TOUGH

Targeting Optimal Use of GPS Humidity Measurements in Meteorology

Deliverable D73

GPS Data Recommendations for European Numerical Weather Prediction

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Summary

One of the main goals in the TOUGH project has been to address the question: "Are ground-based near real time GPS delay data beneficial to numerical weather prediction?". To address it, sequences of long term impact studies have been made using near real time GPS data from most of Western and parts of Eastern Europe.

The answer has turned out to be: "Yes". Based on that we *recommend that European numerical weather prediction centres start prepare themselves for the use of ground-based near real time GPS data in their operations.*

Is has also been found that, to avoid intermittent problems with the NWP forecasts, certain improvements are recommended prior to the inclusion of the European near real time GPS data in operational NWP simulations. Both as regards the handling of the GPS delay data in the NWP data assimilation systems, and as regards the production of the near real time GPS delay data.

In the present report we give first an overview of the NWP impact results from TOUGH. Secondly we provide recommendations what should be done when moving from the current state of ground-based GPS meteorology to an operational phase.

Background

During the three year TOUGH project the Danish Meteorological Institute (DMI), the Instituto Nacional de Meteorologia de Espana (INM), the Universita' degli Studi di L'Aquila, CETEMPS (LAQ), and the UK Met Office (MetO) have performed long term impact studies as well as case studies to test the impact of adding ground-based near real-time (NRT) GPS data to the numerical weather prediction (NWP) models used to forecast the weather. These studies have been carried out as parallel studies, in which a control run, corresponding more or less to the operational runs made a the weather centres, is compared to a NWP simulation in which NRT ground-based GPS atmospheric data are added to all the other observational data being used in the operational setups. The GPS data have been assimilated either in the form of zenith total delays (ZTDs) or integrated water vapour (IWV). The assimilation systems were based on 3DVar or nudging.

Detailed descriptions of the results obtained at each centre can be found at the TOUGH homepage, http://tough.dmi.dk, as deliverables D45 to D48. A comparison of results is made in deliverable D49.

In addition to the above 'standard' impact studies the INM has in collaboration with the Swedish Meteorological and Hydrological Institute (SMHI) done corresponding long impact studies in which an additional source of humidity information, namely 2 metre relative humidity, RH2m, has been assimilated, both with and without GPS ZTD's being assimilated. This work is reported in the deliverables D30 to D32, and also in D46.

A number of additional impact studies have been made addressing specific issues:

A particular aspect when assimilating observational data into NWP models is how to deal with errors of the observations and the errors of the NWP models.

Different, standard treatments have been followed in the above work. In addition to this SMHI and INM have done experiments in which a short term station dependent bias correction have been included in the assimilation procedure (see D16-D17, D46). SMHI and the Finnish Meteorological Institute (FMI) have in collaboration with Chalmers University of Technology done experiments in which the spatial error correlations of the GPS ZTD's are corrected (see D18-D20), while DMI have done a study in which an attempt is made to take the temporal error correlations into account (D23).

A 4DVar impact study for GPS ZTD has been done at DMI (D24).

At the Royal Netherlands Meteorological Institute (KNMI), FMI and DMI experiments with assimilation of GPS slant total delays have been performed, with the Technical University of Delft producing the slant delay data (see D33-D40).

At the TOUGH User Workshop Meteo France reported from a 4DVar impact experiment with NRT GPS ZTDs (included in D72, the TOUGH User Workshop proceedings).

In conclusion 4 institutes have done long term assimilation studies, while in total 7 meteorological institutes have been working on the assimilation of ground-based GPS data in one way or another in the TOUGH project. It is based on those results that the recommendations in this report have been made in a working group consisting of all 7 institutes.

8 additional institutes partake in TOUGH as providers of NRT GPS data: ACRI-ST, Chalmers University of Technology, Norwegian Mapping Authority, Agenzia Spaziale Italiana, Institut d'Estudis Espacials de Catalunya, Swiss Federal Office of Topography, Reseach Institute of Geodesy, Topography and Cartography - Pecny, and Technical University of Delft. They not only provide the NRT GPS ZTD data necessary for the above mentioned assimilation experiments, but were also involved in much of the research carried out in TOUGH. Further GeoforschungsCentrum Potsdam became an associated member of TOUGH, and NRT GPS ZTDs were being made available also by SGN, ROB and BKG. Without their contributions, and the contributions by the owners of the GPS receivers sites themselves, the assimilation experiments upon which these recommendations are based could not have been made.

In the following we first describe the NRT GPS ZTD data, then the NWP setups used by MetO, LAQ, INM, and DMI and the results of their impact trials. Before the discussion and conclusion we sum up the plans for near future use of ground-based NRT GPS data at each of the 7 NWP partners in TOUGH. (It might be of interest to see what the people making recommendations plan to do themselves!)

The impact studies and their results

The ground-based NRT GPS delay observing system

The GPS data analysis centres provide NRT GPS ZTDs for the location of each involved GPS station. The ZTD is sensitive mainly the pressure at the station and the amount of water vapour in the atmosphere above the station, but depends also weakly on temperature. At each processing centre the estimation of the NRT GPS ZTDs is based on processing of GPS data from from a network of GPS stations. The different GPS data processing centres have been using different processing softwares, and also slightly different approaches in their processing strategies; for example regarding GPS satellite orbit information, cut-off times for GPS data download, etc.

During the coarse of TOUGH the NRT GPS delay observing system has increased significantly, in both geographical extent, amount of data, and number of centres processing ground-based GPS delays in NRT. At the end of TOUGH the situation is:

- NRT GPS data were available from the following countries: Belgium, Czech Republic, Denmark, France, Germany, Italy, the Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, United Kingdom, plus a small number of sites in additional European countries.
- The number of unique GPS stations has increased from 150 to 550, thanks to both partners in TOUGH and associated processing centres. (The GPS station operators are acknowledged for their cooperation.)
- The number of NRT GPS ZTD processing centres increased from 5 to 12.
- The amount of observations increased from 222 k observations/month to 1000 k observations/month.
- All centres met timeliness requirements for regional NWP for at least 4 contiguous months at some time during the project. Data delivery to end users were robust during the project. Today 99% of the data are on GTS in BUFR format.
- The analysis centres have demonstrated generally consistent results (among themselves and with NWP models), despite the different softwares and strategies used.

Setups and results of the impact studies

The NWP model and assimilation systems used at DMI, INM, LAQ and METO differ significantly on the general level. Similarly there are large differences in the centres specific setup for use of NRT GPS data, both regarding pre-processing and in the way in which the data are treated during the data assimilation itself. An overview of the setups is provided in the table 1 (continues over two pages). Among the differences to be noted are:

- Use of GPS data from selected (positive list) or all data processing centres.
- Use of bias correction, calculation method for bias.
- Screening during pre-processing.
- Assumed observation error.
- Variational quality control (change of weight given to observations during assimilation stage according to the size of the temporal offset between an observation and the model, and the error statistics.)

A summary of the results is provided in table 2. It should be noticed that whereas 'standard' verification methods have been used for part of the objective verification, the verification systems are not fully identical at different meteorological institutes.

The GPS data provide additional information about humidity, which have lead to the belief that GPS data might be particularly valuable to the NWP models regarding forecasts of precipitation. Further, precipitation is a property of great importance to the costumers of NWP model results, yet the NWP models are far from perfect in forecasting it. Specific attention has therefore been paid to verification of precipitation. However, precipitation verification is difficult. Precipitation and humidity fields varies much faster, both spatially and time-wise, than other key atmospheric quantities considered in meteorology, such as pressure, wind, and temperature. This makes the standard objective statistical methods used for verification of NWP model results less well proscribed for precipitation. Secondly the precipitation data to which the different met centres have access are not the same, with differences in both geographical coverage, density of measurements, and integration time for measurements. The subjective verification for the case studies have therefore in particular been focused on precipitation. On maps of observed versus predicted precipitation a forecaster might see similarities in structures and/or intensity, where access to the NWP model data would have helped them issue a forecast in a particular situation - even in cases where the objective statistical comparison does not reveal a positive impact.

The INM have for their statistical verification of precipitation been using data from the high density Spanish climate network, up-scaled and gridded similar the NWP model. This makes their verification more robust against some of the problems normally encountered in objective precipitation verification. It is noteworthy that when using this method INM get a positive result, whereas 'ordinary' statistical verification give them a negative results. Comparing to the other centres it should noticed that the INM objective precipitation verification was performed using only Spanish data.

	MetO	LAQ	INM	DMI
Model	UM (Unified model), non-hydrostatic, Mesoscale mode	MM5, non-hydrostatic	HIRLAM, hydrostatic	HIRLAM, hydrostatic
Grid	11 km and 38 vert. levels, height based UK coverage	Nested, 27 and 9 km, 29 vert. levels (sigma levels)	1) 55km and 31 levels, 2) 22km and 40 levels, 3) 17km and 40 levels, hybrid levels	1) Nested 0.45 and 0.15 degree, first experiments 31 vert. levels, then 40. 2) 0.2 degree, 40 vert. levels hybrid levels
Boundaries	MetO Global model	analyses and forecasts from NCEP (and ECMWF, case studies only)	ECMWF forecasts, in some cases analyses	ECMWF forecasts, in some cases analyses
Nesting	1 way	2 way	1 way	1 way
Data assimilation	3DVar (4DVar)	3DVar, FDDA (nudging)	3DVar (4DVar)	3DVar and 4DVar
Control variables	Relative humidity, ψ, χ, unbalanced pressure, log of aerosol conc.	M (mixing ratio), ψ, χ, Φ_u	1) q_u, Vort., Div_u, $P_{s,u}$, T_u u=unbalanced, statistical back. err. structure func. 2) q, U, V, T, P_s analytical back. err. structure func.	q, U, V, T, P_s
Cycling	3h (3DVar), 6h (4DVar)	3h (NCEP+3DVvar) 6h (ECMWF+3DVAR) 3h (FDDA)	6h	6h 6h+3h reannalyses every 12 hour for DMI-HIRLAM at DMI
Other observations assimilated	Conventional ATOVS AMSU-B SSMI winds Quickscat winds	Implicit through use of NECP/ECMWF analysis fields ZTD/IWV (via HIRLAM) in MM5 resolution In case study: SYNOP, RS, SSMI	Conventional AMSU-A RH2m	Conventional ATOVS in some Quickscat in some

Table 1. Setup of NWP impact studies: General properties.

	MetO	LAQ	INM	DMI
GPS data selection	Selected processing centres Gross error check Closest survivor to analysis time Height offset > 300 m out Height correction	All sites used obs. near analysis time ($\pm$1h) are averaged Height correction	Selected stations from each processing centre obs. closest to analysis time gross error check (87mm resp. 56 mm) height correction	1) Obs. closest to anal. time, no gross error check 2) Obs. weighted averages according to processing centre and offset to anal. time 3) As 2, but including gross error check Height correction
Bias correction	28 days running average (Obs-fg)	No	1) No bias correction 2) SMHI 3-day running mean 3) Diurnal	no
Variational quality control	No	No	Var QC with 72 mm limit (effect small)	some experiments with QC limit 60mm, some without QC
σ_o used in data assimilation	8 mm	7 mm	adjusted $\sigma_{o,infl}$=18mm corresponding to standard σ_o=8mm	First runs with σ_o=10mm, other runs with σ_o=12mm

Table 1 (continued). Setup of NWP impact studies: Treatment of GPS data.

	MetO	LAQ	INM	DMI
Common variables verified	Neutral, except: RH mixed T2m neutral to positive Visibility neutral to positive	Neutral to positive Td positive (lower atmosphere, using GPS-PW)	Neutral, except: RH near surface positive T2m neutral to positive P_s neutral to positive in some cases	Neutral, except: T845hPa neutral to negative $H_{upper-air}$ neutral to positive T2m neutral to positive
Precipitation	**Obs.:** 6h acc. rain gauges **Objective:** ETS, RMS, FAR, POD, Missed: Neutral to positive at all thresholds	**Obs.:** 12h acc. rain guages **Objective:** ETS RMS, FAR, Bias, Accuracy: Neutral to positive **Subjective** (case studies): Positive	**Obs.:** 24h acc. rain guages from high resol. Spanish network, smoothed and gridded to resolution of NWP model **Objective:** ETS, TSS, POD, FAR, Bias: Negative for thresholds $<$ 1mm increasingly positive at larger thresholds. FAR negative, but POD more positive. **Subjective** (case studies): Tendency of better distribution of precip. in heavy precip events.	**Obs.:** 12h acc. rain gauges **Objective:** ETS, Accuracy, FAR, Bias: Negative at small thresholds, neutral at larger POD: Neutral at small thresholds, positive at larger. **Subjective** (case studies): Positive.
Precipitation tendency	Neutral	Neutral	Moistening of atmosphere. In general increased precipitation except for large thresholds.	Moistening Increased precipitation, but also correct decrease of precipitation in some medium to heavy precipitation events.

Table 2. Results of the impact studies.

Near future plans for use of ground-based NRT GPS data at the TOUGH NWP partner institutes

Institute	Operational NWP	Other use	Other	E-GVAP	GPS processing centre
MetO	Currently passive assimilation (monitoring). Possibly operational assimilation. Optimisation for 4D-Var	Verification and now-casting	Proposed GRAS SAF assim. s/w package.	Yes	Yes, UK, Rep. Ireland, N. Irish, Icelandic sites. Started
LAQ	Yes		No		No
INM	Currently passive assimilation, future active assimilation	Verification		Yes	No
DMI	Not yet, first further parallel impact studies	Monitoring and validation		Yes	No
KNMI	No plans	Possibly verification and now-casting		Yes	Yes, Dutch sites. Started
SMHI	Possibly operational assimilation	Probably validation		Yes	Yes, Nordic sites
FMI	No plans		Research on slant delays	Yes	

As regards processing of GPS data into ZTD the table lists the Netherlands, Sweden and the UK as countries where the meteorological institutes will be processing ground-based GPS data in NRT. They belong to the group of 11 countries: Belgium, Denmark, Finland, Netherlands, Iceland, Ireland, Norway, Sweden, UK that have within EUMETNET decided to start the project E-GVAP (EUMETNET GPS Water Vapour Programme). The purpose of that programme is to move from the current phase of NRT GPS ZTD processing into a phase for operational meteorology. Preparations for an operational NRT GPS ZTD observing system are also being made in a number of other European countries.

Conclusion and recommendations

In the TOUGH project 4 partners have carried out extensive impact studies, covering all seasons. The studies include a number of more detailed case studies of strong precipitation events. The NWP models utilised cover a wide range of model types and data assimilation system types. Notice that in the studies the NRT GPS data have been used in addition to all the data types normally used in an operational NWP setup, not in isolation. Under these circumstances it is well known that a large impact from a single extra observing system is not likely.

It has been found that ground-based NRT GPS data in general has a neutral to positive impact on NWP weather forecasts. We are confident that the GPS ZTD data when treated properly, are beneficial to the NWP models.

It has further been demonstrated that production and assimilation of the GPS ZTD data in NRT on a European scale is possible.

Based on that we recommend that European NWP centres prepare themselves for the use of ground-based NRT GPS data in their operations.

However, it has also been found that the NRT GPS ZTD observing systems, as well as the NWP pre-processing and data assimilation systems, are not yet at a stage where they can be considered mature for large scale operational use.

On the observing system side there are intermittent problems with the consistency of the NRT GPS products between different producers. In part this is because during part of the TOUGH project there was focus on timeliness issues. Now they can be demonstrably met focus on procedures for handling issues of data quality and homogeneity in processing and delivery are recommended.

On the NWP side there are difficulties in dealing efficiently with inhomogeneous data quality during the pre-processing and assimilation of the GPS data. Screening and data assimilation functions less well when some of the statistical assumptions behind do not hold. Standard assumptions are that all observation data of a given type, (e.g. NRT GPS ZTDs) can be described with the same statistical error characteristics (e.g., observation error of a given size, Gaussian error distribution centred on true state. It is straightforward to operate with observation errors individual to each site, but not to relax the assumptions about the observation error distribution.)

A separate, but related, issue is that the NWP data assimilation systems used here, as their control variable for humidity all use variables for which the statistical assumptions (Gaussian error distribution) about the errors of the control variables used in the data assimilation are not valid.

No clear conclusion has been found regarding the necessity of bias correction of the GPS ZTD data, and the timescale over which to estimate the biases. It may vary from region to region and NWP model setup to setup. It is clear that part of the bias is due to the NWP models, and that it varies regionally and with time.

It has been found (again) that verification of precipitation is difficult. Different types of verification (e.g. objective versus subjective, and raw rain gauge measurements versus gridded precipitation observations) can result in different conclusions. Much attention was paid to this in TOUGH.

Most institutes prefer to assimilate GPS ZTD, which is well suited to their assimilation systems. However, at LAQ the best results were obtained via assimilation of GPS-PW, with GPS-PW being derived currently via NWP model pressure information. Measurements of pressure, temperature at the GPS sites will enable an NWP model in-dependent conversion from GPS ZTD to GPS PW, which might be particular use full in regions with complex terrain. Similarly use of pressure measurements can improve on the assumptions made in the processing of GPS data to ZTD.

Recommendations regarding a ground-based NRT GPS ZTD observing system

As regards an observing system for NRT GPS delays for operational meteorology the partners responsible for the data processing have, based on their own work in TOUGH, on the validation work in TOUGH, and on discussions in TOUGH about the NWP results, made the following recommendations (copied from deliverable D57 'Final GPS ZTD/IWV system evaluation') for an ground-based NRT GPS ZTD observing system:

- All analysis centres shall use the same orbits and clocks (the best possible and available) and the same models (IERS conventions, effects such as tides).
- There is a need for central monitoring – agree on a common set of European stations included by all analysis centres, at least 10 key stations.
- Coordination between operators is important when selecting new station locations.
- A main concern is to understand the error characteristics:
  - Orbit and clock errors
  - The geodetic datum.
  - Mapping functions.
  - Ocean loading (period of 12 hours).
  - Antenna phase centre variations with AZ, EL, and time (ageing).
  - Multipath – very site (and time?) dependent.
- Analysis Centres monitoring activities shall include:
  - Data quality, including multipath characteristics coupled to station environment.
  - Timeliness and amount of data from each station.
- Centralised monitoring activities shall coordinate:
  - ZTD characteristics (mean, variability, random walk, etc.) and station coordinates (consistent time-series).
  - In particular the key sites are monitored in order to assess the level of agreement in ZTD and coordinates.
- Assimilation centres monitoring shall include:
  - Station performance (statistics from assimilation system).
- All monitoring results should be made publicly available, normally via a central web site, urgent matters handled differently.

Within EUMETNET the EUMETNET GPS Water Vapour Programme (E-GVAP) has been started. It is currently joined by 11 countries. Its purpose is to transform the current ground-based NRT GPS delay observing system into a system for operational meteorological use. This will be done in liaison with the geodetic community. It will include a data monitoring and feedback facility. The above recommendations will be considered by E-GVAP. Further information about E-GVAP can be found at http://egvap.dmi.dk. Also in a number of non E-GVAP countries processing in NRT of ground-based GPS delays is being (or has been) improved, and collaboration established with between the geodetic and meteorological sides. The data from those processing centres will also be monitored by the E-GVAP monitoring facility provided the NRT GPS data are made available to E-GVAP. A main issue to be solved is assuring access to GPS data for NRT processing into delays for countries in which NRT GPS delays are currently sparse. For commercial and political reasons this will often have to be solved on the national level.

In conclusion, we know how to make a NRT GPS delay observing system of the quality needed for operational meteorology, and the work has begun. Meteorological institutes not yet involved in this work are recommended to start work in this field.

Recommendations regarding use of NRT GPS ZTDs in NWP

Our main recommendation is that *NWP centres begin prepare themselves for use of NRT GPS in their operational, regional NWP forecasts.*

This includes:

- Start downloading NRT GPS delays to their databases and monitoring of it.
- Upgrade their data assimilation system so that it can assimilate GPS ZTD data or IWV data.
- Start producing the statistics of the observed NRT GPS - NWP first guess ZTD (or IWV) offsets on a station by station and producer by producer basis. This will:
  - Help determine whether bias correction is required for model and region of interest
  - Help deciding how to set up the pre-processing
  - Help decide which NRT GPS data to select from sites processed by more than one processing centre
  - Help decide whether the distribution of the offsets for some sites is so non Gaussian that the data should not be assimilated. - Help decide on the various limits to use in the variational quality control during data assimilation.
- Make impact studies with/without NRT GPS delays to determine optimal setup.
- Move toward use of data assimilation systems that can utilise the high time resolution of NRT GPS data (such as 4DVar).
- The NWP centres are encouraged to change their data assimilation control variable for humidity to a property with proper statistical errors (Gaussian distribution). For the NWP models utilised here that was not the case. This is not a problem specific to use of GPS data, but for GPS data it is of greater importance than for many other observation, as the ZTD (or IWV) is an integral measure, not an in situ measure, requiring significant skill of the data assimilation system to distribute properly the humidity deduced from a ZTD.
- Consider instalment of pressure and temperature sensors at GPS sites (or vice versa), in particular in regions with complex terrain.

As mentioned several European meteorological institutes are preparing themselves for NRT GPS as an observing system. It is less clear whether a corresponding amount of effort will be put on on improving to the operational level the ability of the NWP pre-processing and data assimilation systems to utilise in an optimal way the NRT GPS ZTDs emerging from this new type of observations. In both TOUGH and COST716 is was clear that progress in this area came slower and at a higher cost than on the observing system side. Much of the progress was made as a result of external funding - which is significantly less post-TOUGH. It is necessary that the NWP institutes themselves include also this type of work in their plans. Contacts between institutes to discuss results and further progress will be beneficial.

The EUMETSAT GRAS SAF, as part of its activities under the Continuous Development and Operations Phase (CDOP – to start in March 2007) is proposing to develop and maintain a formal deliverable software package to assist NWP centres to assimilate ZTD data in their operational models. This is to encourage more NWP centres to exploit this new data type without them having to develop their own data-specific software from scratch.

Now-casting Now-casting was not studied in TOUGH. Never-the-less we find it important to include in the recommendations. The time resolution of NRT GPS data is high. Currently 2-4 observations/hour with an update every hour, with a potential for faster updates in the future. From the observations, maps showing the evolution of the distribution of IWV can be made and used as a guidance for forecasters. This is a field which deserves more focus. Maps of IWV are now being produced in E-GVAP, visible via http://egvap.dmi.dk/

GPS slant total delays GPS slant total delays include information about the local variability of the water vapour field. More so when the Galileo satellite system is launched. In TOUGH methods were developed for estimation and assimilation of NRT GPS slant total delays. The results are promising. This is an area of research which deserves further support on the national and European level.