Introduction
TOUGH (Targeting Optimal Use of GPS Humidity Measurements in Meteorology) is a research project supported by the EU 5th Framework Programme. The main purpose of this project is to develop and refine methods enabling the use of GPS data from existing European GPS stations in numerical weather prediction models, and to assess the impact of such data upon the skill of weather forecasts. The contributions from the Chalmers are:

- GPS data analysis in near real time
- Assessment and characterization of correlated estimation errors (spatial as well as temporal)
- GPS system research, assessing the stability and accuracy of time series of the estimated atmospheric propagation delays.

GPS Data Analysis
We have operated the NKGS GPS data analysis center, first during COST Action 716, and later during the TOUGH project. The Swedish GPS network SWEPOS consists of 21 geodetic stations (on temperature controlled concrete pillars on bedrock) and 45 other permanent reference stations (mostly on top of buildings). A total of 26 stations deliver data from Denmark (on a test effort basis). Data from additional stations, mainly in northern Europe, are also processed; resulting in a total of about 115 stations that deliver data every hour. On the average the bulk of the estimated Zenith Total Delays (ZTD) are delivered around the stipulated maximum delay of 1 hour and 45 minutes.

Spatial and Temporal Correlation of the Estimation Errors for the Zenith Total Delay (ZTD)

We have studied the spatial correlation structure of the estimation errors when the GPS technique is used to derive the atmospheric propagation delay in the zenith direction. These error correlations are parameterized using an analytical function. For spatial scales smaller than 200 km the GPS error correlations become significant; for larger spatial scales, the error correlations are small and slowly decreasing with distance. These results are based on a study of the differences between the propagation delays obtained from the HIRLAM numerical weather model, and the corresponding GPS estimates.

The temporal correlations of the propagation delay estimation errors are also examined and the decorrelation times are of the order of 1–2 days. The temporal correlation results are derived for Swedish GPS sites, using the relation between the estimation errors for the vertical coordinate and the zenith propagation delay. The longer correlation times are found for the inland stations in the northern parts of Sweden. One explanation for this effect is the possible accumulation of ice and snow on the antennas and the remaining atmospheric delays.

We have also performed a statistical assessment of reprocessed SWEPOS data, using different elevation cut-off angles, we find significant differences in the estimated trends of the ZTD time series. We have compared the different techniques of GPS, VLBI, WVR, and radiosondes (RS) in terms of estimating the Integrated Precipitable Water Vapour (IPWV):

- VLBI: +0.03 ± 0.01 mm/yr
- RS: +0.04 ± 0.01 mm/yr
- WVR: +0.13 ± 0.01 mm/yr
- GPS: +0.24 ± 0.01 mm/yr

The influence of vegetation

Many continuously operating GPS sites are located nearby areas of vegetation. As the size and characteristics of the vegetation change with time, it is important to assess the impact of vegetation on the GPS signal and the ZTD time series estimated from the observed signals. The effect is most clear on the GPS signal and the ZTD time series estimated from the receiving antenna and the orbiting satellites. We have studied the spatial correlation structure of the estimation errors when the GPS technique is used to derive the atmospheric propagation delay in the zenith direction. These error correlations are parameterized using an analytical function. For spatial scales smaller than 200 km the GPS error correlations become significant; for larger spatial scales, the error correlations are small and slowly decreasing with distance. These results are based on a study of the differences between the propagation delays obtained from the HIRLAM numerical weather model, and the corresponding GPS estimates.

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