TOUGH

Targeting optimal use of GPS humidity measurements in meteorology

TOUGH team
Xiang-Yu Huang, Henrik Vedel, DMI, Denmark
Nils Gustafsson, Martin Ridal, SMHI, Sweden
Adrian Jupp, David Offiler, John Eyre, Met Office, UK
Beatriz Navascues, Jose Garcia-Moya, INM, Spain
Rossella Ferretti, Claudia Faccani, Guido Visconti, LAQ, Italy
Siebren de Haan, John de Vries, Sylvia Barlag, KNMI, The Netherlands
Heikki Jarvinen, Reima Eresmaa, FMI, Finland
Odile Fanton d'Andon, Olivia Lesne, Weiping Jiang, ACRI, France
Gunnar Elgered, Jan Johansson, Chalmers Tech. Univ., Sweden
Oddgeir Kristansen, Halfdan Pascal Kierulf, Hans-Peter Plag, NMA, Norway
Francesco Vespe, Rosa Pacione, ASI, Italy
Antonio Rius, IEEC, Spain
Elmar Brockmann, LPT, Switzerland
Jan Dousa, Vratislav Filler, GOP, Czech Rep.
Hans van der Marel, TUD, The Netherlands

Collaborating team
Eric Calais, Jennifer Haase, Wen-Yih Sun, Purdue University, USA

Contact information: tough@dmi.dk

Scope of the TOUGH project

Knowledge of the atmospheric distribution of water vapour is of key importance in weather prediction and climate research. It is tightly coupled to processes like energy transfer, precipitation, and is an important greenhouse gas. However, currently there is lack of knowledge about the actual humidity field, due both to a shortage of observations and a sub-optimal handling of humidity in the data assimilation systems, which are used to make estimates of the actual atmospheric field. Such fields are used to start numerical weather prediction models and for climate monitoring.

Global Positioning System (GPS) signals are particularly sensitive to water vapour; observations from ground based GPS receivers can provide additional information related to the atmospheric content of humidity.

The TOUGH project is to develop and refine methods enabling the optimal 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 TOUGH project is a new project, to start in year 2003, funded in part by the above institutes and in part by the European Commission.

Objectives of the TOUGH project

The TOUGH project has the following main objectives:

- Carry out research to optimise the assimilation of ground-based GPS in numerical weather prediction models. This research will include, among other things, a proper modelling of the GPS measurement errors and application of more advanced, 4-dimensional, assimilation techniques. Each step/component in the optimisation of the assimilation techniques will be verified by impact studies.
- Develop methods for use of GPS slant delays in numerical weather prediction.
- Running a research mode data collection, by co-ordinated pre-processing and distribution of ground-based GPS measurements from an all-European network through a few European processing centres in support of the proposed data assimilation research efforts. This work will be closely linked with the COST 716 Action. The data processing centres will provide pre-processed data from subsets of the total European network, and each subset of the data should have comparable error characteristics. These error characteristics will be documented through comparisons of data from stations included in several of the network subsets (network overlap).
- Investigate the benefit of using ground-based GPS-data in numerical weather prediction using the improved assimilation software through extended parallel data assimilation and forecast experiments, with and without ground-based GPS measurements, covering all four seasons. Special emphasis will be devoted to the verification of precipitation forecasts.
- Promote the idea of an operational utilisation of ground-based GPS measurements to the numerical weather prediction community in Europe.

TOUGH work plan

WP#	Work Package Name	Start	End	Year 1	Year 2	Year 3
1000	**Management**	**00**	**36**			
1100	Overall Management	00	36			
1200	Scientific Coordination	00	36			
1300	Data supply co-ordination	00	36			
1400	Meeting preparation and participation	00	36			
2000	**User Requirements**	**00**	**03**			
3000	**Error Modelling for variational assimilation**	**00**	**24**			
3100	Bias reduction schemes	00	24			
3200	Modelling of spatial error correlation	00	24			
3300	Modelling of temporal error correlation	00	24			
4000	**Variational assimilation development and tests**	**00**	**36**			
4100	Develop and optimise 4Dvar assimilation	00	33			
4200	Mesoscale data assimilation development and tests	00	36			
5000	**Optimisation of GPS/surface humidity assimilation**	**00**	**36**			
5100	Refining methods of surface humidity assimilation	00	24			
5200	Testing combined GPS / surface humidity assimilation	24	36			
6000	**Development of methods for use of slants delays**	**00**	**36**			
6100	Slant delay retrievals	00	30			
6200	Slant delay validation and observation error studies	06	24			
6300	Observation operator development	00	18			
6400	Assimilation tests	18	36			
7000	**Assimilation impact statistics / extreme case studies**	**00**	**36**			
7100	Co-ordination of case studies and compiling results	00	36			
7200	Case studies and extensive impact studies	06	30			
7300	EUCOS scenario impact studies	00	24			
8000	**GPS ZTD data provision and monitoring**	**00**	**36**			
8100	Product quality monitoring and reporting	00	36			
8200	NWP User GPS ZTD/IWV data server maintenance	00	36			
8300	Regional GPS ZTD data production	00	36			
8400	Furnishing continuous radiosonde and NWP output	00	36			
8500	Validation database development and maintenance	00	36			
8600	User validation and feedback	03	33			
9000	**GPS ZTD System Research**	**00**	**30**			
9100	Robust quality indicators	00	09			
9200	Long term bias elimination	00	30			
9300	Co-ordinate system biases	00	24			
9400	Biases correlated with seasonal signals	00	24			
9500	Optimal combination of regional solutions	00	09			
10000	**Exploitation and dissemination**	**00**	**36**			

Expected starting time: Primo 2003

The GPS measurements

The raw GNSS data consist of ranging measurements from visible navigation system satellites such as the Global Positioning System (GPS). If the positions of the satellites and receivers are precisely known, the ranging measurements can be used to detect delays due to the atmosphere. This is possible since the propagation speed of the radio signals is sensitive to the refractive index of the atmosphere, which is a function of pressure, temperature and humidity, and the ionospheric electron content. The ionospheric delay is dispersive and can be removed using observations on two frequencies. The remaining accumulated delay for a raypath is the integral of the refractivity along the trajectory of the ray through the atmosphere:

$$d = 10^{-6}\int_l N\,dl \quad \text{where} \quad N = k_1\frac{P_d}{T} + k_2\frac{e}{T} + k_3\frac{e}{T^2}$$

The refractivity N is described as a function of temperature T, the partial pressure of dry air P_d, and the partial pressure of water vapour e and constants, k_1, k_2, and k_3, which have been determined experimentally (Smith et al 1953, Thayer 1974, Bevis et al 1994). Small scale horizontal variations may be neglected, to first order, so that observations at all satellite elevation angles can be mapped to a single zenith delay value which can either be used directly or transformed to integrated water vapour with auxiliary information on the surface pressure field (Bevis et al 1992).

Since the concept was initially proposed, the quality of the data has steadily improved through several major efforts, for example the EC projects MAGIC (Haase et al 2001, Vedel et al 2001), WAVEFRONT (Dodson et al 1999), NEWBALTIC (Emardson et al 1998), CLIMAP(Haas et al 2001), and the U.S. ARM (Gou et al 2000), GPS/STORM (Rocken et al 1995), CORS (Fang et al 1998).

MAGIC (Meteorological Applications of GPS Integrated Column Water Vapour Measurements in the Western Mediterranean) was a 3-year research project financed in part by the European Commission to develop the tools necessary for the meteorological users to integrate the GPS derived humidity products into their numerical weather prediction models, and test these models in severe storm situations. In the project, a prototype system for deriving and validating robust GPS integrated water vapour (IWV) and zenith tropospheric delay (ZTD) data sets was developed, both in post-processing and near-real-time mode. An extensive a database of 1.5 years of ZTD data is available for more than 50 sites in Spain, France, and Italy. The database has been validated through continuous comparisons with radiosondes. The comparison shows differences with a standard deviation on the order of 10 mm ZTD or the equivalent error in IWV of 1.6 kg/m^2. The continuous comparison with independent data sets demonstrated that there are long-term differences that require further investigation, especially for climate applications. This includes biases and seasonal variations of the amplitudes of the offsets between
GPS and radiosonde ZTD´s, see figure 1. Continuous comparisons with HIRLAM NWP fields show a standard deviation of 17 mm ZTD or 2.7 kg/m$^{2.}$ A higher standard deviation for the HIRLAM fields than radiosondes indicates that there is significant information contained in the GPS observations that is unknown to the NWP model, and hence the potential to improve the model.

Assimilation of ZTD data in NWP models

Early trials to assimilate simulated ground-based GPS measurements with simplified variational data assimilation schemes were carried out by the Mesoscale Meteorology group at the National Centre for Atmospheric Research (NCAR), Boulder, USA (Kou et al 1996, de Pondeca et al 2000). The main limitation of these early NCAR trials with variational data

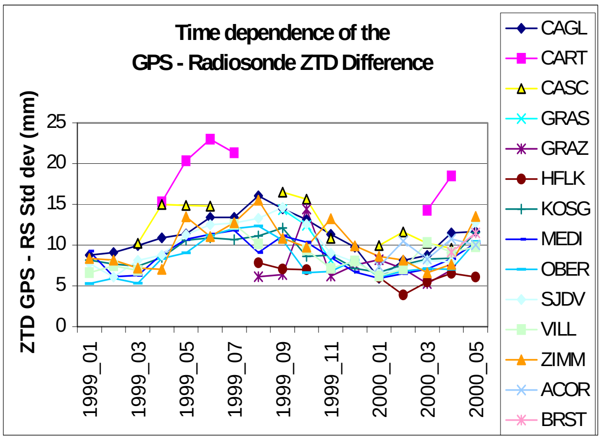

Figure 1. Time dependent behaviour of the standard deviation of the GPS versus radiosonde ZTD difference over a 1.5 year time period in the Mediterranean area.

assimilation of GPS data was the lack of a proper description of the background error covariances, thus the forecast errors were not properly accounted for and therefore the assimilation became sub-optimal. The more mature variational data assimilation schemes developed by European weather services for operational purposes included proper background error constraints. The meteorological services involved in the COST 716 Action and the MAGIC Project developed and tested 3D variational methods for the assimilation of ground-based GPS data. Assimilation tests were carried out for a 2 weeks period in June 2000. The overall large scale statistical impact on forecasts of temperature, wind, and humidity fields was neutral when comparing to high quality meteorological observations predictions by forecasts with and without GPS ZTD data added to the pool of ordinary observational data in the data assimilation. This was not unexpected, given the number of GPS ZTD observations compared with conventional observations. However, rainfall forecasts for a specific case, studied in detail because of severe rain in the period, were improved, see figure 2. This was a very encouraging result, that was undetectable in the overall statistics, but has the potential to have a significant socio-economic impact, since these intense short duration high precipitation events are a principal cause of weather related damage in the Mediterranean region.

On the other hand, COST 716 data assimilation tests for the same June 2000 period and for Central and Northern European model integration areas have indicated significant bias (systematic observation error) problems associated with the GPS Total Zenith Delay measurements. These bias problems were temporarily avoided by introduction of bias reduction algorithms**,** based on a comparison between GPS measurements and forecast model data. The origin of the problem is yet not clear, however. Simulation studies and results from trials to model the spatial correlation of GPS observation errors support the possibility of slowly varying and horizontally correlated observation errors associated with the GPS measurements.

As can be seen in the TOUGH workplan above addressing these issues will be part of the TOUGH project. Further the project will, among other things, include development and test of software for production and assimilation of slant delays and for 4DVar data assimilation of GPS data.

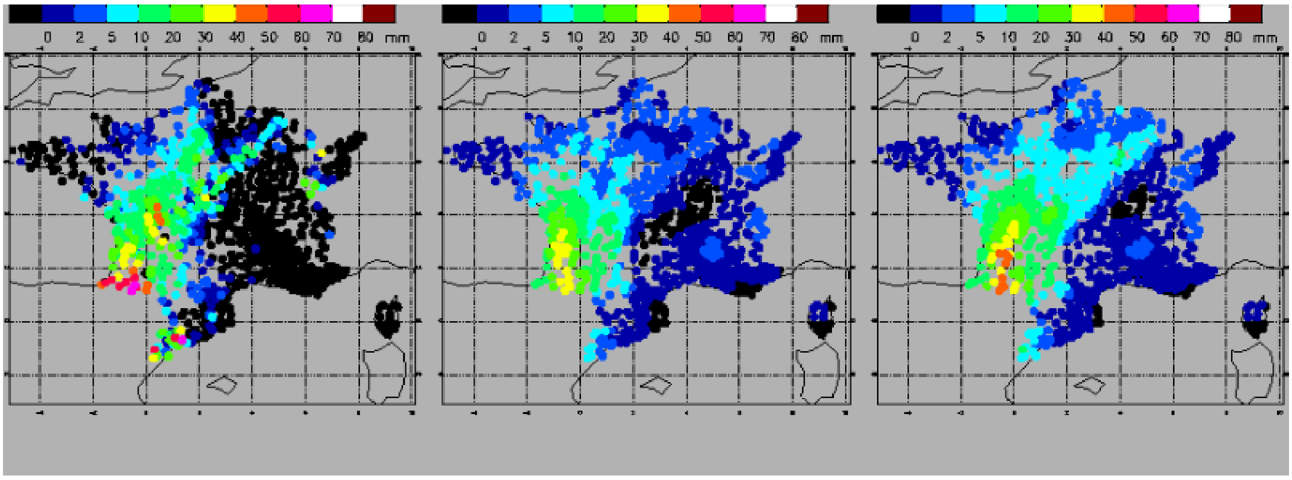

Figure 2. Observed 12 hour accumulated precipitation for period of high rainfall in the Pyrenees and north-eastern Spain (left panel), forecast precipitation without GPS data (centre panel), forecast precipitation with GPS data (right panel).

References

Bevis, M., S. Businger, T.A. Herring, C. Rocken, A. Anthes, and R. Ware, *J. Geophys. Res.*, *97*, 15,787-15,801, 1992.

Dodson, A., B. Buerki, G. Elgered, A. Rius, and M. Rothacher, *WAVEFRONT Final Report*, October, 1999

De Pondeca, M.S.F.V and Zou, X., *Tellus*, 53A, 192-214, 2001.

Emardson, T.R., G. Elgered, and J.M. Johansson, *Journal of geophysical research*, *103* (D2), 1807-1820, 1998.

Fang, P., M. Bevis, Y. Bock, S. Gutman, and D. Wolfe, *Geophys. Res. Lett.*, *25* (19), 3583, 1998.

Guo, Y.R., Y.H. Kuo, J. Dudhia, D. Parsons, and C. Rocken, *Monthly weather review*, *128* (3), 619-643, 2000.

Haase, J., H. Vedel, M. Ge, and E. Calais, *Physics and Chemistry of the Earth (A), 26(6-8), 439-443,2001*.

Haas, et al., *CLIMAP final report*. 2001.

Kuo, Y.-H., Zou, X. And Guo, Y.-R., *Mon. Wea. Rev*., 124, 122-147, 1996.

Rocken, C., T.V. Hove, J. Johnson, F. Solheim, R. Ware, M. Bevis, S. Chiswell, and S. Businger, *J. of Atmos. and Ocean. Technology*, *12*, 468 - 478, 1995.

Smith, E.K., and S. Weintraub, *Proc. IRE*,, *41*, 1035-1037, 1953.

Thayer, G.D., An improved equation for the radio refractive index of air, *Radio Sci.*, *9*, 803-807, 1974.

Vedel, H., K. S. Mogensen, X.-Y. Huang, , *Physics and Chemistry of the Earth*, 26, p497, 2001.