COST-716 Near Real-Time Demonstration Project

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Abstract

The operational potential of ground-based GPS data for Numerical Weather Prediction (NWP) is investigated in the European COST-716 action. A near real-time trial was started in March 2001 involving seven analysis centers, each processing a GPS network and delivering estimates of Zenith Total Delay (ZTD) to a gateway at the UK Met Office. In order to be useful for NWP the estimates must arrive within 1h45m. The network consists presently of about 250 GPS stations in Europe, of which several are processed by more than one analysis center.

In this paper an overview is given of the activities within the framework of COST-716, and the organization, results and achievements of the near real-time demonstration trial. The overall consistency between the GPS solutions is about 5-6 mm for the ZTD, or 1 kg/m^2 in terms of Integrated Water Vapor (IWV). The GPS ZTD estimates agree with zenith delays derived from radiosonde at the 10 mm level. Three analysis centers have demonstrated that it is possible to deliver more than 95% of the data within the time limit of 1^h45^m, routinely. For a demonstration phase, the current near real-time performance is shown to be capable of meeting the requirement, although improvement is desirable for a future operational scenario.

IWV is computed routinely from the ZTD estimated by GPS, using surface pressure and mean temperature from nearby synoptic stations. Although the new generation of NWP models can directly assimilate the ZTD from GPS, IWV turned out to be a very useful quantity as well for verification and comparison purposes, and as input for a number of newly developed forecasting tools.

1. Introduction

Global Positioning System (GPS) signals are delayed due to neutral molecules in the lower part of the atmosphere. In high precision geodetic applications the delay is estimated along with the geodetic parameters by introducing so-called Zenith Total Delay (ZTD) parameters. The ZTD can be separated into a hydrostatic and wet delay. Together with ground-level air pressure and temperature data, the Integrated (column) Water Vapor (IWV) can be inferred from the estimated ZTD, and it was soon realized that this would be a useful quantity for meteorological applications, see e.g. Bevis et al. (1992). The operational potential of this technique for Numerical Weather Prediction (NWP) application is investigated in various projects, e.g. the very dense Japanese network (Naito et al., 1998), SuomiNet in the USA (Ware et al., 2000), and in European projects such as MAGIC, CLIMAP, WAVEFRONT and the COST-716 action. In this paper an overview is given of the activities within the framework of COST-716, and the organization, results and achievements of the COST-716 near real-time demonstration project.

Within COST-716 a near real-time trial was started in March 2001 involving seven analysis centers, each processing a GPS network and delivering estimates of ZTD to a gateway at the UK Met Office in a well-defined format. In order to be useful in a near real-time environment such as NWP, the estimates have to arrive within 1^h45^m. The network consists presently of about 250 GPS stations in Europe, of which several are processed by more than one analysis center. The overall consistency between the GPS solutions is about 5-6 mm for the ZTD (1 kg/m^2 for IWV). For more than 140 stations the estimated ZTD is arriving at the Met Office within the time limit of 1^h45^m.

Although the estimated ZTD can be assimilated directly into Numerical Weather Prediction (NWP) models (see e.g. Baker et al, 2001), Integrated Water Vapor (IWV) is a very useful quantity as well. The IWV is computed routinely from the ZTD estimated from GPS, using surface pressure and mean temperature from nearby synoptic stations. A number of forecasting applications have been created using the IWV computed from GPS.

2. COST-716

In 1999 a European COST action was started to investigate the exploitation of ground based GPS for climate and numerical weather prediction applications:

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COST-716. COST is the French acronym for European co-operation in the field of scientific and technical research. COST-716 is a co-operative action of 15 European countries: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Hungary, Italy, Netherlands, Norway, Spain, Sweden, Switzerland and the United Kingdom. It brings together research and development groups from the fields of geodesy and meteorology. The primary objective of the action is "The assessment of the operational potential on an international scale of the exploitation of a ground based GPS system to provide near real time observations for numerical weather prediction and climate applications" (Elgered, 2001). Within COST only support is given for coordination of activities. There is no direct funding of research, hardware or software. The action is planned to continue until 2004.

The COST action 716 is divided into four projects, each run by a working group. For working group 1 (State of the art and product requirement) the participating countries have reviewed the current status in their country. The final report for working group 1 has been presented at the COST-716 workshop in Oslo by Pesec (2000), available from the COST-716 home page http://www.oso.chalmers.se/geo/cost716.html.

Working groups 2 and 3 became active in September 1999. The main task of working group 2 (Demonstration project) was to develop a near real-time demonstration system, including all the steps from data acquisition up to delivery to participating Numerical Weather Prediction centers, and to verify the operational reliability of the hardware and software codes. The first observations for the near real-time demonstration system were processed in March 2001. The system now comprises about 250 stations processed by 7 analysis centers in near real-time. To test and validate algorithms, dataflow, etc. for the near real-time demonstration working group 2 has also produced a reference dataset for benchmarking purposes.

The specifications for the near real-time demonstration system have been defined by working group 3 (Assimilation into NWP). This includes the user requirements from operational meteorology, climate research and climatology communities (COST-716, 2002), available from the cost-716 home page http://www.oso.chalmers.se/geo/cost716.html.
Working group 3 is also developing an approach for assimilation in Numerical Weather Prediction (NWP) models, and use in climate research and prediction and use in climate monitoring (climatology), and will make an assessment of the impact and sensitivity of GPS data. Working group 3 is also monitoring the timeliness and quality of NRT data delivered by working group 2.

Working group 4 (Planning for the operational phase) started in 2001. Working group 4 is reviewing several implementation options for a possible operational phase, including an assessment of optimal density and impact on current observing system, cost/benefit analysis and recommendations for international, operational work.

In addition to working group meetings, COST-716 has organized two workshops to promote co-operation within Europe. The first workshop was held 10-12 July 2000, in Oslo, Norway, and the second workshop took place 28-29 January 2002, in Potsdam, Germany. The final Workshop is planned for November 2003, in the Netherlands.

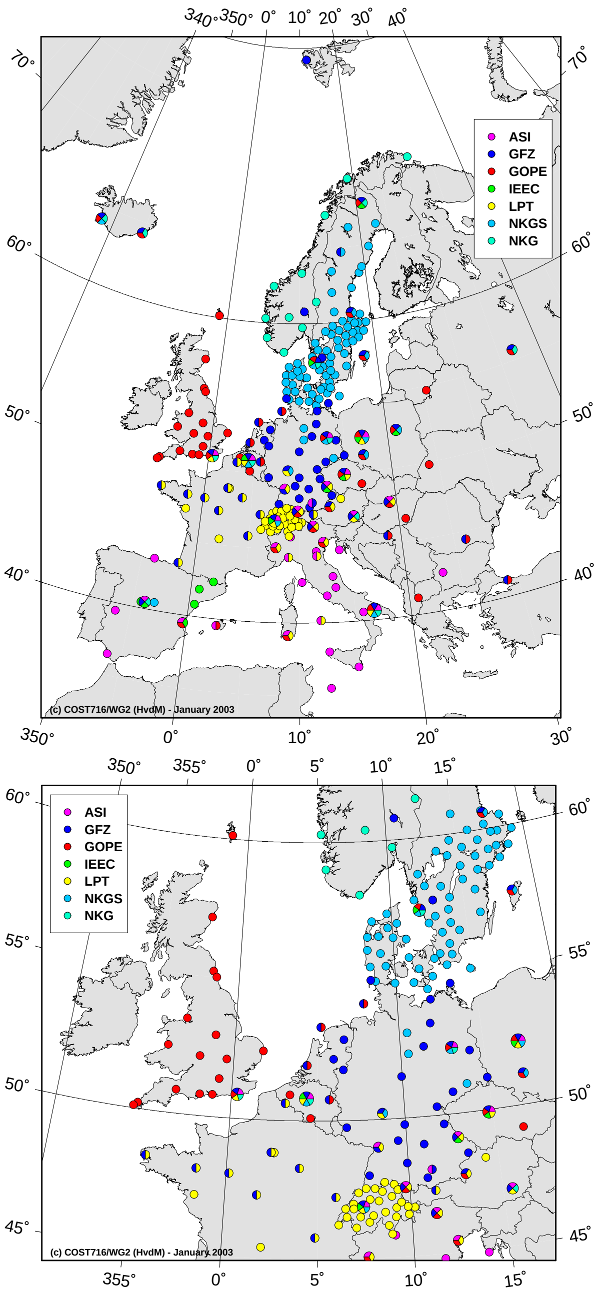

Figure 1. GPS stations in the near real-time network demonstration and analysis centers processing the data. Please note that only analysis centers are indicated. The data providers, on which the analysis centers rely for the data, are not listed in this figure (status of January 2003).

3. Near real-time network demonstration

One of the main goals of COST-716 is to demonstrate that it is possible to use data from ground based GPS for operational meteorology. For this reason a near real-time network demonstration has been organized using existing GPS infrastructure and analysis centers. The purpose of the near real-time network demonstration is threefold. Firstly, to prove that GPS networks can provide properly validated ZTD's in near real-time. Secondly, to create a dataset that can be used to assess the impact for NWP applications. Thirdly, to establish data formats and procedures, and verify hardware and software codes in an operational manner. To meet these requirements it was decided to organize the GPS processing around several near real-time networks, each handled by an analysis center.

In order to be useful for meteorology and climate applications, the networks should cover (at least) Europe and the Northern Atlantic as much as possible. The density and size of the networks primarily depends on the number of stations, within each area, which can provide NRT data, and can be handled by each network. Fig. 1 gives the geographical distribution of the stations with their analysis centers.

The analysis centers that participate in the near real-time demonstration are:

ASI	Agenzia Spaziale Italiana, Matera, Italy
GFZ	GeoForschungsZentrum, Potsdam, Germany
GOP	Geodetic Observatory Pecny, Czech Republic
IEEC	Institut d'Estudis Espacials de Catalunya, Barcelona, Spain
LPT	Federal Office of Topography, Wabern, Switzerland
NKG	Nordic Geodetic Commission (NKG); Statens Kartverk, Norway
NKGS	Nordic Geodetic Commission (NKG), Onsala Space Observatory, Sweden.

The near-real time demonstration started in March 2001 with two analysis centers, GFZ and GOP. GOP is processing a European network with stations from the UK (Dousa, 2002), while GFZ contributes stations from the German Atmospheric Sounding Project (GASP) network (Gendt et al, 2003), with some of the Dutch and French data. IEEC, ASI and LPT joined the demonstration network in respectively May, June and December 2001. ASI and IEEC are contributing two networks centered on the Mediterranean from the MAGIC campaign (Haase et al, 2001; Flores et al, 2000; Pacione et al, 2002). LPT is processing a very dense Alpine network centered on Switzerland, with some of the French stations (Brockmann et al, 2001). The Nordic Geodetic Commission, NKG, started to contribute data in April 2002, after having participated for a short period in October 2001. NKG is processing mainly two sub-networks of Scandinavian stations. The Norwegian stations are processed by Statens Kartverk, Norway (NKG), together with a number of global stations for orbit determination. Onsala Space Observatory, Sweden (NKGS), is providing a dense network for Sweden, and has recently added a large set of Danish stations. Presently, seven analysis centers are active, but contributions from one or two more analysis centers may be expected in the near future. For instance, ACRI (Valbonne, France) is planning to take over the one of the MAGIC networks that was originally processed by CNRS, France (Haase, 2001).

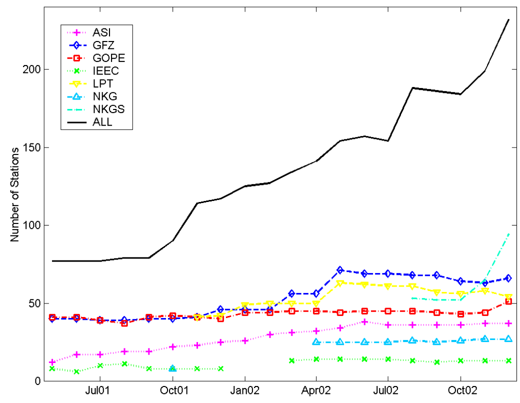

Figure 2. Number of GPS stations participating in the near real-time demonstration (May 2001 until December 2002).

Fig. 2 gives an overview of evolution of the number of stations in the near real-time demonstration from May 2001 until December 2002. In January 2003 the network consisted of a total of 247 stations, as shown in Fig. 1, of which 71 stations were processed by GFZ, 53 by GOP, 38 by ASI, 14 by IEEC, 63 by LPT, 27 by NKG Norway and 94 by NKG Sweden. GFZ and NKG Norway each are also processing about 25-30 globally distributed stations, which we have not counted (the network count is 276 when stations outside Europe are counted). About 27 stations are processed by two analysis centers, 12 stations are processed by 3 analysis centers, 9 stations are processed by 4 analysis centers, 5 stations by 5 analysis centers and 3 stations are processed by 6 analysis centers. The remaining 191 stations are processed by one analysis center. The actual number of stations observed at any given time is a little less because of occasional station outages.

Each of the contributing analysis center is relatively free to organize the processing as they think is best, as long as properly validated ZTD's with a well defined quality indicator are computed, and this data is made available within a target of 1 hour and 45 minutes to a ftp gateway at the Met Office using hourly files in the COST v1.0f format (COST-716, 2001a). This means that the analysis centers are free to decide which stations they process, to choose the software and processing strategy they prefer and the interval at which ZTD parameters are estimated. The reason for this strategy is very simple. Within COST only support is given for coordination of activities. There is no funding to buy any hardware or support analysis centers, so COST-716 has to build upon existing projects and initiatives. Another reason for not having strict guidelines is that, by having different analysis centers and strategies, it is possible to evaluate the advantages and disadvantages of each approach.

As each network handles the data issues within its own area, COST-716 has access to data that is not in the public domain or on anonymous ftp servers. Therefore, COST-716 is not limited to data available from only IGS and EUREF, but the spacing between the stations can vary significantly among the networks, as can be seen in Fig. 1. In addition, each analysis center will also need data outside its area in order to be able to give absolute estimates of ZTD and/or improve orbits in near real-time.

Table 1. Processing strategy for the NRT project.

	s/w-strategy	Elev. cutoff	window@ int	ZTD Intv.
ASI	GIPSY-SLW	10	24h@300s	15m
GFZ	EPOS-PPP	7	12h@120s	30m
GOP	Bernese-NEQ	10	12h@30s	60m
IEEC	GIPSY-SLW	10	24h@300s	15m
LPT	Bernese-NEQ	10	7h@30s	60m
NKG	GIPSY-PPP	10	24h@300s	15m
NKGS	GIPSY-PPP	10	3h@300s	15m

The analysis centers use different software packages and analysis strategies, as outlined in Table 1. GFZ and NKG use Precise Point Positioning (PPP), after having computed satellite orbits and clocks from a global network each. NKGS uses the NKG orbits and clocks if available in time, or else JPL's rapid orbits and clocks. ASI and IEEC on the other hand use a sliding window (SLW) approach using the IGS Ultra Rapid orbits, while GOP and LPT process the data on a hourly basis using normal equation stacking (NEQ) also using IGS Ultra Rapid orbits. The centers using Ultra Rapid orbits refrain from orbit adjustments, although all of them check the accuracy codes to exclude bad satellites. To increase the robustness of the NRT processing ASI, GOP and LPT also check the post-fit residuals to exclude possibly more bad satellites. None of the analysis centers estimate station coordinates simultaneously with the ZTD parameters. Instead, they keep the coordinates fixed onto the ITRF values or their own coordinate solutions, which they updated regularly (e.g. monthly) using longer time spans of GPS data. For more information on the processing strategies of ASI, GFZ, GOP, IEEC and LPT see respectively Pacione et al (2002), Gendt et al (2003), Dousa (2002), Flores et al (2002) and Brockmann et al (2001).

GOP is also providing ultra rapid orbits using a 3-hour update rate, as alternative to the IGS Ultra Rapid Orbits, and has studied its application within the COST-716 project (Dousa, 2003). During a 3-month test period both GOP and IGS ultra rapid orbits were used, giving similar statistical results in terms of ZTD quality, though occasionally some stability problems were observed in both orbit products.

For the exchange of ZTD data the COST v1.0 format is used (COST-716, 2001a). COST v1.0 is an ASCII format that can be converted easily into BUFR (WMO, 1995, COST-716, 2001b), the standard binary data format used on the GTS network, so that it can be inserted in the regular meteorological data flow on a continuous basis[1]. The COST format has been adapted from the CLIMAP format to include slant delays, processing statistics, q/c information and includes also surface meteorological data and IWV. COST files can contain data for more than one station (virtual files)[2]. The COST-716 files are uploaded once per hour by the GPS analysis centers to a ftp gateway at the Met Office, where they remain on-line for one week. The data is mirrored by a ftp server in Delft, which also maintains an archive of all the data on-line.

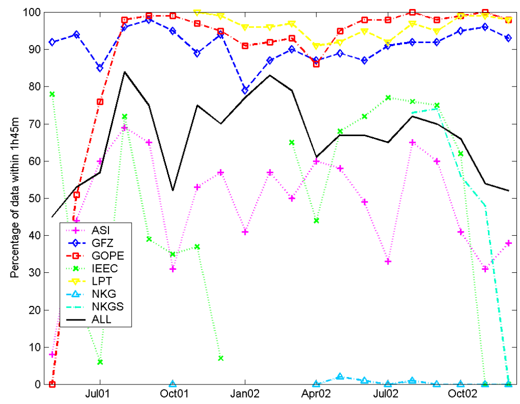

Figure 3a. Percentage of data arriving within 1^h45^m at the Met Office for various analysis centers for the period May 2001 until December 2002.

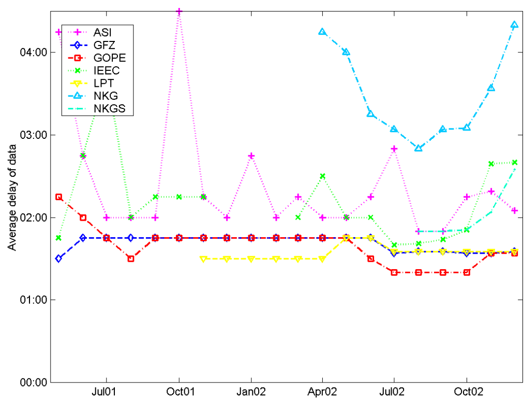

Figure 3b. Average delay of the data arriving at the Met Office for various analysis centers for the period May 2001 until December 2002.

At least three analysis centers are now capable of delivering more than 95% of the data within 1^h45^m, and the latency for the others is still improving, as is shown in Fig. 3. Fortunately, the analysis centers with the best

[1] A proposal for a BUFR specification for GPS has been submitted to WMO for approval to use on the GTS (COST-716, 2001b)
[2] The COST format does not contain any co-variance matrix information, which would be needed for a combined product.

scores are also the analysis centers processing most of the data. The top scores represent over 140 stations. Actually, the amount of data processed versus the latency is a delicate balance: waiting longer would mean more data, but also longer delay. Most of the datasets of the top three performers arrive just within 1^h45^m, as each waits as long as possible for the raw GPS data to arrive. The latency is measured as the difference in time between the time of the first ZTD estimate and time of arrival of the COST-716 file, which has as side effect that an increase in the ZTD rate will result in somewhat worse latencies even when the actual processing time remains the same. Therefore, analysis centers providing a higher ZTD rate are somewhat in a disadvantage concerning the measured latencies.

Although these results are already quite satisfactory, there is room for improvement. The latency of the hourly raw GPS data, and in particular the reliability thereof, is a limiting factor that could be improved. Another limiting factor that could be improved for some of the analysis centers is the availability of satellite orbits and clocks. For a demonstration phase, the current NRT performance is shown to be capable of meeting the requirement, and the indicated improvement is desirable for a future operational scenario.

Presently, it is not foreseen to combine the ZTD estimated by individual networks, but to make results available as soon as possible. This means that for some stations two or more estimates of ZTD will be available. A combination step would only delay the results, and add an additional layer of complexity. Also, combination of results is not advisable because the analysis centers do not follow the same guidelines or use the same software, and therefore, a pure mathematical combination will only degrade the individual results. Only a physically meaningful verification with NWP models can show the properties of the individual solutions. Because we do not plan to combine the ZTD, we can have different types of networks (regional and mesoscale) and different analysis strategies involving different sampling rates for the ZTD. The ZTD will be assimilated directly into NWP models; therefore, the GPS stations do not necessarily have to be equipped with meteorological sensors, though this is desirable for climatological applications.

The trial will continue at least until the end of the COST-716 action. It is likely that for an eventual operational phase a different organization is needed. This issue is addressed in COST-716 working group 4.

4. Benchmark dataset

The algorithms, dataflow, formats and assimilation into Numerical Weather Prediction (NWP) models have been tested on 15 days of GPS data, which were processed off-line, but to near-real time quality, for the period of June 9-23, 2000. In contrast to the actual demonstration, where analysis centers are processing different GPS sub-networks, all analysis centers processed a common network. The idea was to have a campaign that can be used to (i) test and validate the algorithms, dataflow, formats and assimilation into NWP models for the near real-time demonstration project, (ii) can serve as a benchmark against which to test various processing environments and assimilation into NWP, and (iii) to show the potential use of GPS-ZTD for NWP already in an early phase of the project.

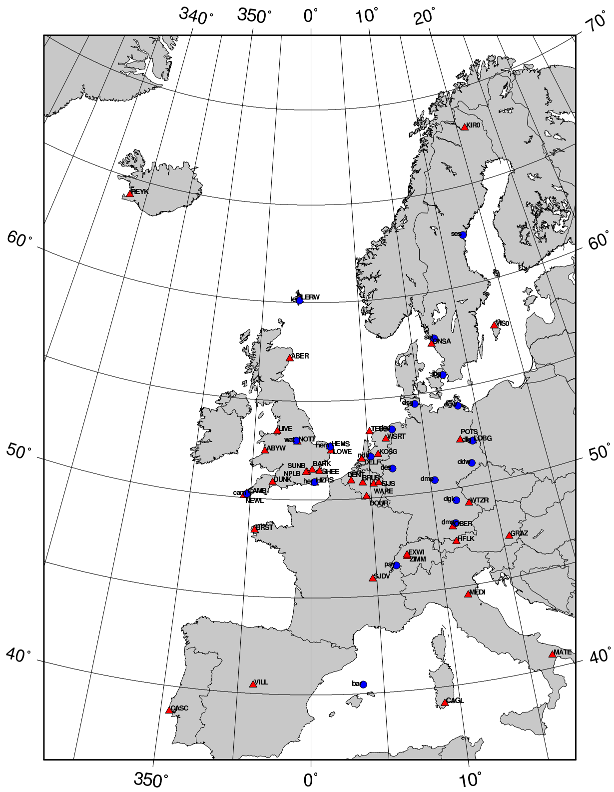

Figure 4. Map of the GPS stations (triangles) participating in the benchmark campaign 9-23 July, 2000, with nearby radiosondes (circles).

Of the 44 common stations, about 25 were centered on the North Sea, of which 15 in the UK, thus forming a dense sub-network, as is shown in Fig. 4. This area and time was selected because the early part of the period was characterized by fine weather associated with a high-pressure system over the UK, but which rapidly broke down, giving heavy rain with little warning in the NWP forecasts. The selected period did not have a strong atmospheric flow (dynamics) and showed predominantly convective weather phenomena. It is expected that under these conditions GPS will contribute significantly to improve NWP forecasts of precipitation. The other stations were selected close to sites where radiosonde are launched or sites equipped with radiometers for validation purposes.

The benchmark dataset was processed by the same GPS analysis centers as the NRT campaign, except for an additional center CNRS, who's work will be taken over by ACRI (Valbonne, France) for the NRT demonstration, and NKG, for which only one solution was submitted. Many of the selected 44 stations were processed by all analysis centers, while several analysis centers added other stations to their solutions. In total 102 sites were processed by 7 analysis centers; 44 sites were used by 3 or more centers, 2 sites by 2 centers and 56 sites by 1 center. For comparison purposes also four analysis centers produced solutions with post-processed quality, which included 69 sites (with 43 sites processed by 3 or more centers, 1 site by 2 centers and 25 by only 1 center).

The individual solutions were compared with combined solutions of near real-time (NRT) and post-processed quality, computed using the IGS combination procedure developed by Gendt (1998). First, one hour mean values for each analysis center were computed. Then a preliminary combined solution is formed excluding sites with a standard deviation larger than 20 mm. The global mean standard deviation (over all sites) from the preliminary solution is used for weighting analysis centers during the final combination. In the final combined solution a mean (bias) is computed per station, and analysis center estimates are corrected for this bias so that gaps in the data will not result in jumps in the combined product. Outliers are eliminated using a limit of 2.5 times the standard deviation per epoch.

Table 2. Differences of NRT and Post-processed solutions with respect to Combined-Post-Processed solution (units: mm ZTD)

Center	#	NRT		Post-Processed	
		StDev	Bias	StDev	Bias
ASI	43	4.1	-0.7±1.8		
CNRS	41	5.3	-1.5±1.3	3.2	-2.2±1.3
GFZ	41	4.8	-5.0±1.4	2.9	-3.9±1.3
GOP	42	6.4	1.2±1.7	2.8	1.4±1.0
IEEC	23	5.1	-1.1±1.8		
LPT	43	5.1	2.4±1.0	3.3	4.8±1.3
NKG	39	4.5	0.8±1.0		

The result of the comparison of the NRT solutions with the combined post-processed solution is given in Table 2. The overall consistency between the solutions is about 5-6 mm for the Zenith Delay, or better than 1 kg/m^2 in Integrated Water Vapor. The results for the benchmark campaign are indicative for the near real time trial: e.g. the GOP near real-time solution is compared routinely with a post-processed solution by GOP, showing an internal consistency between these solutions on the level of 4-6mm, with a bias below the 1mm (Dousa, 2002).

The zenith total delay (ZTD) from the benchmark campaign has been compared ZTD computed from radiosonde measurements. The zenith wet delay (ZWD) and integrated water vapor (IWV) have been computed by integrating the radiosonde profile, but the zenith hydrostatic delay (ZHD) has been computed from the observed surface pressure using the formula from Saastamoinen (1972). In Fig. 5 the standard deviation of the ZTD differences is plotted as function of the distance to the radiosonde. The agreement between ZTD from GPS and radiosonde is roughly between 10 and 15 mm for the near real-time processing for nearby stations, and slightly better for post-processing. The bias between GPS ZTD and radiosonde is between 5 and 20 mm, depending on the station and the GPS processing center. These results are very similar to those found in the near real-time trial, where for ten sites GPS IWV is compared with IWV from (reduced) radiosonde profiles, resulting in a consistency of 1.2-2.0 kg/m^2, or 8-13 mm in terms of ZTD (Dousa, 2002).

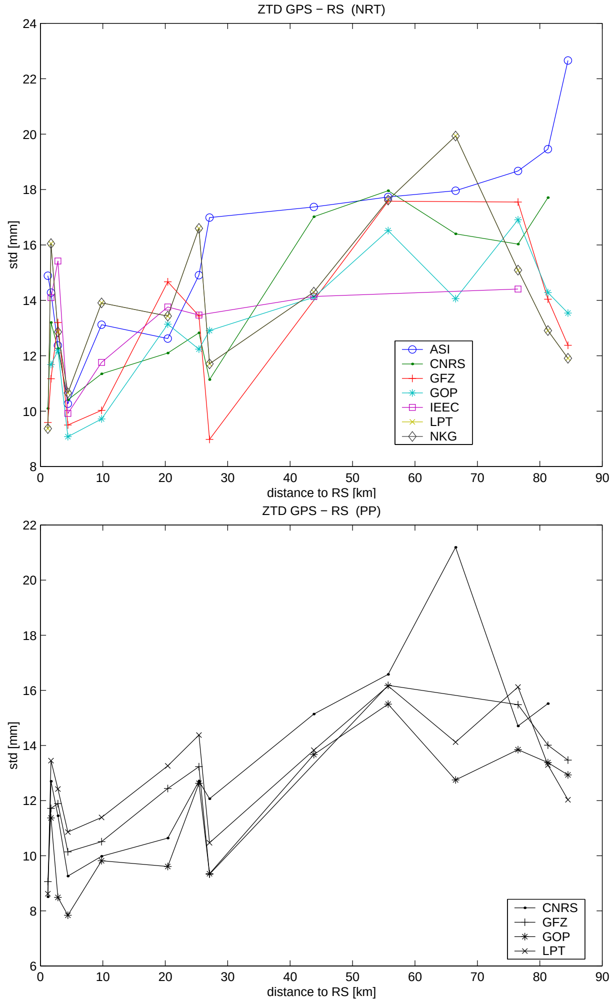

Figure 5. Standard deviation of the difference in ZTD with nearby radiosondes, plotted as function of the distance to the radiosonde, for the near real-time processing (top) and post-processing (bottom).

The GPS Zenith Total Delays from the Benchmark campaign have been assimilated into Numerical Weather Prediction models of the Met Office, SMHI, DWD and DMI in order to study the effect on the weather forecast (Higgins, 2001). One of the problems encountered so far is the bias in the ZTD estimates. At the moment the best results show a neutral impact, with a possible improvement in the prediction of precipitation. Ways to use NWP into geodetic activities, using the benchmark data, have been explored in (Cucurull et al, 2001).

5. Concluding remarks

To demonstrate the application of ground based GPS data for Numerical Weather Prediction (NWP); a near real-time trial was started in March 2001. The near real-time trial involves 7 processing centers, each processing a GPS network in near real-time, delivering estimates of Zenith Total Delay (ZTD) within a nominal time interval of 1 hour 45 minutes to a gateway at one of the meteorological institutes. About 250 GPS stations are processed, several of which are processed by more than one analysis center. A standard format has been defined for the exchange of GPS derived data that is compatible to standard meteorological data formats. The overall consistency between the solutions, as determined from the benchmark campaign, is about 5-6 mm for the ZTD, or 1 kg/m^2 in terms of Integrated Water Vapor (IWV).

Although the ZTD can directly be assimilated into NWP models, the ZTD is routinely converted into IWV at KNMI in the Netherlands. For the conversion the pressure and temperature measured at GPS site, if available, or the pressure and temperature from nearby synoptic sites is used. The data is displayed on the World Wide Web and is compared to ZTD and IWV computed from the HIRLAM and Met Office NWP models, see http://www.knmi.nl/samenw/cost716.html. The results are also available in ASCII format.

The IWV is used not only for verification and comparison purposes, but it is also used for forecasting applications. KNMI has developed a display showing IWV from GPS and HIRLAM analysis and predictions, together with Meteosat IR and WV brightness temperature (De Haan & Barlag, 2003). The Met Office has developed an application using winds at 3km to advect IWV values at times other than nominal (within 2 hours) to enable more detailed contours to be drawn, and hence simulating a network with an equivalent spatial resolution that was much higher than the original network (Nash et.al., 2002). However, the requirements for forecasting applications are even stricter on latency than the requirement for Numerical Weather Prediction.

Results from assimilation trials by working group 3 using COST-716 data are reported by various authors, see e.g. Higgins et al (2001), Cucurull et al (2002), Tomassini et al (2002), Gendt et al (2003), Guerova et al (2003), Ridal & Gustafsson (2003) and Vedel & Huang (2003). In general, it was found that statistical verification against observations indicates a neutral impact of GPS ZTD's, with some improvement in the short term forecast of significant precipitation (Vedel & Huang, 2003). However, in periods with low precipitation sometimes a weak over prediction was observed, which indicates that there could be biases in the GPS data and therefore the need for bias reduction schemes (Ridal & Gustafsson, 2003). Gendt et al (2003) and Tomassini et al (2002) reported also a significant improvement in the rms of the predicted relative humidity, and some smaller improvements in temperature and wind, and mixed results for the short term forecast of precipitation. Guerova et al (2003) found a significant impact on the forecast of precipitation in one out of three cases in Switzerland, with a neutral to small negative impact for the other two cases. Cucurull et al (2003) reported a positive impact of assimilating GPS data in high-resolution models, improving meso-scale weather forecasts in particular for strong storm events in the western Mediterranean. Further work on tuning the NWP models for GPS data, bias reduction schemes and parallel assimilation trials are performed within working group 3. More results are expected to become available in the near future.

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