmosphere
- can be considered as an observation of atmospheric humidity

Introduction

Properties of tropospheric delay

In case the signal comes from zenith, the tropospheric delay induces an apparent increase of ca. 2.5 m in distance measurement

Tropospheric delay is dominated by the hydrostatic component, which is accurately modelled using surface pressure only

The remaining part:

- is called *wet delay*
- is difficult to parameterize in terms of surface meteorology
- is responsible for most of the noise in geodetic applications
- is *closely related with atmospheric humidity* and therefore is of interest in meteorology

GNSS as a meteorological observing system

General aspects

Advantages

- dense observing networks can be built and maintained with 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

GNSS as a meteorological observing system

Observations

In their raw format, the observations consist of a group of *pseudorange measurements* between the transmitting GNSS satellite and the receiver

Geodetic processing allows production of meteorological observations:

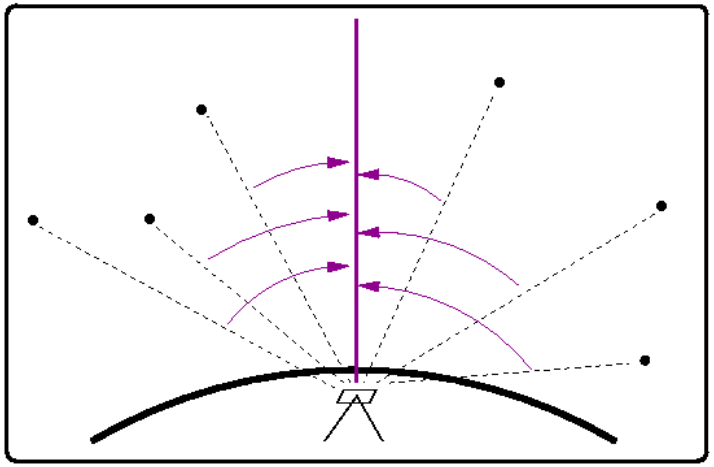
- Zenith Delays
  - Integrated Water Vapour
- Slant Delays

GNSS as a meteorological observing system

Zenith Delays

Zenith Total Delay (ZTD) represents tropospheric delay in a vertical column

- Zenith Hydrostatic Delay (ZHD) represents surface pressure
- Zenith Wet Delay (ZWD) represents the amount of water vapour in the vertical column



GNSS as a meteorological observing system

Integrated Water Vapour

Using atmospheric temperature and humidity profiles, ZWD can be converted to Integrated Water Vapour (IWV)

$$IWV = \left[10^{-6}\left(\frac{k_3}{T_m} + k_2'\right)\rho_v R_v\right]^{-1} ZWD$$

This can be useful for comparison purposes (e.g. against radiosonde measurements or satellite retrievals)

However, the conversion *increases noise level* and *complicates the observation error statistics*

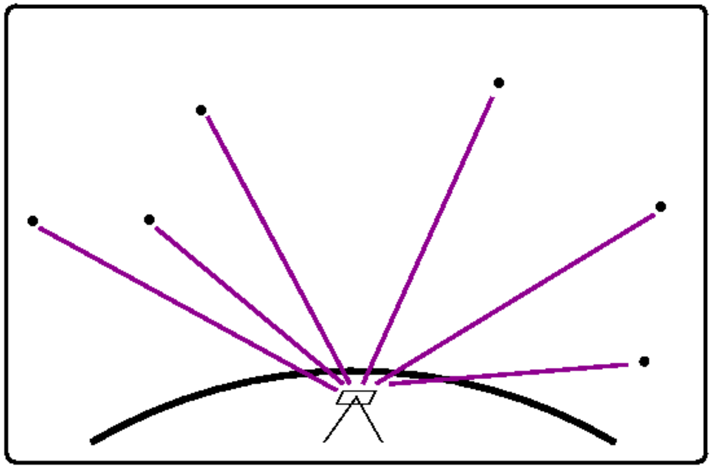
➔ use of IWV is not recommended in data assimilation

GNSS as a meteorological observing system

Slant Delays

Slant Total Delay (STD) represents tropospheric delay along the actual signal path through the atmosphere

STD can be separated in hydrostatic and wet components and processed further to Slant Water Vapour (SWV)



GNSS as a meteorological observing system

Observations from NWP point of view

Zenith Delay

- Processing and assimilation architectures *close to operational*
- *Isotropic atmosphere* assumed – may be suboptimal near fronts
- Shows potential for *nowcasting*, *synoptic scale data assimilation* and *climate monitoring*

Slant Delay

- Processing and assimilation methods are still *under development*
- Captures *anisotropic structures* in fine scales, e.g. humidity gradients
- Shows potential for *fine scale data assimilation* and *tomography*

Observation modelling

Tropospheric Delay

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

Observation modelling in the HIRLAM model

Zenith Total Delay

Interpolation of the model state gives $ln\ p_S$ and vertical profiles of T and q at the receiver location

- compressibility factors are assumed unity (hydrostatic balance)
- the profiles are shifted vertically to correspond the receiver height
- ZHD is obtained from $ln\ p_S$
- ZWD is obtained from the numerical integration of q/T in vertical
- ZTD = ZHD + ZWD

Observation modelling in the HIRLAM model

Slant Total Delay

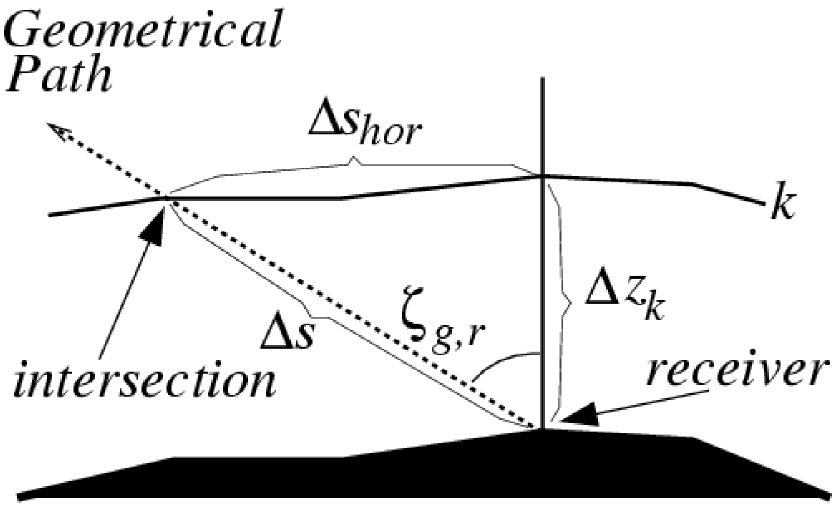
The first task of the STD modelling algorithm is to determine the signal path

- the satellite azimuth and zenith angles are used
- 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

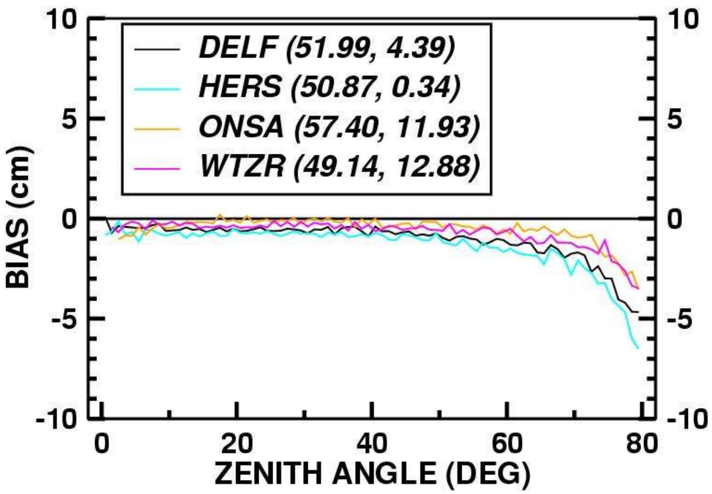
Integration of refractivity along the signal path

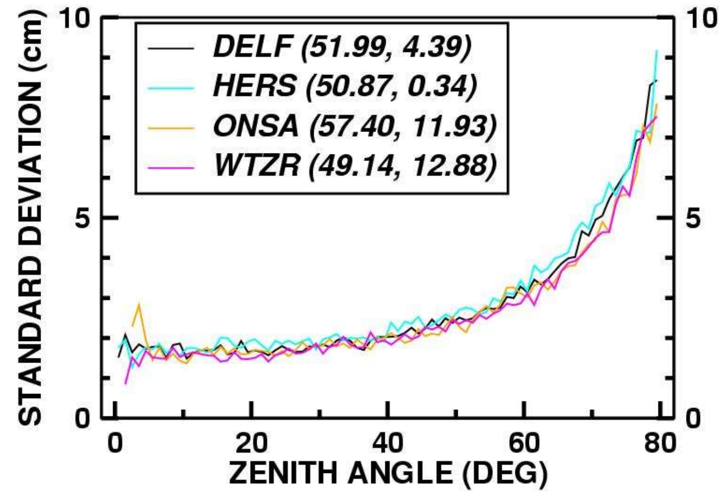


Eresmaa and Järvinen, 2006: An observation operator for ground-based GPS slant delays. *Tellus*, **58A**(1), 131-140.

Observation modelling in the HIRLAM model

Slant Total Delay bg-ob statistics





The modelled STD is systematically lower than the observed; especially at large zenith angles

- can be an indicator of incorrect modelling algorithm

Biases are specific for receiver station, but standard deviations are not

ZTD data assimilation

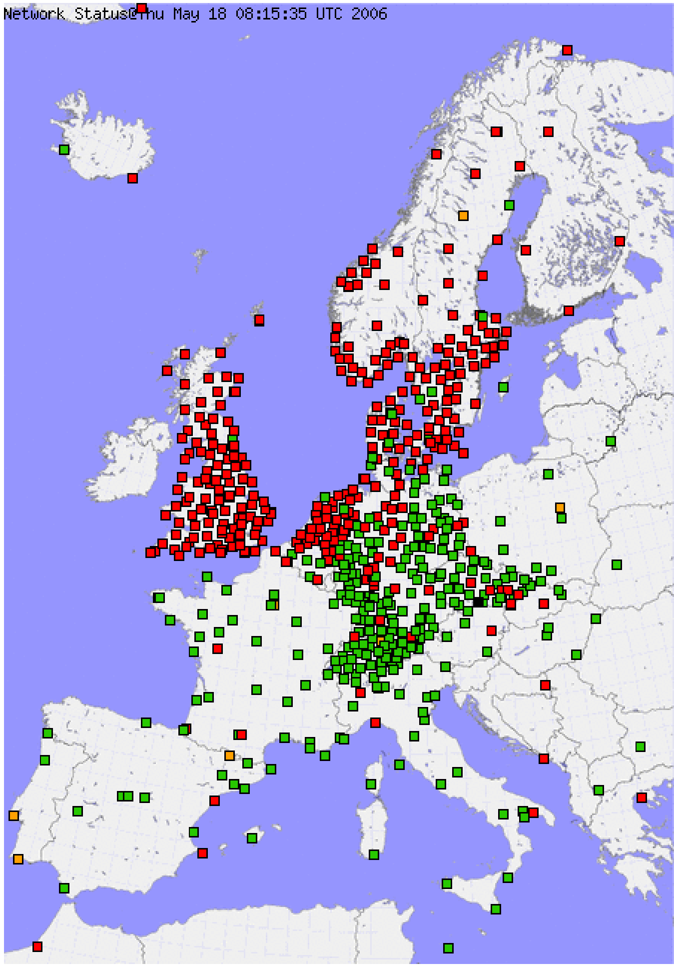
Near real-time data flow in Europe

Currently more than 500 receiver stations in Europe provide data for ZTD processing

Geodetic processing by more than 10 analysis centres

Drawback: the observations are not consistent with each other, since different analysis centres use different processing strategies!

The geographic distribution of the observations is exceptionally irregular



EUMETNET GPS Water Vapour programme: E-GVAP

ZTD data assimilation

Impact on Numerical Weather Prediction

Assimilation experiments with ZTD data show neutral to slightly positive impacts on NWP

Problems to be dealt with

- *Data quality is inhomogeneous* as several analysis centres are processing ZTD with different processing methods
- Observations are *significantly biased*, and the biases are specific for receiver station
- Spatial and temporal *observation error correlations* are difficult to be accounted for

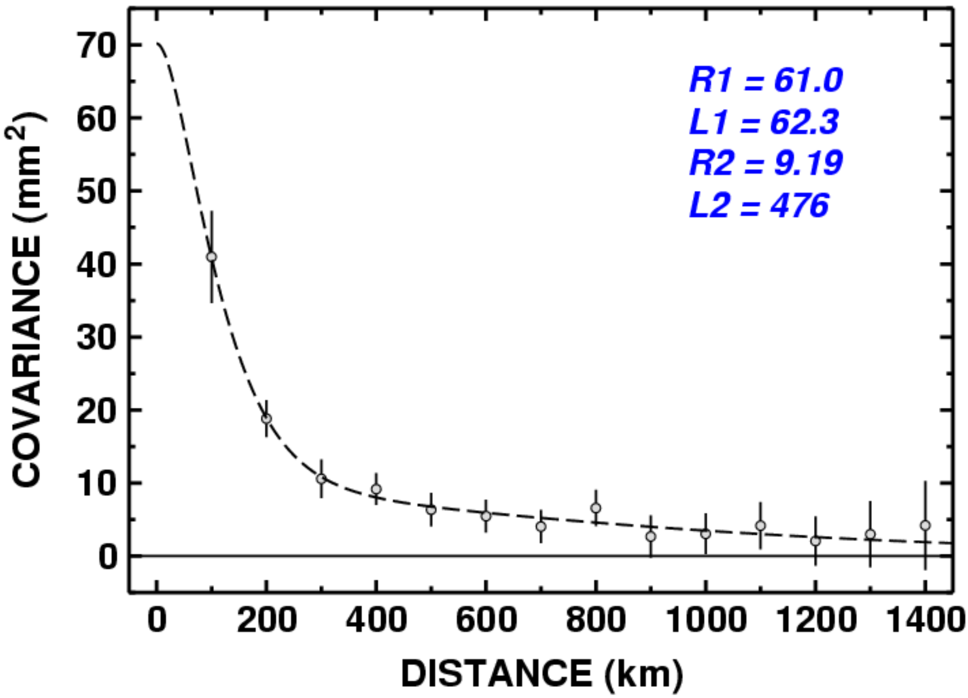
ZTD data assimilation

Spatial observation error correlation

ZTD observations show error correlations in *spatial length scales of several hundred km*

However, application of *a proper algorithm for bias correction* might eliminate the need for specifying the error correlations!

$$f(r) = R_1\left(1+\frac{r}{L_1}\right) exp\left(-\frac{r}{L_1}\right) + R_2\left(1+\frac{r}{L_2}\right) exp\left(-\frac{r}{L_2}\right),$$



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Further reading

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