Ground-based GNSS receivers as a meteorological observing system

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Abstract

The microwave signals continuously broadcasted by the Global Navigation Satellite System (GNSS) satellites are influenced by the ionospheric and tropospheric effects as they travel through the atmosphere to the ground-based receivers. Using a sufficiently dense network of GNSS receivers, the impact of the neutral atmosphere, i.e. tropospheric delay, can be estimated as a by-product of the geodetic processing. Since these delays can be regarded as atmospheric humidity observations, there is potential for utilizing them in the meteorological applications, such as Numerical Weather Prediction (NWP) and nowcasting.

Several advantages can be attributed to the ground-based GNSS as a meteorological observing system. First, receiver networks can be built and maintained at a relatively low cost. Second, the quality of the processed delay observations is insensitive to the weather conditions. Third, the temporal resolution of the delay observations is high. On the other hand, there are still open questions to be solved before use in NWP can be expected to be effective. These include the proper handling of the observation biases and complicated observation error correlations, both spatial and temporal.

Activities targeting to operational assimilation of the GNSS delay observations have taken place at several NWP centres in Europe, including the Finnish Meteorological Institute (FMI). The three-dimensional variational data assimilation system (3D-Var) of the High Resolution Limited Area Model (HIRLAM) has been modified for assimilation of GNSS Slant Total Delay (STD) observations, i.e. the estimates of the tropospheric effect along the actual signal paths between the GNSS satellites and the receivers. The characteristics of the STD data assimilation are reviewed.

INTRODUCTION

Global Navigation Satellite System (GNSS) is the basis for many novel geodetic positioning applications. The two currently available navigation satellite systems are the Global Positioning System (GPS) and the Globalnaja Navigatsionnaja Sputnikovaja Sistema (GLONASS) maintained by the US and the Russia, respectively. The Galileo navigation satellite system, which is under development by the European Space Agency (ESA), is expected to be completed within the time frame of a few years. Ground-based GNSS meteorology is an example of a scientific application taking advantage of the GNSS.

The ground-based GNSS meteorology serves primarily the atmospheric humidity monitoring. Humidity plays a key role in several atmospheric processes relevant for Numerical Weather Prediction (NWP). However, the existing observing networks are not capable of detecting humidity in the high spatial and temporal resolutions required by the future NWP systems. Since dense GNSS receiver networks can be built at a low cost and they can provide observations with high temporal frequency, the meteorological potential of such a new observing system is high.
METEOROLOGICAL GNSS OBSERVATIONS

According to the definition used in the geodetic literature, the tropospheric delay $\Delta^T$ is an integral of refractivity $N$ along the path $s$ taken by the microwave signal through the atmosphere (e.g., Hofmann-Wellenhof et al., 2001):

$$\Delta^T = 10^{-6} \int N ds.$$  \hspace{1cm} (1)

Refractivity $N$ of the neutral air is governed by pressure $p$, temperature $T$ and specific humidity $q$ according to

$$N = \frac{k_1 p}{T} \left( \frac{k_2 - k_1}{0.622 + 0.378q} \right) + \frac{k_3 qp}{(0.622 + 0.378q)T^2},$$

where the refraction coefficients are $k_1 = 77.60$ K/hPa, $k_2 = 70.4$ K/hPa and $k_3 = 3.739 \times 10^5$ K$^2$/hPa (Bevis et al., 1994).

Zenith Delay observations

The meteorological GNSS observations are by-products of geodetic positioning with highly sophisticated estimation software packages. The most easily processed meteorological observation is Zenith Total Delay (ZTD), which is an estimate of the tropospheric delay for a signal approaching the GNSS receiver from the local zenith direction. Processing of ZTD makes use of so-called mapping functions defining the ratio between tropospheric delay at zenith and at any other elevation angle. By using additional surface meteorological data, ZTD can be further processed into Zenith Hydrostatic Delay (ZHD), Zenith Wet Delay (ZWD) and Integrated Water Vapour (IWV) (Bevis et al., 1992). These additional processing steps increase the observation error and complicate the error covariance structures.

Both geodetic processing and meteorological data assimilation methodologies for ZTD are currently close to operational implementation at several institutes. In Europe, for instance, there is a continuous flow of ZTD observations processed in near-real-time from more than 500 receiver stations by more than 10 geodetic analysis centres. The impact of ZTD assimilation on NWP forecasts has been investigated by data assimilation experiments. On average, these experiments show mainly neutral or slightly positive impacts on precipitation forecasts. However, in cases of high convective activity, the benefit of assimilating ZTD data seems to be more significant (e.g., Vedel et al., 2004).

From the point of view of data assimilation, ZTD is a somewhat problematic observation due to the heavy preprocessing procedure. The observation error statistics, needed for the optimality of the data assimilation, have turned out to be difficult to determine. The slowly varying observation biases are different for different receiver stations. There are non-negligible observation error correlations in large spatial and temporal scales (Eresmaa and Järvinen, 2005). Moreover, since the ZTD data at continental scale is a mixture of analyses of several geodetic institutes having different analysis strategies, the ZTD observations are not necessarily consistent with each other.

Slant Delay observations

Estimation of the tropospheric delay along the actual slanted signal propagation path is another processing approach. This approach leads to Slant Total Delay (STD) observations. The geodetic processing methods currently in use favor estimation of ZTD instead of STD, since the measurement random noise can be much more efficiently filtered out from ZTD observations than from STD observations. Consequently, the STD observation accuracy is worse than ZTD observations.
The processing methodologies and the data assimilation techniques for STD are still at the stage of development. The potential advantage of STD observations lies in their ability to capture the fine-scaled anisotropic atmospheric features, such as steep horizontal humidity gradients. Such anisotropic features are most typically associated with mesoscale weather systems often accompanied by large precipitation amounts. During these conditions, assimilation of STD instead of ZTD is expected to be more optimal choice. However, the benefit of STD observations is expected to be of significance mainly in mesoscale NWP systems with grid spacings of the order of 5 km or smaller. It is likely that the NWP models with coarser grids do not explicitly describe the anisotropic features in sufficient detail.

DATA ASSIMILATION OF SLANT DELAY OBSERVATIONS

The three-dimensional variational assimilation system (3D-Var) (Gustafsson et al., 2001; Lindskog et al., 2001) of High Resolution Limited Area Model (HIRLAM) (Undén et al., 2002) has been modified for enabling data assimilation of STD observations. These modifications include the coding of the observation operator and its tangent-linear and adjoint versions, as well as estimation and specification of the observation error statistics and tuning of the observation quality control parameters. No extensive assimilation experiments have yet taken place.

Slant Total Delay observation modelling

In principle, variational data assimilation methods allow assimilation of any observed quantity, as far as the observation can be reasonably accurately modelled as a function of the model state variables. In the case of ground-based GNSS observations this means that neither the ZTD nor the STD observations need to be explicitly converted to humidity observations. Instead, an algorithm for the observation modelling needs to be written. This algorithm is called observation operator in the NWP terminology.

Eresmaa and Järvinen (2006) give a detailed description of the STD observation operator implemented in the HIRLAM model. The observation operator is built upon the concept of Geometrical Path (GP): the points, where the GNSS signal intersects each of the NWP model levels, are determined making use of the geometrical azimuth and zenith angles of the satellite, as viewed from the receiver station and assuming the signal path to be a straight geometric line. A specific correction is included on top of the GP approximation in order to account for the refractive bending effect. Once the signal path is determined, the model quantities (logarithm of the surface pressure \( \ln p_s \), the temperature \( T \) and the specific humidity \( q \)) are interpolated from the grid points to the intersections using a bilinear interpolation. The refractivities at the intersections are obtained through Eq. (2). Numerical integration of refractivity is based on the assumption that the vertical refractivity distribution between two adjacent model levels is of the form

\[
N = \exp(a + bz)
\]  

(3)

as a function of geometric height \( z \). The parameters \( a \) and \( b \) are determined for each layer specifically. This allows analytical piecewise integration along the path to obtain the model counterpart of the STD.

The observation operator has been validated against geodetically processed STD observational data set. The data set is processed at the Delft University of Technology and it contains data from 17 receiver stations for period 1-24 May 2003. The geodetic processing method has been described by de Haan et al. (2002). The model counterparts (background values) have been produced using the observation operator with six hour forecasts of HIRLAM at 22 km grid resolution. Fig. 1 shows the mean and standard deviation of the background minus observation difference for four individual receiver stations as a function of zenith angle. The conclusions from Fig. 1 are as follows:
1) The background STD is systematically lower than the observed, especially at the large zenith angles. This might be interpreted as a deficiency in the observation operator. However, the systematic difference can also be due to observation biases.

2) The biases are different for different receiver stations. This indicates that the systematic observation errors are, at least partly, related with the local effects specific for each antenna – receiver combination.

3) The standard deviation increases rather uniformly with increasing zenith angle, as one might expect on the basis of increasing signal path length within the thickest parts of atmosphere. There are no significant differences between different receiver stations. It is concluded that the observation accuracy is about the same for all receiver stations in the network.

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**Figure 1:** Statistics of background minus observation difference for Slant Total Delay observations. Mean (left) and standard deviation (right) as a function of satellite zenith angle.

**Slant Total Delay observation error statistics**

The observation error statistics have been estimated using the same data set that was used for observation operator validation. The estimation method relies on determining the statistical properties of the background minus observation difference (innovation). Since the innovation is contributed not only by the observation error but includes also the contribution from the background error, some additional information is required for estimation of the statistical properties of the two contributors. We have chosen to use the randomization method (Andersson et al., 2000) for determining the background error statistics in observation space. Subtraction of the background error contribution from the innovation variance directly yields an estimate for the observation error variance.

Figure 2 shows the estimated standard deviations of the background minus the observation difference (solid line), the observation error (dash-dotted line) and the background error (dashed line). For all satellite zenith angles, the observation error is larger than the background error. This implies that the weight of the STD observations should be tuned lower than the weight of STD background values in the assimilation. Both the observation and the background error standard deviations increase with the increasing zenith angle. However, the increase is steeper for the observation error contribution. Our interpretation is that various nuisance factors affecting the GNSS measurements, such as the multipath and the antenna phase center variations, most notably increase the observation error at large satellite zenith angles. These factors have no effect on the delays modelled by the observation operator and NWP fields.
A statistically optimal analysis scheme also accounts for the observation error correlations. The implementation of the assimilation system allows specification of these as well, but so far these correlations have not been estimated. The effect of the observation error correlation in the STD data assimilation is highlighted in Figs. 3 and 4 showing the specific humidity analysis increment at a single HIRLAM model level in a single meteorological case.

The left panel of Fig. 3 shows the STD analysis increment in case where all of the observation errors are assumed to be uncorrelated, i.e. correlation coefficient is set to 0.0. The right panel shows the corresponding analysis increment for radiosonde observations, for which the assumption of uncorrelated errors is more justified. The patterns show certain similarities, e.g. the regions of positive and negative increments are roughly in the same place in the middle of the receiver network. However, the overall magnitude of the analysis increment for STD is obviously too large compared with radiosonde increment. In other words, uncorrelated STD observation errors result in too large analysis increment.

Figure 4 shows the STD analysis increment obtained by taking into account the error correlation between the observations from the same receiver station. The observation error correlation is set to 0.3, but the observation errors between different receiver stations are still assumed uncorrelated. The STD analysis increment is decreased notably and it is in a much better correspondence with the radiosonde analysis increment.

CONCLUDING REMARKS

The ground-based GNSS meteorology shows potential for atmospheric data assimilation and Numerical Weather Prediction. The main advantage of this concept is that it allows monitoring of atmospheric humidity with very high spatial and temporal resolution with reasonable costs.

Widely adopted variational data assimilation techniques support the direct assimilation of the meteorological GNSS delay observations into NWP systems. Assimilation of the ZTD observations is already very close to operational utilization. These observations assume horizontally isotropic refractivity distribution and are better suited for synoptic scale NWP systems. The STD observations can potentially capture the fine-scaled anisotropic atmospheric features and can therefore be very useful in areas with strong horizontal humidity gradients. Assimilation of STD observations are expected to become more important when the NWP development approaches kilometric scale modelling. However, the data processing and assimilation techniques for STD observations are still at a research stage.
Figure 3: The specific humidity analysis increment of STD (left) observations and of radiosonde observations (right) in a single case data assimilation experiment with the HIRLAM model. The STD observation error correlation is set to 0.0.

Figure 4: The specific humidity analysis increment of STD observations in a single case data assimilation experiment. The observation error correlation is set to 0.3.

The methodological development for assimilation of STD observations is ongoing. This paper reviews the activities taken at FMI for STD data assimilation. The observation operator has been implemented in the HIRLAM model, and the observation and background error standard deviations have been estimated for this new observation type. The focus will next be turned towards correct specification of observation error correlations and bias correction algorithms. Assimilation experiments are planned with HIRLAM with grid resolution of about 5 km.
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