THE USE OF GPS MEASUREMENTS FOR WATER VAPOR DETERMINATION

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More systematic, integrated use of GPS techniques could lead to better information about the highly variable features of the hydrologic cycle and more.

Atmospheric water vapor is the dominant greenhouse gas in the earth's atmosphere, and so quantifying the feedback of water vapor in global warming is therefore of paramount importance. This feedback is also crucial for other feedback processes, such as snow–sea ice and clouds, that also play a significant role in climate. The lack of detailed knowledge of the hydrological cycle thus is a major limiting factor toward a better understanding of the earth's climate system. The inaccuracy is substantial and concerns practically all aspects of the hydrological cycle. At present, even such a basic quantity as the global annual precipitation rate is probably only possible to be determined to an accuracy of some 10% (Adler et al. 2001). The main reason for this appears to be the high spatial and temporal variability of the water cycle, for which the sampling properties of current observing systems are wholly inadequate. To find new and cost-efficient ways to improve the global observing system is a central objective for the weather and climate prediction communities.

Global Positioning System (GPS)-based measurements offer here new and promising possibilities. One of these is the capability to provide data at similar

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quality under all weather conditions. Regional networks, providing high temporal information of the integrated atmospheric water vapor, are being established all around the world; vertical profiling by the radio occultation (RO) technique is similarly taking place, using satellites in low-earth orbit.

In order to assess the present situation a workshop was held at the Environmental Systems Science Centre (ESSC) at the University of Reading, Reading, United Kingdom, during 29–31 August 2001, with the main objectives of summarizing ongoing work, to suggest a strategy for international cooperation, and to take steps to further a longer-term research program in this area. Twenty people attended the workshop, from China, Japan, the United States, and from several European countries (Fig. 1).

We begin with a brief review of the GPS methodology and connected previous work. For a more comprehensive background the interested reader is directed to Lee et al. (2001).

BACKGROUND ON USES OF GPS DATA.

The GPS consists of 28 satellites distributed in six orbital planes transmitting L-band radio signals on 19- and 22-cm wavelengths. Although designed as a navigation aid by the U.S. Air Force, the number of advanced civilian applications has grown steadily with time. Civilian organizations from all around the world have established the International GPS Service (IGS) network, which includes more than 100 globally distributed tracking stations, providing orbit determination with 5-cm accuracy in support of geodetic and geophysical research activities.

Like visible light, radio waves are refracted when passing through the atmosphere. If we define the index of refraction, n, as the ratio between the speed of light in a vacuum and the speed of light in the atmosphere, it is found that at microwave wavelengths the dependency of phase refractivity on atmospheric variables can be approximated by the following empirical expression (Kursinski et al. 2000):

$$N = 77.6\, P/T + 3.73\, 10^5\, P_w/T^2 - 4.03\, n_e/f^2, \quad (1)$$

where the refractivity $N = (n\text{-}1)\times 10^6$; T is temperature in degrees kelvin; P and P_w are total pressure and partial pressure of water vapor in hectopascals, respectively; n_e is the free electron density in electrons per cubic meter; and f is the signal frequency in hertz.

Above 90 km, the pressure and water vapor terms are negligible, so N is therefore directly proportional to the electron density. In the stratosphere and upper troposphere, water vapor is negligible and N can be used to deduce accurate temperatures with the application of the hydrostatic equation. In the lower troposphere, where water vapor can contribute as much as 30% of N, N can be used to deduce accurate profiles of water vapor given independent estimates of temperature, for example, from global analyses or short-term forecasts.

In the atmospheric sciences, there are two primary methods by which GPS is being used (Ware 1992; Bevis et al. 1992). In the first method, dual-frequency signals are collected at ground-based receivers and used to obtain the signal delay and thus the integrated water vapor along the path from the GPS satellites to the receiver (Rocken et al. 1993, 1995; Bevis et al. 1994; Businger et al. 1996). It is interesting to note that this possibility was first recognized during investigations into errors in geodetic measurements (Davies et al. 1985; Elgered 1993).

GPS receivers established for geodetic applications are now available in different regional and local networks around the world. The resulting integrated water vapor data are of excellent quality and are practically equivalent to radiosonde measurements. They have been used successfully for model validation in field experiments (e.g., Bengtsson 2000; Ware et al. 2000; Wolfe and Gutman 2000), as well as in short-range numerical weather prediction (NWP) (e.g., Kuo et al. 1996; Guo et al. 2000).

A potentially useful feature of the GPS data is their very high temporal resolution (typically a few minutes), which so far has not been explored systematically, but that we expect in the future will provide detailed information on fronts, squall lines, and other small-scale meteorological systems. It could be used even more extensively than at present in numerical weather prediction. With comprehensive data assimilation, there are interesting possibilities of better determining the high-frequency exchange of water between the atmosphere and the land surface.

In the second method, atmospheric soundings are obtained through a radio occultation technique using satellites in low-earth orbits (LEOs), which, as they rise and set relative to the GPS satellites, measure the change in frequency of the GPS signals (Melbourne et al. 1994). The Doppler-shifted frequency measurements are used to compute the bending angles of the radio waves, which are a function of the atmospheric refractivity. The refractivity is a function of the electron density in the ionosphere and temperature, pressure, and water vapor in the atmosphere [Eq. (1)]. Hence, the radio occultation measurement technique provides useful information about the structure of the ionosphere, stratosphere,

Fig. 1. Participants in the ESSC (University of Reading) Workshop on GPS Meteorology, 29–31 Aug 2001.

and troposphere. The occultation soundings provide important information on the temperature and water vapor fields of the global atmosphere, and together with the ground-based GPS systems will contribute to a better definition of the global and mesoscale water vapor distribution.

Following the highly successful GPS/MET experiment (Ware et al. 1996), additional satellite missions providing soundings of atmospheric refractivity on a global basis using the radio occultation method have been launched [the Challenging Minisatellite Payload (CHAMP), Satelite de Aplicaciones Cientificas-C (SAC-C)] or are planned [the Gravity Recovery and Climate Experiment (GRACE), Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), Meteorological Operational (MetOp) satellite, and the Global Change Observation Mission (GCOM)]. In the workshop the first preliminary results from CHAMP and SAC-C were presented, with the CHAMP experiment aiming at a quasi-continuous monitoring of the earth's atmosphere during the satellite's lifetime.

WORKSHOP OBJECTIVES. The first objective to be addressed was how GPS data could be used more systematically in meteorology. The workshop emphasized the validation of the atmospheric water cycle at high temporal and spatial resolution. As Huffman et al. (1997) and Adler et al. (2001) have demonstrated, separate estimates of global precipitation differ considerably. A specific interest here is to find ways to better validate the diurnal hydrological cycle, which at present is poorly described by most models. For example, Dai et al. (2002) have shown how GPS data can be used to document the diurnal cycle of the precipitable water. Another application is to use the high-frequency data to diagnose models and to better understand the exchange of water between the atmosphere and the land surface. A third application is to investigate the transport of water vapor at high temporal resolution on synoptic and subsynoptic scales.

For operational NWP we examined recent operational or quasi-operational experiences and discussed the possible use of the high temporal frequency information provided by the GPS data. Of particular interest are the different attempts to derive the vertical distribution of water vapor from a high-density network by means of tomography.

A second objective of the workshop was to consider how the regional GPS data networks could be integrated into a potential global observing system, including GPS radio occultation observations, for operational forecasting, climate monitoring, and research. Different projects are working on this, such as a European Cooperation in the Field of Scientific and Technical Research (COST) initiative (information available online at www/geo/cost716.html). We believe that a global GPS network of water vapor profiles with its unique characteristics would constitute a major contribution to a future global observing system for weather prediction, atmospheric research, and climate monitoring and prediction.

The ESSC workshop presentations had three sessions: ground-based GPS measurements, space-based GPS measurements, and assimilation of GPS data into NWP models, although there was, by the nature of the topic, considerable overlap of discussion within each session.

GROUND-BASED GPS MEASUREMENTS. There is substantial activity involving ground-based GPS measurements in studies at various scales from national to global. Many of these initiatives are assessing the accuracy of ground-based GPS estimates of integrated water vapor (IWV) and their utility in improving near-real-time weather prediction, but they also are developing and refining the fundamental techniques of observation, data processing, and distribution.

G. Elgered (Chalmers University) reported on a special European Concerted Research Action (designated as COST Action 716) for the exploitation of ground-based GPS for climate and numerical weather applications. This has been signed by 15 countries and will remain in force for five years until 2003. Its primary objective is to assess the potential for an international ground-based GPS system to provide near-real-time observations for operational NWP and climate applications. The GPS network is gradually growing and presently includes some 85 stations. Using part of this network, Gradinarsky et al. (2002) show a trend toward moister conditions over Onsala, Sweden (Fig. 2).

The technique for extraction of 3D water vapor fields has developed from assuming zenithal symmetry of atmospheric refraction, through estimating horizontal gradients in refractivity by using observations of multiple satellites, to full tomographic modeling using high-density GPS receiver networks. In the tomography approach, judicious positioning of the receivers is vital to avoid generating singular or ill-conditioned results from the inversion process. In most of the examples discussed by A. Dodson (Nottingham University) the receivers were located around and on the flanks of mountains, such as Mount Kilauea in Hawaii and Mount Etna in Sicily. However, Flores et al. (2001) reported results with excellent agreement with radiosonde observations from the REGINA campaign at the Onsala Space Observatory, Sweden, during the summer of 1998.

A group at the University of Bath operates steerable 93-GHz radiometers with collocated GPS receivers at three sites in SW England as well as portable 93-GHz radiometers with integrated GPS receivers and self-calibrating software. The group's 1999 field campaign showed good agreement between GPS and radiosonde measurements, and they have had

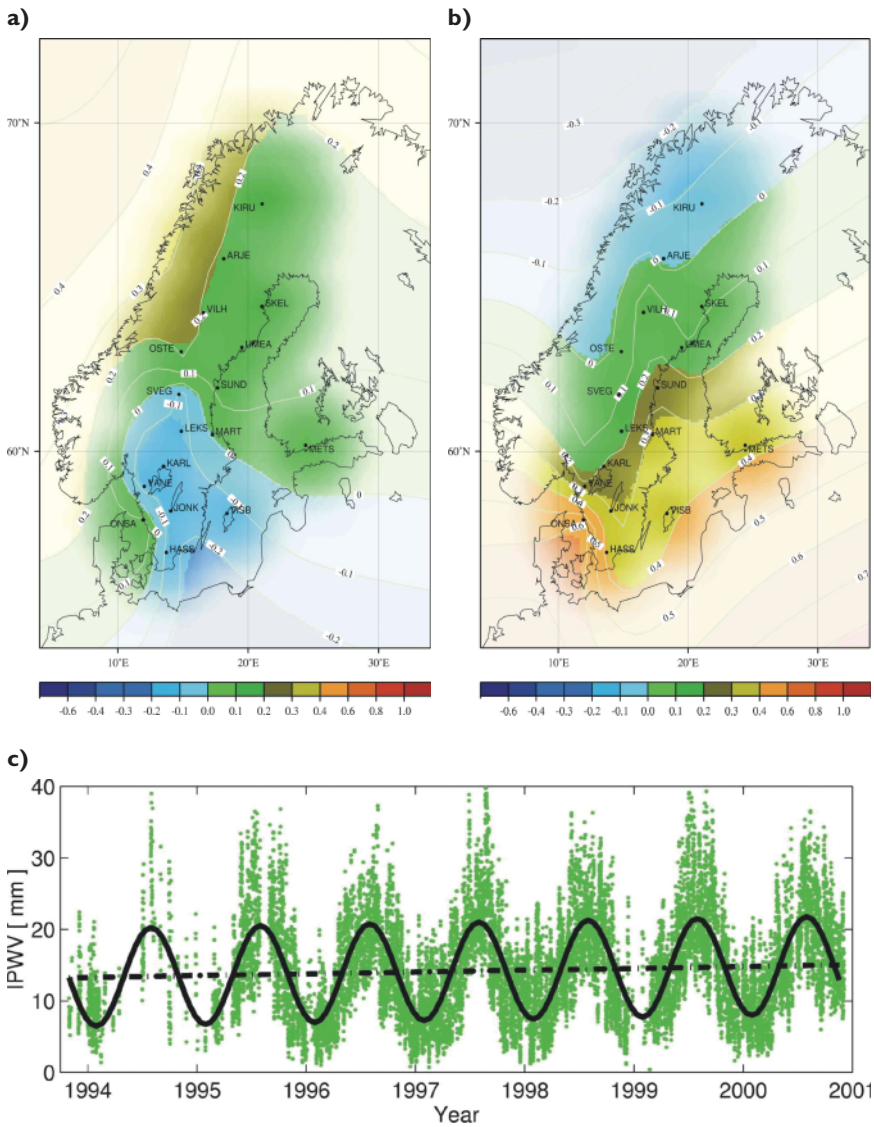

Fig. 2. (a) Summer and (b) winter trends through 1995–2000 in integrated water vapor as measured by the GPS network over Scandinavia; and (c) the time series for the Onsala site, denoted by ONSA in the upper figures. The formal uncertainty (one sigma) of the estimated trends is 0.13 mm yr^{-1}.

promising results of tomographic inversion of refractivity fields using GPS data processed with the GPS-Inferred Positioning System (GIPSY) software package.

SuomiNet, a university-based GPS network providing real-time precipitable water data, will establish up to 100 internet-connected GPS receivers in the United States and internationally (Ware et al. 2000). Even more powerful than the scalar precipitable water (PW) measurements are vector "slant water" (SW) measurements of integrated water vapor along GPS ray paths (Ware et al. 2000). At elevation angles above 10 , the accuracy of GPS-sensed SW has been validated by comparison with water vapor radiometer measurements (Braun et al. 2001). At lower elevation angles—near the horizon—GPS ray paths extend several hundred kilometers in the boundary layer. Researchers have compared slant delays computed by ray tracing through numerical model output with slant GPS observations. They have concluded that GPS slant delays can be calculated to an accuracy of 1% below 2 elevation (Pany et al. 2001). Such ray paths intersect many cells in a high-resolution model, providing powerful constraints on moisture fields. Putting slant GPS data together in a 3D variational scheme, with microwave profiler (Gueldner and Spaenkuch 2001) and surface humidity measurements at each GPS site, produced results that were far better than those obtained using Barnes (radiosonde) analysis. Individual convective features were resolved in the resulting analysis (MacDonald et al. 2002). Currently, work is in progress to analyze 3D wind and moisture fields using slant GPS and microwave profiler data, combined with wind profiler and background data to obtain full dynamic and mass fields. R. Ware [University Corporation for Atmospheric Research (UCAR)] showed promising results of refractive tomography using slant GPS from a 16-site GPS network in Hawaii and a 24-site GPS network in Oklahoma.

There were two dense GPS net campaigns during 2000 and 2001 in Tsukuba, Japan (about 40 km northeast of Tokyo). In the 2000 campaign, the dense (1–3 km) network consisted of 75 GPS receivers within a 20 km × 20 km region (Fig. 3). Dual-frequency water vapor radiometers were operated to observe IWV along GPS slant paths, and upper-air sondes were used for validation. GPS slant path delays were estimated using the Bernese, GPS Analysis-MIT (GAMIT), and GIPSY software. Use of phase center variation models and multipath stacking maps reduced noises and biases. This enabled the successful retrieval of realistic IWV distributions around precipitating disturbances. The improvements were significant at sites with serious multipath problems. Downward-looking observations were carried out on Mount Tsukuba in 2001. Preliminary results of the analyses show that the atmospheric excess phase delays derived from the downward-looking observations are compatible with those calculated from the model atmosphere.

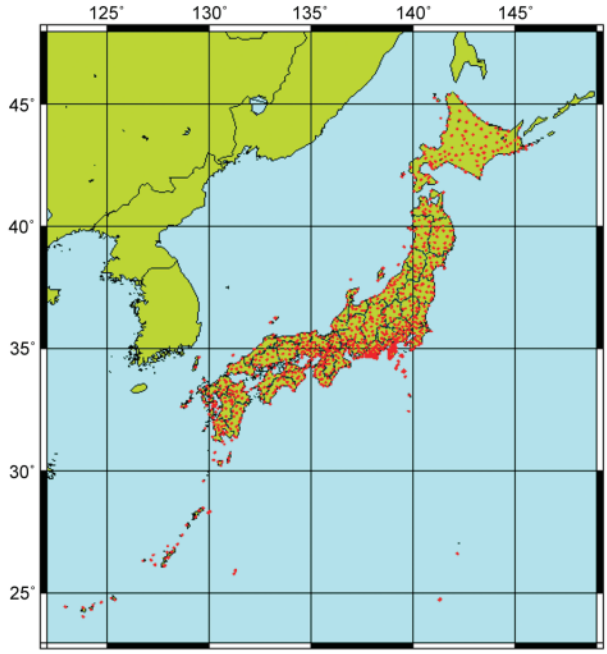

Fig. 3. The surface-based GPS network in Japan, providing water vapor measurements for use in mesoscale numerical weather prediction models.

The GPS Atmospheric Sounding Project (GASP) aims to develop a system for the operational determination of IWV using GPS and to assimilate these data into NWP models. GASP uses over 100 sites mostly from the Satellite Positioning Service (SAPOS) of the German National Survey. However, with very few collocated meteorological stations, meteorological parameters have to be interpolated; accuracies of 0.3 hPa are achieved routinely, corresponding to 0.1-mm IWV. Validation with internal consistency checks yields errors and biases of 1-mm IWV. Similar figures are found using comparisons with water vapor radiometers and radiosonde measurements. Analysis reveals that the biases are not constant, but vary with the diurnal cycle, and exhibit a long-term trend, which is yet to be explained. GPS techniques have improved the phase definition of frontal passages, the daily water cycle, and are helping to identify errors in humidity analyses. J. Nash and N. Latham (Met Office) reported on their experiences of running an operational network of GPS receivers, mainly based

in southern England, which started in 1998. The requirement for 50-km resolution required finding non–Met Office sites, which raised some interesting communication problems and logistical issues. The network has been running about 22 h day^{-1}, with most of the data being accessible within 15 min of reception. The GPS data are processed by the Geodetic Observatory Pecný (GOPE) in the Czech Republic and are converted in IWV by Koninklijk Nederlands Meteorologisch Instituut (KNMI) in the Netherlands. Differences between the GPS and radiosonde estimates of IWV are found to vary with a standard deviation of around 1.2 mm. Issues for the future are to determine the relevance of GPS IWV data for the operational automated upper-air network, to identify the most cost-effective spatial resolution, and to improve overall network performance. Other GPS campaigns with ground-based receivers, based in Shanghai and Wuhan, China and in Tibet, have investigated the relationship between the mesoscale water vapor fields and convection.

ASSIMILATION OF GROUND-BASED GPS DATA INTO NWP MODELS. The GPS/MET experiment produced useful data long after its expected lifetime. R. Anthes (UCAR) detailed many of the advantages of such GPS observations, such as all-weather day/night capability, high accuracy, and low bias. One of the main benefits is potentially higher vertical resolution than traditional satellite sensors are capable of, and so GPS will complement present satellite soundings. GPS observations have a number of applications, such as real-time measuring of upper-tropospheric and lower-stratospheric temperatures and climate monitoring (globally averaged measurements will be accurate to 0.03 K, sufficient to observe trends or variability of 0.1 K decade^{-1}). Anthes highlighted the improvements in 5-day NWP forecasts by assimilating bending angles (rather than derived *P, q,* and *T,* from radio occultation measurements), particularly in the Southern Hemisphere, and presented a few examples from the recent SAC-C campaign, which showed excellent agreement with radiosonde measurements of temperature and humidity.

D. Offiler (Met Office) outlined advances made at the Met Office in the assimilation of ground-based GPS data into the U.K. mesoscale model. COST 716 data for July 2000 have been successfully used in a near-real-time experiment, in which code has been written to perform various quality controls on the input data.

W. Wergen [Deutscher Wetterdienst (DWD)] described the first experiences in assimilating IWV measurements from GPS into DWD's Local and Global Models. The approach used in the Local Model was to assimilate observations using a 3-hourly nudging period. He showed examples of the differences in IWV analyses generated with the Local Model with and without GPS data.

GPS data are obtained from a national network of some 100 sites using the operational assimilation cycle of a high-resolution limited area model [Lokal Modell (LM)] as a reference. The comparison of GPS minus LM IWV for the period May–August 2001 gives a bias of 0.6 kg m^{-2} (i.e., a slight positive bias of the GPS data with respect to LM analysis), and a root-mean-square (rms) of 2.3 kg m^{-2}.

Several numerical experiments have been performed to test and tune the use of GPS IWV for the LM. The assimilation of GPS involves relaxing the model IWV values toward the observed ones. A "pseudo observed" profile of specific humidity based on the observed IWV and the model humidity field is nudged at each single vertical level of the model. At present the GPS-derived profiles are treated like radiosonde profiles; for example, they have a lateral radius of influence of approximately 120 km. This appears to be reasonable for the reduced network of 50 stations used in tests, but may have to be modified later for a denser network.

First assimilation tests (Tomassini et al. 2002) show that the model IWV is relaxed toward the GPS IWV successfully during the assimilation period. For instance, the assimilation of GPS data, during one day in April 2001, reduces the rms difference between the GPS and the model IWV from 2.0 to 1.3 kg m^{-2}. However, some problems were encountered in the case of a wintertime low-level inversion, in which the GPS data led to an overly dry analysis. This implies that care must be taken in nudging IWV in the presence of strong vertical humidity gradients or low IWV. The GPS data improve the analysis in cases of severe precipitation but conversely tend to deteriorate the analysis in some areas without precipitation. Further work has to be dedicated to the tuning of IWV nudging, in particular with respect to the vertical distribution of the observational information and to its lateral spreading (e.g., testing a radius of influence smaller than 120 km). Assimilation experiments over longer time periods and the subjective and statistical evaluation of the resulting forecasts, with a focus on the precipitation, are required to assess the impact of GPS data.

SPACE-BASED MEASUREMENTS AND THE GLOBAL OBSERVING SYSTEM. Encouraged by the experiences gained from the 1993–

95 GPS/MET mission, the very first results are being obtained from SAC-C and CHAMP. Additional missions are planned for launch in the next five years: GRACE (United States–Germany), COSMIC (Taiwan–United States), MetOp (EUMETSAT), and GCOM (Japan).

The COSMIC Project, a collaboration between the United States and Taiwan, aims to place a constellation of six GPS microsatellites in orbit in 2005 to measure pressure, temperature, humidity, refractivity, and ionospheric parameters, with an ultimate goal of improving NWP, supporting ionospheric research and space weather, and providing a consistent global climate monitoring capability. Substantial effort is being put into resolving the issues involved with sounding the lower troposphere, with use of higher-gain antennas and open-loop tracking to achieve usable data at heights down to a few kilometers. The multipath problem is being addressed using a number of inversion algorithms; the most promising appears to be the Canonic Transform Technique (Gorbunov 2002). UCAR has developed the COSMIC Data Analysis and Archive Center (CDAAC), which can process radio occultation (RO) data from all RO missions. CDAAC is now processing data from SAC-C and CHAMP. The ultimate intention is to combine CDAAC and SuomiNet analyses for full synergy of the available observations.

In the Observing System Simulation Experiment (OSSE) study, synthetic occultation observations from various configurations of the Global Navigation Satellite System (GNSS) constellation of satellites have been generated from European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses and used in a 1D variational assimilation of predicted bending angles. A. Rhodin (Max-Planck Institut) showed that forecasts could be significantly improved by up to 1 day, and that further improvements might be expected by making better use of the information content of the data. The optimal number of satellites required appears to lie between 12 and 24 in an ideal situation.

C. Marquardt [(GeoForschungsZentrum (GFZ)] reported on the status of the recently launched German Challenging Minisatellite Payload satellite (CHAMP; Reigber et al. 2000). The satellite carries a Jet Propulsion Laboratory (JPL)-built "Blackjack" GPS receiver; first occultation measurements were obtained during a number of measurement periods ranging from hours to several weeks during the first half of 2001 (Wickert et al. 2001). Since mid-2001, CHAMP has delivered radio occultation measurements more or less continuously. At the time of the meeting, more than 10 000 temperature and water vapor profiles had been gathered and processed successfully.

Retrieval algorithms in the current processing system are similar to those used for GPS/MET data. The agreement between CHAMP profiles and operational meteorological analyses is as good as for GPS/MET when antispoofing (A/S) of the GPS signals was switched off. This indicates that—thanks to its improved receiver and antenna characteristics—CHAMP is able to deliver atmospheric sondings with a quality comparable to GPS/MET even under the less favorable A/S-on conditions.

The multipath issue in the sounding of the lower troposphere is addressed by advanced retrieval algorithms like the canonical transform method (Gorbunov 2002), which generates remarkably good reconstructions of bending angle profiles in simulation studies. Applying this algorithm to CHAMP data, however, does not seem to significantly resolve problems already known from GPS/MET, such as a negative bias in refractivity, resulting in a significant dry humidity bias. This suggests that more emphasis than previously anticipated might have to be put on the role of the GPS receiver's internal sampling and tracking algorithms for the further processing of the raw GPS data.

Similar to UCAR's CDAAC, GFZ maintains a Radio Occultation Data Processing, Archiving and Distribution Center as part of its Information System and Data Center (ISDC; see their Web site at http://isdc.gfz-potsdam.de) for CHAMP. The ISDC will also serve as an archiving and distribution platform for further upcoming radio occultation missions like GRACE.

GPS satellite missions from the European Space Agency (ESA) are enabling researchers to address outstanding technical issues, such as multipath ambiguities in the lower troposphere and the selection of optimal inversion methods. The ESA Galileo program will be a constellation of open-access, dual-frequency satellites in orbit by 2008. The signals should be a significant improvement on current GPS capabilities, and would be well suited for use in radio occultation applications. Future missions such as Galileo will double the observed RO profiles, while the improvements in quality of the measurements will not only significantly improve the retrieval of lower- and upper-tropospheric profiles, but also enable better use of ascending RO observations.

OTHER INTERNATIONAL INITIATIVES. As part of IGS, a number of countries are collaborating to collect, process, and disseminate data from GPS re-

ceivers worldwide. Since 1997, a tropospheric product has been produced using a global network of about 200 stations (Fig. 4). This product is the zenith path delay (ZPD) of the neutral atmosphere, with a sampling rate of 2 h and is available with a delay of a few weeks. The products are generated from submissions from all the IGS analysis centers and therefore has good reliability and an internal consistency of the order of 3-mm ZPD for bias and standard deviation. For about 40 sites the surface meteorological data are also collected and can be directly used for conversion into IWV. For the other stations, model data have to be used for this step.

Recently, IGS has started a pilot project to generate a ZPD product with low latency. Presently, it is generated every 3 h with a delay of 2 h. The product is intended for use by regional groups for checking their near-real-time tropospheric products. If necessary, the product can be generated much faster and could even be used for assimilation into global models.

DISCUSSION. GPS data, whether obtained from occultation or in situ measurements, are potentially very important for climate and numerical weather prediction applications. Observations are essentially weather independent and observational quality and sampling characteristics are virtually the same in all geographical regions and at all times. Furthermore, the measurements are absolute, and will not change in time, as long as changes in equipment and processing algorithms can be accounted for. Within a modern data assimilation system, for example, based on a variational methodology, occultation data can be assimilated directly and the relative importance of temperature vis-à-vis humidity will be determined as a function of the relative weight of each parameter and with more influence given to humidity in the lower atmosphere and more influence to temperature aloft.

The in situ network provides information on integrated water vapor at high temporal resolution and also high spatial resolution regionally. So far these data have been evaluated in short-range weather prediction studies using high-resolution limited area models.

For climate applications the priorities are unbiased observations and long-term data series. As originally suggested by Yuan et al. (1993), GPS-based measurements have distinct advantages here since they are absolute, with—at least in principle—no long-term drift. Six-year-trend studies with Scandinavian GPS data [Fig. 2; Gradinarsky et al. (2002)] suggest that GPS data are suitable for long-term monitoring of atmospheric water vapor. As a preliminary study the working group recommended that available GPS data would be used to validate integrated water vapor of the reanalyses datasets from the (National Centers for Environmental Prediction) NCEP–NCAR and ECMWF.

The workshop considered the potential of building a comprehensive global observing system based on a combination of in situ and space-based observations. Such a system would constitute an important part of a global observing system for climate and weather applications. Given the current project to redesign the global observing system, the World Meteorological Organization (WMO) is keen to keep abreast of both research and operational developments in the use of GPS observations, M. Mlaki (WMO) told workshop participants.

The GPS in situ system now comprises some 2000 stations and is increasing rapidly in number. The Japanese national system alone constitutes some 1000 stations. The GPS receiver systems are portable and inexpensive, produce observations continuously at high temporal resolution, and need few calibration checks.

The European COST 716 project, discussed above, is pursuing realistic real-time trials including assimilation and forecast experiments; similar studies are under way in the United States (Gutman and Benjamin 2001), Japan, and China.

The satellite occultation measurements are very attractive as a key component of the global observing system. A particular advantage is acquisition of data in the active weather zones where we presently have

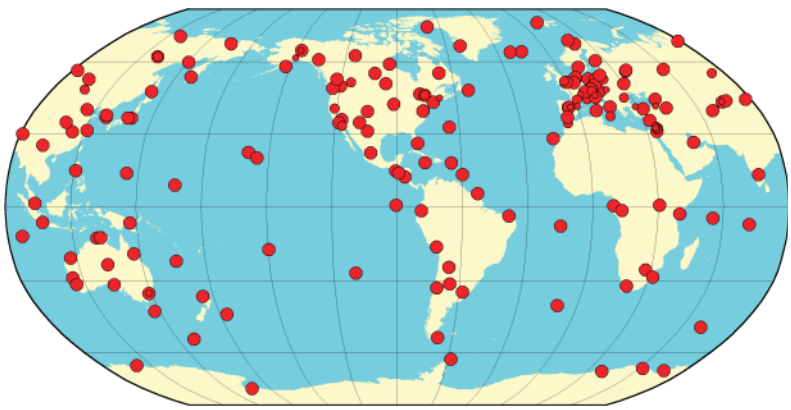

Fig. 4. The IGS network of ground-based GPS stations. Observations from this network may constitute a preliminary dataset toward the systematic monitoring of global water vapor.

few space-based observations due to heavy clouds and precipitation. The measurements will complement satellite temperature soundings; the occultation data will have a higher vertical resolution but a lower horizontal resolution and the error characteristics will be quite different from the vertical temperature and humidity soundings.

In conclusion, a GPS-based system appears robust and economically attractive. Because of the long experience, realistic experiments, and careful preparation, we anticipate that a workable operational system can be established with minimum delay.

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