MEASUREMENT OF ATMOSPHERIC WATER VAPOUR AND REFRACTIVITY PROFILES USING GPS

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ABSTRACT

An extensive set of comparisons is presented between atmospheric water vapour content deduced from GPS, radiometric and radiosonde measurements, leading to conclusions on the accuracies of the techniques and also insight into the horizontal and vertical structure of water vapour. In addition to long term (3-year) comparisons we also report results from an intensive short campaign to investigate the potential of the technique in determining horizontal and vertical structure using tomographic inversions.

INTRODUCTION

This work is concerned with a technique that emerged from the field of Geodesy as a nuisance factor in precise point positioning. The possibility of using GPS for remote sensing of atmospheric water vapour was proposed in the early 1990's and demonstrated in the mid 1990's. Proposals on data inversion using tomographic techniques were first made in 1997 [1] and the first results have been demonstrated by ourselves [2] and one other team (Flores et al 2000 [3]), almost contemporaneously.

GPS water vapour profiling has application in the following areas:

A. As a diagnostic tool in EHF radio propagation studies.
B. As a method to assist in the calibration of EHF radiometers.
C. As a quantitative input to climatological and meteorological modelling, and:
D. As a source of data for operational meteorological forecasting.

We have reported developments in A and B in [4-6]. Increasingly as a result of interest from and collaboration with UK meteorologists we have become involved in C and D [5]. Applications in operational meteorology and meteorological modelling are in a phase of exciting change. There is now mounting belief that the fine structure of the water vapour field (as might be measured on a network of GPS stations) will make an important contribution to improvements in forecasting and modelling [7].

MEASUREMENTS

This paper reports the results from 4 extensive measurement campaigns:

1) Three UK sites for three years with co-sited GPS measurements and 6-hourly radiosonde launches
2) A one-year comparison of GPS and 93 GHz radiometer measurements
3) Two-year GPS measurements at closely spaced sites.
4) A 4-site GPS measurement campaign with 20-minute interval radiosonde launches in daytime

The three site long-term data are used to deduce the rms and mean differences between GPS and radiosonde measurements. Comparison with 93 GHz radiometer measurements gives a technique for the removal of the oxygen and rain terms from the radiometer data and permits the derivation of an empirical water vapour attenuation and IPWV relationship. Through (3) and (4) we have been able to investigate assumptions on the azimuthal symmetry for water vapour retrieval and to investigate the potential of tomographic techniques for the retrieval of horizontal and vertical refractivity fields.

Differences between GPS and radiosonde retrievals from long-term data
In this comparison we have processed approximately 3 years of data of data for each of the sites (April 1998 to May 2001). We used the JPL GIPSY-OASIS processing software with an improved mapping function, taking account of the occurrence of horizontal gradients of refractivity. Our conclusions are summarized in Table 1 alongside all the other known results published to date.

Table 1 Comparison of GPS water vapour (IPWV) measurements from various studies

First Authors	Date	Comparison	Difference (mm rms)
Rocken (1995, USA)	7/5/1993 to 2/6/1993	Radiometer	1 - 2
Sierk (1997, Europe)	5/1994 (30 days)	Radiometer	4.0
Xiaohua (1999, Sweden)	8/1995 to 11/1995	Numerical weather prediction (NWP)	2.4
Emardson (1998,Sweden)	8/1995 to 11/1995	Radiometer	2.4
Tregoning (1998, Tasmania)	11/1995 to 12/1995	Radiosonde Radiometer	1.5 1.4
Emardson (2000, Sweden)	1994 to 1997	Radiosonde Radiometer	2.0 1.4
Westwater (1998 USA)	15/9/1997 to 5/10/1997)	Radiosonde Radiometer	1.6 1.2
Ohtani (2000, Japan)	1/9/2000 to 3/9/2001	NWP	2 to 4
Davies: Cambourne	4/1998 to 5/2001	Radiosonde	1.7
Davies: Hemsby	4/1998 to 1/2001	Radiosonde	1.2
Davies: Lerwick	4/1998 to 5/2001	Radiosonde	1.6

In converting from zenith total delay (ZTD) to zenith wet delay (ZWD) and thence to IPWV, we used surface temperature and pressure data together with a model on-average atmosphere. Interestingly we found that there was very little change to the measured rms differences when we took the actual temperature and pressure profiles from the radiosonde data rather than use the surface data plus model.

We also made comparisons in non-precipitating conditions by excluding records with rainfall in the previous hour, since it was thought that rain could contaminate the relative humidity sensor on the radiosonde. No discernable improvement was noted in the rms or mean differences in ZTD, ZWD or IPWV for this comparison.

When consecutive days of ZTD from GPS were examined it was found that occasionally there would be a disparity at the day boundary owing to the processing employed in GIPSY. The ZTD measured from GPS between 2230 and 0130 was removed from the data files and the comparison with radiosondes repeated. Again no discernable improvement in differences was observed.

Clearly our results agree well with those measured by other authors over shorter intervals of time. The larger rms errors seen at Cambourne are probably as a result of the increased tidal loading at that site, which although partially modelled out, still appears to contribute residual errors. Overall we witness rms differences in IPWV in the order of 8% between GPS and radiosondes and mean differences in the order of 2.5% (GPS – radiosonde).

Considering the relative crudity of the radiosonde instrumentation and the complex modelling assumptions made in the GPS measurement, it is difficult to ascribe these long-term differences to errors in one or other of the techniques. Our intensive short-term campaign gave further insight here.

Comparison with radiometer measurements
Given techniques for removal of oxygen and rain terms from radiometer data taken at frequencies sensitive to water vapour, it should be possible to check the GPS water vapour estimates against estimates from the radiometer. The two are linked via a mass absorption coefficient and the independent estimate of that coefficient obtained through radiometer-GPS comparisons can be used as a measure of the accuracy of the GPS technique. Unfortunately radiometry is itself an imperfect technique, exhibiting uncertainties associated with the temperature of the absorbing medium and absolute calibration (off-set error). Taking the two instruments together permits the application of a multiple regression technique, with the mass absorption coefficient as the truth test and the radiometer off-set error and effective medium temperature as intermediate outputs.

A regression line fitted to the GPS and radiosonde data alone gave an empirical water vapour attenuation and IPWV relationship of the form: $A_{zwv} = 0.0409IPWV + 0.0210$ dB. This relationship agrees well with a study [8] based on data from radiosonde profiles used together with the best established water vapour attenuation model. The 0.021 dB constant term represents a small as yet unexplained off-set error in either the GPS or radiosonde determination. The water vapour attenuation-IPWV regression relationship can be used to make comparisons with radiometer data. Removal of oxygen losses should make the process more informative and in Fig. 1 this has been achieveded by using surface pressure and temperature plus a model atmosphere. The scatter around the regression line during periods with rain and cloud removed gives an independent assessment of the rms error in IPWV for the GPS technique, giving a value < 2 mm.below shows the results with the radiometer off-set error optimised with $T_m = 293$ K.

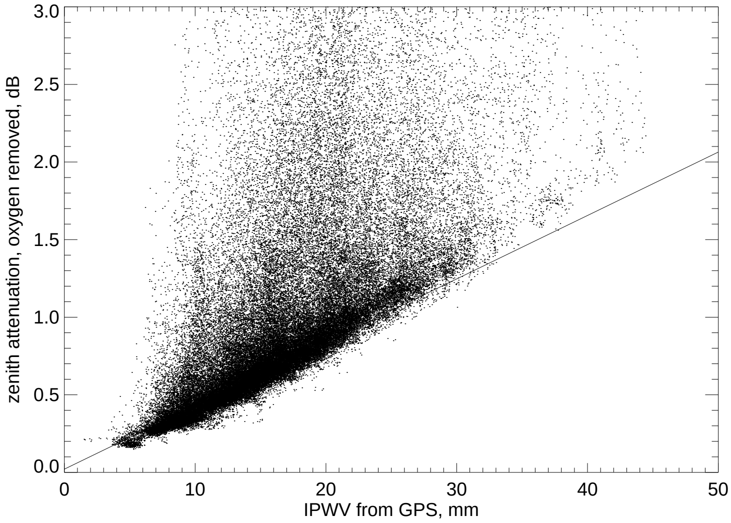

Fig.1 Zenith attenuation plotted against IPWV from GPS.

Investigations on assumption of azimuthal symmetry for water vapour retrieval
Use of a simple (cosecant) mapping function is questionable when steep horizontal gradients of water refractivity are present, such as might be associated with the passage of weather fronts. In our study of this aspect we used the integrated horizontal refractivity gradients available within the JPL GIPSY-OASIS precise point positioning technique. Three relevant investigations were conducted:

The comparisons between GPS and radiosondes discussed earlier (using the improved mapping function) had no data de-selected on account of the passage of frontal systems. The rms differences to were seen to be very small (1 to 2mm IPWV), hence for three years data at three sites we can conclude that the passage of frontal systems had little effect on the accuracy of the GPS measurement.

We compared the integrated horizontal gradients of refractivity for a two-year period between the Chilbolton and Sparsholt sites. These were not significantly different for 80% of the time. During the 20% of time when differences were observed we attempted to see if evidence of the passage of frontal systems was visible from synoptic charts, but could not draw conclusive evidence.

One of the four GPS sites in our measurement campaign at Camborne [2] had the benefit of frequent radiosonde launches (every 20 minutes during daytime). Agreement between Zenith Total Delay from GPS and the radiosonde profiles is again excellent. Making comparisons on the wet delay term (related to IPWV) leads to very interesting conclusions. Most data points again show excellent agreement, but there are short periods when successions of data points are clearly exhibiting a systematic difference, despite the use of an improved mapping function. During those periods the integrated horizontal gradients at the sites also showed significant differences [5].

These findings are of interest because there is almost certainly new information in the systematic departure between the two measurements as a result of the fine-scale horizontal structure of water vapour in the atmosphere. An example comparison between a map of ZWD drawn from weather stations and horizontal gradients of zenith wet delay is given in [2]. This opens up opportunities both for improved weather prediction and real-time radio propagation prediction.

Potential of the use of tomographic techniques in the retrieval of horizontal and vertical refractivity fields
This is one of only two known studies of this type [2,3]. We were able to take advantage of the new GIPSY-OASIS mapping function which performs a first order Taylor expansion of the refractivity at a given height with respect to the horizontal position vector. We then made an assumption that the horizontal integrated refractivity gradient is only due to the variations of "wet" refractivity. This allows the hydrostatic delay to be modelled uniformly over short distances and then subtracted from the slant delay.

Our tomographic method is a modification of that applied at the University of Bath to studies of the ionosphere [9]. A critical aspect is the choice of ortho-normal basis functions for the matrix inversion. The vertical profile is described by a set of ortho-normal basis functions using singular value decomposition from a real set of radiosonde refractivity profiles. These basis functions are then allowed freedom in the horizontal using spherical harmonics. Another powerful feature of our approach is an ability to produce four-dimensional inversions, taking the time evolution of structures on board as an additional variable.

Tomographic reconstruction of the refractivity fields was performed using slant delays from the four GPS receivers in Cornwall. A "wet" refractivity reconstruction, representing a 2-dimensional (vertical) slice of the troposphere was compared to a radiosonde profile taken on the same day, which shows encouragingly similar features.

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ACKNOWLEDGEMENTS
We wish to thank the Jet Propulsion Laboratory of the California Institute of Technology for allowing us to use the GPS Inferred Positioning System Orbit Analysis and Simulation Software (GIPSY OASIS) and the UKMO for access to routine radiosonde and surface meteorological measurements (supplied through the British Atmospheric Data Centre). Acknowledgement is also due to the Institute of Engineering Surveying and Space Geodesy at the University of Nottingham for access to their GPS observation database and Trevor Baker of the Proudman Oceanographic Laboratory for the supply of ocean tide loading coefficients for Camborne. Finally we thank Dave Jerrett from Ground Based Remote Sensing, UKMO, for the provision of GPS data and radiosonde profiles for Camborne.