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GPS Slant Delay Assimilation in COSMO-DE

M. Bender, K. Stephan, Ch. Schraff, R. Potthast

GPS Data Assimilation

The GPS microwave signals are delayed by the Earth's atmosphere. The delay depends on the atmospheric state along the signal path and is a valuable tool for atmosphere sounding. The Slant Total Delay (STD) by the neutral atmosphere is given by

$$STD = 10^{-6}\int_S N(s)\,ds + S - G$$

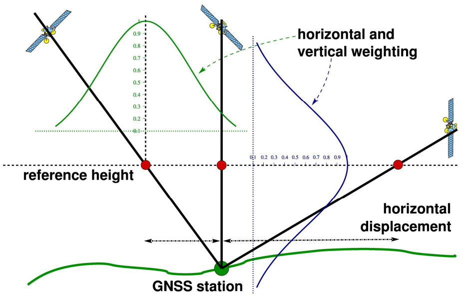
where N = 10^6 (n-1) is the refractivity, n is the refractive index, S is the curved signal path between the GPS satellite and the receiver and S-G is the difference between the geometric distance G and the length of the signal path S. The refractivity depends on the atmospheric state:

$$N = k_1\frac{p_\mathrm{d}}{T} + k_2\frac{e}{T} + k_3\frac{e}{T^2}$$

Here, p_d is the partial pressure of dry air, e is the partial pressure of water vapour, T is the temperature and $k_{1,2,3}$ are empirical constants.
The GPS assimilation operator estimates the STD using the model fields p, T, and rh. A raytracing algorithm provides the curved signal path S in the atmosphere which is required to evaluate the integral shown above.

Localisation of STDs

A **Local** Ensemble Transform Kalman Filter (LETKF) is used to assimilate the GPS STDs togeteher with other observations. The STDs are integrated along the whole signal path from the satellite to the receiver, hence are highly non-local observations. There is no established methodology where to place STDs within the LETKF and several localisation strategies need to be tested.



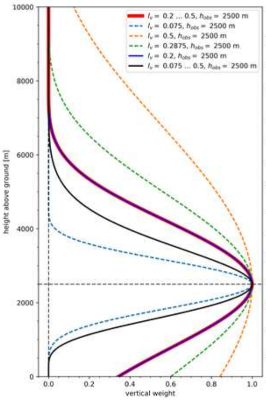
1) STD at the GPS station The contribution to the slant delay increases with decreasing height, i.e. the surface layer above the GPS antenna has the maximum impact.
2) STD above the GPS station The STD could be located in an optimum height above the station. This would also be done for assimilating ZTDs.
3) STD somewhere on the signal path The STD could be located in an optimum height on the signal path. This would lead to a horizontal displacement from the GPS station which depends on the height and the elevation of the STD.

The combination of a large number of STDs provides information about spatial atmospheric distributions, especially about the vertical humidity distribution, which is not contained in ZTDs. However, the assimilation system must be able to utilize this kind of information. The LETKF has no knowledge about the slant path and the localisation strategies 1) and 2) discussed above would lead to some STD mean value which is presumably comparable to ZTD assimilation. The third strategy might add some extra spatial information.

COSMO-DE Assimilation System

The German weather service (DWD) operates the limited-area numerical weather prediction model COSMO-DE with a horizontal resolution of 2.8 km and 50 hybrid vertical layers up to 22 km. Observations are assimilated in hourly cycles using an ensemble Kalman filter for convective-scale data assimilation (KENDA) which is based on the LETKF. The operational setup runs with a 40 member ensemble and uses latent heat nudging of radar precipitation. Currently, SYNOP, TEMP, PILOT and AIREP observations are assimilated.

LETKF analyses are based on observation minus first guess statistics from a sufficiently large ensemble. For each grid point all observations within the horizontal and vertical localisation length are considered and a set of weights is estimated which maps the first guess ensemble on the analysis ensemble. The localisation length can be defined for each observation type, in case of STDs there is also some freedom to choose their position.
For STD assimilation it seems that the assumed height of the STD and the vertical localisation length are most important. The STDs are located on the signal path 2500 m above ground. Depending on the elevation this leads to a horizontal displacement up to ~5 km (ε= 30°) or ~15 km (ε=10°), which is regarded by the LETKF.



The vertical localisation length l_v defines the vertical distribution of weights for each observation. The impact of an observation is limited to its surrounding if a small l_v Is chosen (l_v=0.075) and increases with increasing l_v (l_v = 0.29, l_v=0.5). A combination of observation height (here 2500 m) and l_v can be used to select a certain vertical range and a certain impact near the ground. A value l_v= 0.2 was chosen in the experiment.

Assimilation Experiments

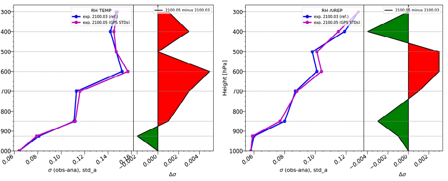
A number of assimilation experiments were carried out in an environment which is close to the operational setup but allows flexible variations of most parameters. The analyses were obtained with an hourly cycle and 24-hour forecasts were started every 6 hours. GPS data from more than 300 stations within the COSMO-DE region were available and the STD data were used together with the operational observations and latent heat nudging. STDs are available every 2.5 minutes but only the last data set within each hour is used to balance the number of STDs with the conventional observations.

GPS STD Assimilation Experiment	
Period	26.5. – 2.6. 2016
NWP System	COSMO-DE KENDA
Resolution	2.8 km
Forecasts	24 hours at 0, 6, 12, 18 UTC
Observations	SYNOP, TEMP, PILOT, AIREP + GPS STDs
STD Error	15 mm in zenith, mapped to STD
STD Localisation	horz. 20 km, vert. l_v = 0.2

Verification of Analyses

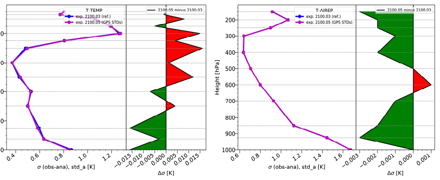
The hourly analyses of the assimilation cycle were compared to radiosonde (TEMP) and flight observations (AIREP). It turns out that the verification with AIREP data leads to much better results.

Verification of the vertical humidity distribution


Radiosonde
Flight Observations

The STD assimilation shows a positive impact on the standard deviation of the humidity in the boundary layer which is also supported by a positive verification with SYNOP data. A clear impact could be expected near the STD height of 2500 m (740 hPa) but cannot be seen in the data.

Verification of the vertical temperature distribution

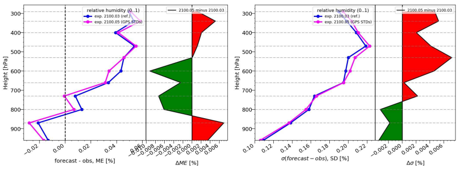


The impact on the temperature is quite small. The analyses don't show any strong impact at 2500 m where the weighting function for the STD data is close to one. One could even guess that the turning point from a positive to a negative impact is close to this height.

Verification of Forecasts

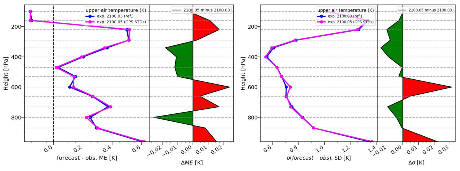
For each day of the experiment two 24 h forecasts at 0 and 12 UTC were investigated. At a lead time of 12 h all forecasts were verified with radiosonde profiles and compared to the reference experiment without GPS data.

Verification of the vertical humidity distribution


Mean forecast – obs.
Standard deviation

The STD assimilation shows a psitive impact on the humidity bias between 850 and 550 hPa (1500 and 4500 m) which is almost centered at the STD height of 2500 m (740 hPa). The impact on the standard deviation is almost neutral with a slightly positiv impact in the boundary layer.

Verification of the vertical temperature distribution



The impact on the temperature profile is almost neutral regarding the rather short period of the experiment.

Michael Bender
Michael.Bender@dwd.de

Deutscher Wetterdienst
FE12 Datenassimilation
Frankfurter Straße 135
D-63067 Offenbach