Exploitation of Ground-Based GPS for Meteorology
COST Action 716 Workshop
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Abstracts

(GPS water vapour dynamics and tomography studies with a dense network of GPS receivers during the ESCOMPTE campaign (Marseille, June 2001): Preliminary results)

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The ESCOMPTE project is a large international effort designed to study the chemical and atmospheric dynamics of pollution and pollutant dispersion in the area of Marseille. The field campaign took place in June-July 2001. Associated with that project, we deployed a large array of 18 GPS receivers over the Northern part of urban and suburban Marseille. The typical separation between receivers is about 3 kilometres. Our scientific objectives are numerous and concern measurement validation, analysis methodology, and urban boundary layer dynamics. In the first part of our work, we plan to validate the GPS measurements of the integrated water vapour by comparisons with other means of measurements (radiosondes, microwave radiometers, lidars) which were located nearby and operated simultaneously as well as high resolution (~ 1 kilometre) numerical models. Then we will explore more advanced processing of the GPS data, taking advantage of the deployed network: water vapour horizontal gradients and tomography. Once again our results will be compared to numerical model outputs. In parallel, we will participate to the scientific investigations focusing on the atmospheric dynamics mechanisms responsible for pollution episode onsets and dispersion. In particular, the evolution of the water vapour distribution with the onset of the sea breeze, or the end of a mistral could reveal an interesting role. In this presentation, we will show the GPS campaign network deployed, argument our scientific objectives, and present our first results in both methodological advances and atmospheric dynamics studies.

Impact from high-frequency assimilation of GPS-IPW in the Rapid Update Cycle over the US

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A series of numerical weather prediction experiments concerning the impact of GPS integrated precipitable water (IPW) observations have been carried out over the past few years using the Rapid Update Cycle, a high-frequency data assimilation / mesoscale modeling system used operationally in the United States. GPS-IPW observation networks carry promise for improving the accuracy of 3-d moisture fields, and initial experiments with the RUC support this assertion, as shown by forecast skill from ongoing parallel 3-h cycles with and without GPS-IPW assimilation. The degree of impact from the GPS-IPW has increased as the number of stations in the US GPS-IPW network has increased, and is shown in a reduction of error from lower-tropospheric relative humidity short-range forecasts. A new experiment is now underway to examine GPS-IPW impact from hourly assimilation using the current version version of the RUC with hourly assimilation frequency, improved data assimilation, and more sophisticated model physical parameterizations over multi-week periods. These results will be presented and compared with the ongoing, multi-year RUC experiments at the workshop.
GPS meteorology in the Swiss Alps: Interpolation accuracy for different Alpine areas and near real-time results

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The Swiss Federal Office of Topography operates a permanent GPS network, called AGNES, consisting of presently 21 sites. In addition to the surveying applications the data are used for GPS meteorology. Since 1997 the data are analyzed in a postprocessing mode, since end of 2001 a near real-time processing is established. The station density is an important factor for deriving a precise 4-dimensional field of zenith path delays. Using the postprocessed zenith path delays of the years 2000 and 2001 we study how well we can interpolate the field as a function of the region, the station density, the station height differences and the weather condition. Validations of the zenith path delay field derived from the AGNES network are also realized using data of local GPS campaigns and using meteo data of the Swiss Meteo network ANETZ.

Results of one year near real-time GPS data processing for the COST 716 demonstration campaign

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Since February 2001, within the COST 716 demonstration campaign, the Geodetic Observatory Pecný analysis center (GOP AC) performs the near real-time (NRT) GPS tropospheric monitoring on fully routine basis. In GOP AC, we use the Bernese GPS software V4.2 for double-differenced GPS observation analysis of about 45 sites together with fixed combined ultra-rapid orbits provided by the International GPS Service (IGS). The results are based on 1 hourly GPS data pre-processing followed by the procedure of stacking 12 last hourly normal equations into the final solution. Then, the zenith total delays (ZTD) coming from the last hour of the analysis are extracted for the numerical weather model assimilation and they are delivered to the COST 716 databank at UK Met Office. Besides, we routinely provides the precise ZTD estimation based on the post-processed daily solutions using the combined IGS rapid orbits.

In this paper, we summarize the results of nearly one year routine performance of such a processing system. We compare the primarily NRT solutions to the post-processed precise solutions and to the integrated profiles of available radiosondes. We make the statistics of the supplying data as well as of the subsequent results from its complete performance. Presented statistics of the routine runs could be considered as a real basis for the general expectations on GPS data supply and analysis when planning for the operational stage of the potential GPS meteorology applications.

Ground-based GPS: Benefit in the data sparse Arctic region

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The relevance of water vapour for the radiative budget of the atmosphere as well as aerosol growth, cloud formation and weather forecasting contrasts strongly with the availability of humidity data in the Arctic. Acting as the most important greenhouse gas, the water vapour distribution influences the ground temperatures, while especially in the Arctic the surface temperature feeds strongly back by expansion or shrinking of permanently frozen ground and sea ice extension. About 80 radiosonde stations are located north of 60=B0N, launching in most cases between one and two sondes per day. Up to now this irregular distributed humidity data set is the most extensive, but the reliability of this humidity measurements under Arctic conditions is still under discussion. Additional information like e=2Eg. radiometer data is sparse. An increasing number of ground-based GPS receivers complements the database, providing integrated water vapor (IWV) information, if meteorological ground data is available. An evaluation of IWV data from ground-based GPS even under the low humidity condition of the Arctic will be presented. The possibility of the retrieval of IWV data from GPS soundings combined with meteorological data from radiosondes or numerical models will be discussed.
GPS tomography: First results from the permanent Gothenburg network

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We will draw attention to a new technique for retrieval of water vapor fields by using a small network of GPS receivers, referred to as GPS tomography. A subset of the inverse theory utilizing the integrated values of the field distribution is called tomography. Initially its applications were in medicine and geophysics, while as demonstrated lately, it can be applicable quite successfully in the area of atmospheric studies using GPS. Examples of such applications are retrieval of the vertical distribution of the Total Electron Content in the ionosphere and the refractivity in the troposphere due to water vapor. We use a permanent local GPS network consisting of 8 stations in Gothenburg (Sweden) with baselines ranging from a few to 15 km. Results from this network are derived from applying a tomographic method on the measured at each site slant delay values using the software package LOTROS (Local Tropospheric Tomographic Software) which is able to produce a tomographic solution of the refractivity in the troposphere due to water vapor and was developed by Alejandro Flores (Institute d'Estudis Espacials de Catalunya). In tropospheric tomography the slant delay values are obtained from the estimated zenith delay values and atmospheric gradients mapped into the satellite direction. The geometry using GPS is somewhat restricted compared to the classical tomographic approaches where one can choose the direction of the scanning rays, and thus optimize the acquired information for a successful inversion. In the case of GPS tomography, we are limited by the satellite constellation and therefore in certain areas of the field that we want to reconstruct some "information gaps" will be present. Additional constraints in the solution should be imposed in order to fill these uncertainties. We present first results of the simulations of a tomographic solution based on our particular site distribution, sensitivity analyses of the network, as well as some grid optimization results. First comparisons of the tomographic results using real data with results from measurements from radiosondes obtained in the vicinity of the area of the GPS network are also presented. The time scales of interest are hours with a vertical spatial resolution of a few hundred meters.

Assimilation of GPS measurements in Alpine Model: sensitivity experiment

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The Numerical Weather Prediction (NWP) mesoscale model called Alpine Model (aLMo) is used for operational weather forecast in Switzerland. aLMo is the Swiss version of the non-hydrostatic mesoscale model developed by Deutscher Wetterdienst (DWD). Since April 2001 the meteorological observations have been assimilated using the nudging technique. The GPS data provided for COST 716 near real time experiment is assimilated in aLMo. On average 80 GPS sites from West and Southwest Europe are assimilated by the model analysis. A two week period in September 2001 was selected. Results from the experiment are analyzed and discussed in order to identify the model sensitivity to the GPS -derived Integrated Water Vapour.

Verification of limited area forecast model with IWV from GPS networks of Germany and Switzerland

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The GPS Networks of Germany and Switzerland, operated by the GeoForschungsZentrum and Swiss Federal Office of Topography respectively, provide Zenith Total Delay (ZTD) measurement from more than 100 permanent GPS sites. Integrated Water Vapour (IWV) is extracted and compared to IWV derived from a non-hydrostatic mesoscale model - Local Model (LM), used for operational weather forecast in Germany and Switzerland. For the period April-November 2001 GPS IWV is compared against IWV fields from LM analysis and forecast. Special attention is paid to the difference between GPS and model data in the day-to-night behaviour.
Amending numerical weather prediction forecasts using GPS integrated water vapour: a case study

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With GPS an independent observations of humidity can be made. The data quality has shown to be very good and the high temporal resolution can be of great value for forecasters. GPS Integrated Water Vapour can be used to validate the amounts of humidity in Numerical Weather Prediction (NWP) model forecasts. This paper presents a case in which the operational limited area model at KNMI (as well as the global model of ECMWF) under estimated the diurnal temperature cycle strongly. The humidity in the boundary layer of the model triggered evaporation which affected the temperature forecast. We will show the additional information of GPS IWV for NWP models and the discuss the benefit of the GPS IWV observations for amending the operational forecast.

Timeliness and quality of near real time GPS ZTD estimates

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Starting in February 2001, a near-real time (NRT), quasi-operational data stream of GPS Zenith Total Delays (ZTD) has been established within the COST-716 framework. Currently five processing centers are delivering ZTD estimates from nearly 100 GPS sites across Europe. This poster shows the present status of the timeliness of the NRT data delivery and intercomparisons of ZTD estimates from different processing centers. For sites in the Netherlands additional comparisons with radiosondes will be presented.

Invesigation into the causes of biases in ground-based GPS zenith tropospheric delay estimates

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Assimilation of ground-based GPS zenith tropospheric delay (ZTD) data into the HIRLAM numerical weather prediction model was tested for a two week period in June 2000 as part of the EC MAGIC project. The results indicate a qualitative improvement in the precipitation forecasts for one case study. Since then, regional biases in the GPS ZTD data have been discovered. The assimilation tests used GPS ZTD estimates from COST 716 and from the CNRS MAGIC data processing system, which is now running at ACRI-ST and Purdue University. The impact the biases on the assimilation results are unknown, but not expected to be significant because of the non-negative impact of the assimilation over the entire 2 week period. However, an investigation into the source and the time scale of these biases is necessary to improve confidence in future assimilation results. We examine the biases of the GPS ZTD data through comparisons with HIRLAM model values of ZTD and comparison with the ASI solutions for the same time period. Reprocessed subsets of the data with special attention paid to station coordinates and reference frames are expected to shed light on the sources of the biases. Results will be shown.
GPS water vapor data compared with data from Terra/MODIS and with the high resolution regional weather forecast model HRM

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Water vapor is the most variable of the major components of the atmosphere and therefore a critical parameter in short term numerical weather prediction. Integrated water vapor (IWV) data obtained from a network of ground based receivers mainly over Germany are compared with the high resolution regional weather forecast model HRM of the Deutscher Wetterdienst and with data of the MODIS detector onboard the Terra spacecraft. A low bias (0.08 kg/m²) between the HRM model and the GPS data was obtained and can mainly be explained by the bias between the GPS data and the ECMWF analysis data used to initialize the HRM model. First comparisons between the Terra/MODIS data with the GPS data as well as with the HRM model data show that the Terra/MODIS IWV data are slightly lower compared with the HRM as well as the GPS data.

3D variational assimilation of total zenith delay in the Met Office mesoscale model: Results from preliminary trials

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A system for 3- dimensional variational assimilation of GPS Total Zenith Delay (TZD) data into the Met Office UK area mesoscale model has been developed. The model area spans much of North- Western Europe, with many of the COST 716 near real-time GPS stations falling within the domain. The new data source could therefore be of significant potential from a UK perspective. This paper will focus on the impact of TZD assimilation on short- range rainfall forecasts over the UK during summer periods, with attention given to the observation errors and their relation to the observed impacts.

Near real time processing of orbits, clocks, eop and zenith total path delay

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Near real time (NRT) processing of satellite orbits, clocks, earth orientation parameters and zenith total path delay has been carried out at the Norwegian Mapping Authority (NMA) since mid September 2001. The goal is to provide reliable NRT orbits, which can be used in NRT single point processing for an arbitrary number of sites. The parameters to be solved for in the point positioning include zenith total path delay (ZTD).

The availability of GPS data from a global GPS network in near-real time is a prerequisite for the orbit determination. Currently, hourly GPS data from globally distributed IGS stations are used together with data from the Norwegian permanent real-time network. For the analysis the GIPSY/OASIS-II software from JPL is used.

The quality of the NRT global parameters (orbits, clocks and eop) and the ZTD will be discussed. The NRT orbits are found to be in satisfactory agreement with the JPL precise orbits if hourly data from a sufficient number of IGS stations (around 25) are available. However, data delivery from the IGS network is not stable, and the accuracy of the NRT orbits deteriorates rapidly if the number of available sites is reduced.

COST-716 near real-time demonstration project

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In this presentation an overview is given of the activities of working group 2 of COST-716. The organisation, results and achievements of the near real-time demonstration trial are presented. The trial started in February 2001, and involves now 5 analysis centers processing in total almost 100 GPS stations, delivering zenith total delay ZTD with a nominal delay of under 1h45m (for most of the time).
addition, the results of the benchmark campaign are presented.

**GPS slant water vapour measurements: case-study of a cold front passage**

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In the GPS processing Zenith Total Delays (ZTD) are usually estimated under the assumption that the atmosphere is layered and horizontally stratified. This assumption is not always valid. For example, during the cold front passage studied in this paper, this assumption does not hold. In this paper we will take a different approach which involves the estimation of slant delays from GPS observations. The GPS slant delays are compared with NWP model fields and Meteosat water vapour observations.

**Results and analysis of the benchmark campaign**

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**Overview of the processing strategies followed by the 7 analysis centers**

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**Assessment of water-vapour data at the test site Bern from GPS, sun photometry, active and passive microwave sensors**

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Abstract: At our test site in Bern we have operated a set of instruments for several years to develop, validate, improve and apply atmospheric remote sensing methods. Recent improvements were obtained by radiative-transfer modelling, by improved instrument stability and calibration; thus we are able to report on a new multi-sensor assessment of water-vapour data from the experiments of 2001. Vertically Integrated Water Vapour (IWV) is the key parameter observed by three different methods: GPS, microwave radiometry and sun photometry. In addition radiosonde data from Payerne (40 km west from Bern) are used for validation. Furthermore the water vapour amount of the lower troposphere has been measured by a 94 GHz microwave transmission link over a distance of 7.5 km, and by in-situ humidity sensors at the two end points of the link. The long-term objective of this is work is to establish a water-vapour data base for climate research.

**Redesign of the global observing system progress to date and current status**

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The Global Observing System is made up of interconnected observing systems operated by WMO Members. Weather data, has been exchanged freely and in a co-ordinated mode since the late days of the nineteenth century. Nevertheless global observational data coverage is still a major problem as we enter the 21-Century. An example of a regional effort in redesign of GOS noted is the EUCOS (EUMETNET Composite Observing System) Programme to define an integrated ground based EUMETNET composite observing system (EUCOS) optimised at European scale. This provide a framework for co-ordinating observing system design studies -aiming at the definition mentioned above – and possible pilot projects - aimed at developing the necessary collective infrastructure for the future.
implementation of EUCOS.
Observational monitoring reports for April 2001 of the current systems presented for surface BUOY reports, in situ upper air data, AIREP and AMDAR, AIRCRAF DATA (AIREP, AMDAR, ACARS) demonstrate geographical coverage and impact in some geographical areas in particular over the Northern Hemisphere and over land masses. However deficiencies are in evidence over the Southern Hemisphere, Africa and over ocean areas. It was also indicated that real time observation of in-situ Ocean Profiles are becoming a reality through deployment of Argo, a global array of profiling floats to understand and forecast climate.
The presentation based on a 24 h GPS observations from the JPS indicated that in a simulation using a nominal constellation of 24 GPS satellites would provide observations over 12 h of < 800 km average distance. This would be an obvious and very significant contribution to improving coverage over data sparse areas and oceans. Likewise Prediction based on planned and proposed satellite missions showed that radio occultation data sources will increase dramatically from 2005-2006 with implementation of EPS Metop (Gras), Rocsat3 and ACE giving up to 7000 observations per day.
The GOS design process include objectively and critically reviews how well requirements are met and produces evaluation charts in several applications areas (e.g., regional & global NWP, synoptic met, nowcasting, aeronautical meteorology, Seasonal to Inter-Annual, etc.). This includes subjectively interpreting with the help of subject area experts and generates Statements of Guidance (SOG). The SOG for NWP require V (p) (especially in tropics) and T (p) and Q (p) with raob type accuracy over land and ocean and use of the Advanced Microwave Sounding Unit (AMSU) and Increased coverage of aircraft data providing benefit, particularly from ascent/descent.
Where observational and computational resources support regional prediction, the following is true: NWP centers rely rather more on surface-based and in situ observing systems than on space-based systems. Weather radars supply the highest resolution information, but the coverage is spatially limited, vertically and horizontally. Satellites supply information at high horizontal resolution; infrared sounding coverage is limited primarily by clouds.
Accurate estimates of moisture flux are critical for good mesoscale forecasts, especially of clouds and precipitation; the forecasts thus rely heavily upon wind and humidity observations. The greatest observational needs for regional prediction are: More comprehensive wind and moisture observations, especially in the planetary boundary layer. Enhancement of the AMDAR data collections and the addition of moisture sensors aboard aircraft are recommended. Numerous ground-based GPS receivers need only the addition of simple surface observations to be able to deliver estimates of integrated water vapour. Wind profiles are needed at closer spacing. More accurate and frequent measures of surface and soil properties, in that these influence surface fluxes strongly. More accurate estimates of precipitation are sorely needed.
Terms of Reference for Redesign of the GOS include making recommendations on the capability and utilisation of composite observing systems comprising different observing networks. This with a view to meet the requirements of the WMO Programmes; Review deficiencies in coverage and performance of the existing GOS, in particular in the implementation of the Regional Basic Synoptic Networks, the global climate surface and upper-air monitoring networks as well as related regional climate networks. On the basis of monitoring results and regional studies, make proposals to improve the availability of data to meet stated requirements. Other issues relate to costing, joint funding and management of the GOS and the capability of both surface- and space-based systems that are candidate components of the evolving Global Observing System.
The Future activities will optimize use of in situ and remote sensing data (especially over data sparse areas of the globe), and foster development of promising future in situ observing systems such as AMDAR, GPS, and ARGO.
Some aspects of the work plan cover offering redesign options for CBS consideration; Developing criteria for dealing with design issues of the composite GOS, paying particular attention to developing countries and the southern hemisphere. And preparing a document to assist Members of WMO, summarising the results from the above activities.
WMO should continue to participate in future workshops to keep abreast with research results and operational experimentation experience to assure input to the design of the GOS and prepare for assimilation of GPS retrieval data for NWP research and eventual operational purposes.
Comparison of integrated water vapour fields with weather radar observations

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The Met Office runs a network of eight GPS stations located mainly in the South of England and Wales, with a typical spacing of 150km. The combination of Ashtech Z12 and ZFX systems provide hourly data over dedicated telephone lines or network connections to the National RINEX archive and COST-716. Availability statistics and validation against collocated operational radiosonde data are calculated on a regular basis.

Met Office data is processed in near real time by the Geodetic Observatory Pecny (GOP). It can also be augmented with data from the archives of Ordnance Survey and other contributors to the national RINEX archive and post-processed by the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham. Plots of Integrated Water Vapour are shown in comparison to the rainfall data from the weather radar network for selected days during Summer 2001, which show that IWV can enhance the meteorological information available for nowcasting.

Examination of integrated water vapour fields associated with organised thunderstorm outbreaks over the UK in July 2001

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Met Office GPS data for selected days during July and August 2001 were augmented from the archives of Ordnance Survey and other contributors to the national RINEX archive and post-processed by the Institute of Engineering Surveying and Space Geodesy (IESSG) at the University of Nottingham. This work was designed to examine structure in Integrated water vapour fields with a separation of approximately 70km. Plots of Integrated Water Vapour are shown across the southern UK, derived using winds from wind profilers, aircraft and radiosonde at 3km to advect IWV values and enable contours to be drawn.

The examples chosen are being used to examine whether GPS total water vapour can be of use in forecasting intense convection and to test the spacing necessary for an operational network. The distribution of water vapour (effectively averaged over 5 to 6 km in the vertical in summertime conditions) shows significant structure in IWV, with temperature differences also contributing to the patterns obtained. Much of the IWV structure is originally generated by storms to the south of the UK and then the patterns in IWV generated appear to be linked to the subsequent generation of storms many hours later over the UK.

Factors influencing the siting and spacing of a national GPS water vapour network

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Factors influencing the siting and spacing of meteorological GPS total water vapour networks will be examined using measurements obtained from the UK.

This will include an analysis of the relationship of the measurements with those from other upper air observing systems measuring wind and temperature as well as water vapour.
Inversion of ground-based GPS measurements for the remote sensing of atmosphere

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A theoretical technique for the retrieval of atmospheric profiles is presented. The adoption of an optimisation procedure, based on an unconstrained Newton-modified formulation, has allowed us to invert the simulations of GPS signal times-of-flight and arrival-angles received at low elevation angles from a Ground-based receiver. To verify the effectiveness of the methodology proposed, these measurements have been estimated for a specific refraction index profile. The optimisation method has then been used, starting from a vertical profile of refraction index different from the one to be retrieved. In turn, the adoption of the gas ideal law and the integration of the hydrostatic equation allows us the evaluation of the density, pressure and temperature profiles from the refractivity profile obtained from the inversion. For what concerns the effective measurements of the arrival-angle, an interferometric technique based on phase measurements performed by two GPS receiver may be proposed. The atmospheric profiles retrieved are in good agreement (in terms of absolute and relative errors) with those used as reference. We plan, in future, to carry an experimental campaign to measure signal arrival-angles and times-of-flight with the needed accuracy.

Results of GPS meteorology project of Japan

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Part 1. GEONET Analyses and Applications (R. Ohtani)

GPS Meteorology project of Japan, an interdisciplinary cooperation between meteorologists and geodetists, was launched in 1997 as a 5-year project. The Japanese nationwide permanent GPS array with up to 1000 receivers, which is called GPS Earth Observation NETwork system (GEONET), routinely provides water vapor information with high spatial resolution (20 km on average). In the former part of the project, comparisons of GPS precipitable water vapor (PWV) with radiosonde measurements and grid data calculated from numerical weather prediction (NWP) model were carried out to study the errors due to the Japanese climatological and tectonic location as well as due to the data processing method of GEONET. Several case studies of water vapor variations with various scales driven by, for example, sea and land breezes, thunder storms and the Baiu front, were performed. Also, several tomographic techniques were developed to reveal 3-D distributions of water vapor. The results demonstrated the potential capability of GPS-derived PWV data for use in NWP, nowcast of rainfalls, and interdisciplinary environment studies and hydrology.

Part 2. Tsukuba Intensive GPS Campaign Observation

In the latter part of the project, smaller scale water vapor variations with the order of a few km were investigated. Intensive GPS campaign observations with 75 GPS receivers within 20km square area were carried out for total 2.5 months in fall of 2000 and in summer of 2001. Bernese, GAMIT, and GIPSY were used for GPS data analyses to retrieve PWV and slant path delay (SD). Zero-difference method was applied to Bernese to derive SD. By using the IGS's antenna phase center variation model and multi-path stacking maps, antenna and site specific biases and short time scale variations of PWV error were reduced. The elevation dependence of SD error was also removed. Tomography methods were applied to this improved SD. The results show small scale spatio-temporal variability of water vapor in various types of mesoscale weather systems.
Near real-time GPS zenith total delay estimation in the Central Mediterranean area and validation with weather forecast model

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In the framework of the European COST Action 716 operational estimation of GPS Zenith Total Delay in a near real time mode is performed at ASI/CGS since May 2001 for applications in numerical weather predictions and climate research. The GPS network covers the central and southern Europe; over Italy it has a spatial resolution higher than in the other regions. All the available Italian permanent stations providing hourly data are included in the analysis. The network is made by 20 stations and further densification is in progress. The GPS processing for the delivering of ZTD, with a delay of 1.5 hours, is performed using a 24 hours sliding window and a network approach. We describe ASI operational data stream for GPS near real time Zenith Total Delay underlying problems and issues connected to the routine operation. The validation of the NRT results with respect to post-processed estimates as well as with weather forecast model is presented. High resolution simulations are performed using a non-hydrostatic model, the MM5V3 from PSU/NCAR. The comparisons with weather forecast model aim to check the observation quality and to validate the model output.

GPS estimation of tropospheric delay from a moving platform

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Obtaining accurate measurements of atmospheric water vapour content and its variability is important for both meteorological applications and GPS positioning. During the last decade considerable research has been carried out to develop a technique of estimating tropospheric delay using static GPS. The tropospheric delay estimates can then be converted into estimates of atmospheric water vapour. It has been shown using static GPS that it is possible to obtain estimates of atmospheric water vapour to within 1-2 kg/m² of WVR and radiosonde measurements (Rocken et al, 1997, Dodson and Baker, 1998). Atmospheric water vapour estimates with this level of accuracy have potential use for assimilation in to, and validation of, numerical weather prediction models.

It would be beneficial to extend this technique so that tropospheric delay can be estimated using moving GPS receivers. Estimates of tropospheric delay, and hence atmospheric water vapour, could then be obtained from offshore and airborne locations, which would provide a valuable calibration tool for Space Based WVRs, and allow much higher global spatial and temporal resolution of atmospheric water vapour. Previous research in Dodson et al (2001) and Chadwell and Bock (2001) has shown that, for short baseline lengths, it is possible to estimate the tropospheric delay at a moving receiver with a comparable accuracy to that which can be achieved using the static GPS technique.

This paper describes new work that has been performed to verify that the above research could be reproduced in a more dynamic environment and for longer baseline lengths. The results show that tropospheric delay can be estimated at a moving receiver with sufficient accuracy for meteorological applications, even if the baseline length is such that atmospheric conditions at the rover are significantly different to those at the base. The results from both simulation and practical trials will be presented.

Near real-time water vapor monitoring in a German GPS network

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Operational precision determination of water vapor in near real-time within dense German GPS network of 100 sites is being carried out since May 2000 in the framework of the “GPS Atmosphere Sounding” Project (GASP) and has demonstrated an accuracy of better than 2 mm with a standard deviation at the level of better than ± 1 mm. Automatic operation of 100 and more of stations is possible with a processing time of about 10 minutes on a single PC, using parallel analysis of station clusters with the Precise Point Positioning strategy. This is the basis for introducing the GPS technology into the operational weather
An experimental near real time GPS network for meteorological applications

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A system to retrieve automatically the zenith total delay (ZTD) values in a near real time (NRT) mode has been developed, with the purpose of retrieving these observables from the emerging dense networks of GPS. To test the concept and to gain experience to be transferred to the meteorological Institutions, we have used data streams collected using a NRT Spanish network which includes sites maintained by different Institutes. We used Predicted and Rapid orbits from the Center of Orbit Determination in Europe (CODE) and the GIPSY/OASIS-II software package to estimate the ZTD values. In addition, an unattended system for the comparison of the GPS-derived ZTD estimates with the simulated ZTD values carried out with the HIRLAM NWP model has been established in collaboration with the Spanish Instituto Nacional de Meteorología (INM). We discuss the selected approach as well as the results of the comparison obtained during a selected period.

SuomiNet - A new university-based near-real-time GPS network

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UCAR began near-real-time processing of GPS data for the determination of precipitable water vapor in 1996, using data from NOAA's Forecast Systems Laboratory (FSL) GPS network. Based on the demonstrated reliability of GPS determined water vapor and in order to densify the U.S. real-time GPS network and to stimulate increased University involvement UCAR received funding to establish SuomiNet. SuomiNet is a national network of GPS receivers, located primarily at universities, configured and managed to generate near-real-time estimates of precipitable water vapor in the atmosphere, total electron content in the ionosphere, and other meteorological and geodetic information. This talk describes the SuomiNet infrastructure data communications and data analysis. We will discuss the use of gridded weather models for the analysis of SuomiNet and their effect on the GPS results. Further we will discuss our motivation and tests to process GPS observations to near-horizon elevation angles and the inclusion of global stations in the SuomiNet analysis.

EUREF troposphere combination at BKG - first results and improvements

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Since June 2001 the EUREF Local Analysis Centers (LACs) are delivering daily troposphere solutions which are created during or at the end of the computation of the SINEX coordinate solution. Beside the "GeoForschungsZentrum Potsdam" (GFZ) the "Bundesamt für Kartographie und Geodäsie Frankfurt" (BKG) is one of the two institutions which carry out the combination. The combination is done following the rules of the IGS troposphere combination as established by GFZ some years ago.

The EUREF analysis strategy in general is briefly explained. Differences in modelling and parametrization at the LACs are outlined. First results are shown and discrepancies with respect to the modelling differences are explained. Additional comparisons to the global IGS combination are shown. The new EUREF processing options used since GPS week 1130 are outlined and their impact to the troposphere combination solution is explained. The improvements due to this new strategy are shown. Remaining differences within the results are discussed.
A real time GPS filter for regional atmospheric delay derivation

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The Swedish network of geodetic Global Positioning System (GPS) receivers SWEPOS is capable of delivering raw measurement data every second. Estimates of the zenith total atmospheric propagation delay (ZTD) above the SWEPOS sites can be produced in real time. Earlier experiments demonstrated the capability of the system to produce atmospheric parameters every 15 s with a typical delay of 3 s, based on the use of broadcast satellite orbits.

We present the investigation on the limiting number of sites and computational delays in terms of used software as the goal is to include all the 33 sites in the SWEPOS network. We discuss the development of a Kalman filter for real time estimation of the radio path delay in the neutral atmosphere working presently with data from nine permanent GPS sites.

The real time estimates from about two week period have been compared to the results from post-processing of the GPS data. The ZTD quality is typically 15 mm in terms of RMS difference to post-processed ZTD using the more accurate IGS orbits. This level of uncertainty is already useful for navigational applications and if an additional reduction in the uncertainty can be obtained the usefulness for short term weather forecasting could be significant.

We analyze some process modelling aspects in the real time Kalman filter regarding the use of broadcast ephemeris for the calculation of satellite positions.

Use of GPS data in the regional forecast model of DWD

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In the framework of the GPS Atmosphere Sounding Project (GASP) the GeoForschungsZentrum Potsdam (GFZ) uses a dense German GPS network for the determination of vertical integrated water vapour (IWV). Since February 2001, IWV estimates are produced in near-real time and disseminated to the Deutscher Wetterdienst (DWD) to investigate applications for numerical weather predictions. After having assessed the quality of the newly available data, several numerical experiments have been performed to test and tune the use of GPS usage in the regional model "Lokal Modell" (LM) of DWD. A very first evaluation of the results has been made looking at analysis and forecast of precipitation. The signal is mixed, some case are improved but other are deteriorated by the GPS data. The problem appears to be often in days with little precipitation, with the experiments using GPS producing extra rain. An encouraging outcome is that good results are obtained when IWV from GPS are used together with temperature and wind measurements from aircraft. Since the monitoring of the GPS IWV data shows a small positive bias against the LM, experiment with bias correction have been also carried out. Other experiments were dedicated to investigate the impact of data from many stations with a small radius of influence.

GPS derived pathdelays versus four-dimensional meteorological modelling

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A main error source in GPS precise positioning is represented by tropospheric pathdelays. Our approach models the meteorological parameters responsible for the pathdelay in space and time (4-dimensional). This procedure allows the calculation of pathdelays along an arbitrary path in the model area. The software is capable to process arbitrarily distributed meteorological data.

We present results and comparisons of calculations with various input datasets. The calculated pathdelays are validated with pathdelays estimated from several GPS measurements by the Swiss Federal Office of Topography. The comparison has been investigated by statistical analysis.
Use of ground based GPS observations in a 3DVar based data assimilation system

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Using the newly developed HIRVDA 3DVar data assimilation system made for the numerical weather prediction model HIRLAM (high resolution limited area model), which is used operationally at the Danish Meteorological Institute, we study the impact of ground based GPS observations upon HIRLAM model analyses and forecasts out to 48 hours in a 14 day case study. This is done by observational verification of analyses and forecasts made with and without GPS-data included in the data assimilation. The assimilated GPS data are zenith total delays, coming mostly from our partners in the MAGIC project, while some additional data come from the COST ACTION 716 test dataset. The presentation will contain a short description of the GPS data used in the experiments, the assimilation method and the NWP model in the context of using the GPS data, and of the results obtained.