FUTURE

A primary goal in TOUGH was bringing the state of the art in ground-based GPS meteorology to a mature level, rendering it useful to *operational* meteorology, hence improving European weather forecasts.

A meteorological GPS observing system: In the new E-GVAP project (EUMETNET GPS Water Vapour Programme), started April 2005, 11 European national met offices are in collaboration with geodesists transferring the TOUGH and COST716 GPS network into an observing system for NRT GPS ZTD data collection for operational use. More countries will gradually join, and the network will extent and densify. TOUGH recommendations will be used to optimize the system.

Use of GPS delays in meteorology: Many European met offices now plan to start utilising NRT GPS ZTD data in their operations. This will be done in various ways: 1) Validation and improvement of weather models via comparison to GPS observations. 2) Data assimilation of the GPS data into numerical weather prediction models, improving the forecasts. 3) As a tool for now-casting (short term forecasting), via maps integrated water vapour made from GPS ZTD observations.

Climate monitoring: For climate monitoring the long term stability of measurement series is of vital importance. The results from TOUGH regarding long term biases, co-ordinate system biases, and inter-comparison of different GPS processing methods will help improve stability.

GPS slant delays: GPS slant delays represent a next step in ground based GPS meteorology. They provide additional information about the local variability of the atmosphere. In TOUGH, GPS slants were confirmed to be a promising type of new meteorological observations. More slant delays per ground station will become available when the European Galileo satellite system is launched. Optimal use of GPS slant delays in meteorology requires further research.

DMI, March 2006

TOUGH

Danish Meteorological Institute (coordinator)
Swedish Meteorological and Hydrological Institute
Met Office, UK
Instituto Nacional de Meteorologia de Espania
Univ. degli Studi di L'Aquila, CETEMPS, Italy
Royal Netherlands Meteorological Institute
Finnish Meteorological Institute
ACRI-ST, France
Chalmers Univ. of Technology, Sweden
Norwegian Mapping Authority
Agenzia Spaziale Italiana
Inst. d'Estudis Espacials de Catalunya, Spain
Swiss Federal Office of Topography
Res. Inst. of Geodesy, Topo. & Cart., Czech Rep.
Technische Universiteit Delft, Netherlands

Collaborating organisations

COST ACTION 716
University of Purdue, USA
GeoForschungsZentrum Potsdam, Germany
European Commission, Brussels, Belgium

CONTACT POINTS

www: tough.dmi.dk
email: tough@dmi.dk

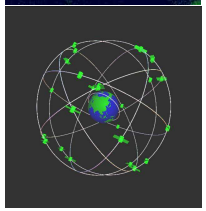
TOUGH

Targeting Optimal Use of GPS Humidity Measurements in Meteorology

FINAL RESULTS

TOUGH was a shared-cost project (contract EVG1-CT-2002-00080) co-funded by the Research DG of the European Commission within the RTD activities of the Environment and Sustainable Development sub-programme (5'th Framework Programme).

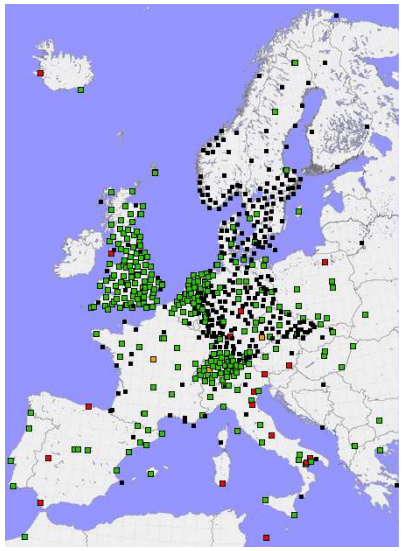
The principle of GPS meteorology



About 24 active Global Positioning Satellites (GPS) orbit the Earth. They purpose is to enable fast positioning by use of GPS receivers. However, the atmosphere bends and delays slightly the GPS radio-signals. This effect can be be measured, and the delays are directly related to properties of the atmosphere of importance to weather forecasting. In the case of ground-based receivers these are the pressure at the GPS antenna and the water vapour above. Utilisation of GPS derived atmospheric delays to improve weather forecasting and climate monitoring we call *GPS meteorology*.

How to utilise GPS observations in meteorology in an optimal way is an area of intense scientific research. TOUGH is an inter European project, launched in order to address key issues in ground based GPS meteorology. TOUGH started February 2003 and ran until January 2006.

GPS receivers

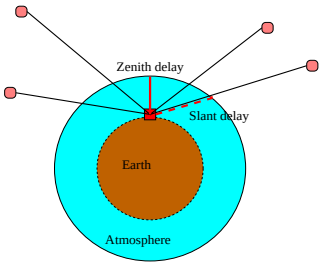


GPS receiver sites, January 2005

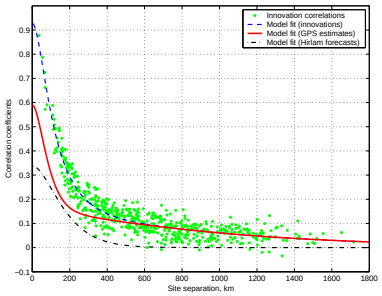
TOUGH RESULTS

In TOUGH we have made and tested methods to improve use of ground-based GPS data in numerical weather prediction (NWP) and climate monitoring. Among other things we have:

- Improved our ability to determine in near real time (NRT) good estimates of the zenith total delay (ZTD) from GPS observations. During the course of TOUGH the timelag between GPS observation and NRT ZTD estimation has gradually decreased. Likewise the quality of the NRT ZTD estimates has gradually improved. Both compared to estimates based on alternative data, and compared to more precise, post processed GPS delay estimates. The different softwares for estimation of NRT GPS ZTDs were found to produce comparable results.

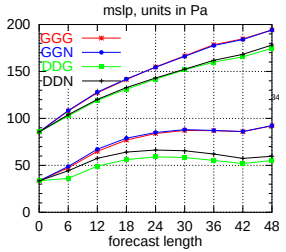


- Studied long term biases and their relation to cut off angle, GPS antenna calibration, environment, and reference frames.
- Made recommendations for a future European NRT GPS observing network.
- Studied error correlations for GPS ZTDs in space and time, and developed a method for correction.

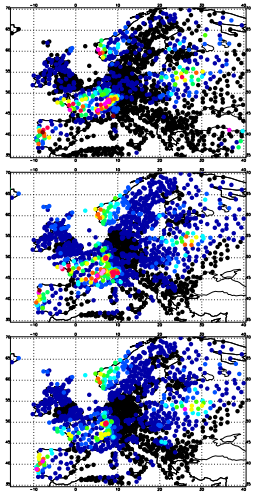


Spatial error correlation for the GPS -NWP ZTD offsets. Red line is the estimated error correlation for the GPS ZTDs.

- Developed methods for estimation of GPS slant delays, estimated GPS slants for a network in the Netherlands, determined their error characteristics, and made tools for assimilation of GPS slant delays in NWP models. The tools were proven to work properly in two data assimilation impact studies.
- Extensive impact studies have been made to investigate and optimise the benefit of using ground-based GPS-data in NWP. It is found that forecasts made with NRT GPS data are on average better than without. In particular the GPS data improve forecasts of medium to heavy rain, in some studies also properties such as surface temperature, pressures, and cloudiness. There are also examples of negative impact.



Statistical verification of surface pressure (July 2003). RMS and bias. High resolution model is green/black with/without GPS, low res. model is red/blue. An improvement in bias is seen for high res. model with GPS.



Precipitation over 12 hours on 2003-10-03.

Upper figure is observations. Middle figure is forecast with GPS data. Bottom figure is forecast without GPS data.

Black-blue-yellow-red runs from no, over light, to heavy rain.

- Made recommendations regarding the use of NRT GPS data in operational weather forecasting.

TOUGH User Workshop

A TOUGH User Workshop was held at the UK Met Office in September 2005, to inform a wider audience about the results obtained in TOUGH. The workshop was attended by specialists in GPS-meteorology and GPS data processing. The presentations from the workshop are available as electronic proceedings at http://tough.dmi.dk.