Development of a UK National Water Vapour Processing System

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Since 1998 the Met Office has worked to investigate the potential of a network of dual frequency GPS receivers for the near real time (NRT) measurement of Integrated Water Vapour (IWV) as a component of the UK upper-air network. This presentation will describe the history of the project, the challenges encountered, associated costs and the future system requirements for handover to operations.

Introduction and Requirement for a National Near Real Time GPS Network

The path delay between a GPS satellite and a ground based GPS receiver depends, after elimination of ionospheric effects, on the integral effect of the densities of dry air and water vapour along the signal path. The total delay in the signal from each satellite is known as the slant delay as the path is most likely to be non-azimuthal. The slant paths are then transferred into the vertical (or zenith) by an elevation mapping function, and this parameter is called the Zenith Total Delay or ZTD. With further calculation, taking into account surface temperature and pressure, we can then convert the ZTD into IWV. From previous work it has been shown that it is possible to estimate the IWV reproducibility of 1 kg/m^2, equivalent to about 3% relative humidity.

In 2002 the Met Office established a project to develop the near real time processing capability for a network of GPS receivers with the main objectives being to increase the number of GPS sites being processed and to process data with the minimum time delay. Since this time the Met Office has placed annual contracts with the Institute of Engineering, Surveying and Space Geodesy (IESSG) at Nottingham University to develop an automated processing system. IESSG are leaders in the field of GPS processing and also maintain the British Isles GPS archive Facility (BIGF) which is funded by NERC (National Environmental Research Council). The decision to develop the project further was made by the customer groups (Numerical Weather Forecasting and nowcasting) on the basis of information gathered from non-real time GPS water vapour plots for the UK. High IWV conditions are often are associated with extreme weather events such as thunderstorms or heavy rainfall which are of obvious interest to the Met Office.

Network - Progress and History

The first Met Office GPS installations specifically for the measurement of IWV were completed in early 1998. Since this time the Met Office has increased the network to a total of 10 GPS receivers installed at meteorological significant locations around the UK.

Figure 1 – GPS Antenna at Lerwick, Shetland Isles   Figure 2 – Ashtech Z-FX GPS Receiver

In order to enable the Met Office to increase network density in the most cost effective manner, it was decided to seek out further sources of GPS stations such as national mapping agencies, the UK Tide Gauge Authority and Universities etc. By 2003 the UK real time ground-based GPS water vapour network consisted of 18 sites operating remotely with automated contribution of hourly data to BIGF and to the COST-716 user community. The network at this time consisted of 9 sites operated by the Met Office, 6 sites operated by the UK Tide Gauge Authority, 2 sites at Morpeth and Herstmonceux (which are operated as part of the IGS EUREF network) and also 1 site at IESSG. All sites have been installed to a standard suitable for reference geodetic work as well as for meteorological studies.

COST is an intergovernmental framework for European CO-operation in the field of Scientific and Technical research, allowing the co-ordination of nationally funded research on a European level. The COST716 Action was concerned with the 'Exploitation of ground-based GPS for climate and numerical weather prediction applications' of which the Met Office was a member nation ran from 1998 to 2003 and helped cooperation and advancement of GPS meteorology in Europe. For more details see www.oso.chalmers.se/~kge/cost716.html/.

Costs of an Individual Sensor Site

Table 1 provides estimated costs for the purchase, installation and maintenance of a GPS site. When installing a GPS site it is recommended that the equipment is co-located on an existing instrument site, with an enclosure/building. The figures in Table 1 are estimates taken from the COST716 Final Report and based on an installation on an existing site, with no special requirements for antenna mounting and/or cable ducting/length. Therefore the estimated cost for installing a single NRT GPS is in the order of 25k – 30k Euros.

Equipment	Maximum Costs (Euro)
GPS Equipment (Receiver, Antenna, cables etc)	20,000
Installation (work services)	5,000
PC and UPS	2,500
Communication connection	500

Table 1. – Estimated GPS site installation costs

From the COST716 Action it was estimated that a NRT GPS network with approximately a 50km average network resolution would be required to realise the full benefits of NRT GPS water vapour. In the UK the only method by which such a network could be realised is by resource sharing with the national mapping agency in the UK, Ordnance Survey GB (OSGB). Ordnance Survey are in the process of transitioning their existing ‘Active’ network of receivers providing positioning updates for differential GPS to a Real Time Kinematic (RTK) network which can provide real time positioning updates to allow almost instant coordinates accurate to a centimetric level. One of the main criteria for this new network would be that all RINEX data would have to be at OSGB’s server in real time. Thus the Met Office has negotiated a resource sharing agreement with OSGB. The Met Office will permit and facilitate installation of OSGB GPS sensors at various Met Office sites throughout the UK (where practicable) in return for access to NRT data from their national network. As a result, by the end of 2004 OSGB equipment had been installed at 5 Met Office surface sites and in return the Met Office has access to data from around 50 OSGB sites. Figure 3 shows the location of the total UK NRT GPS network as of January 2005.

It is only now with the sort of spatial resolution obtained in the mid-UK (see Figure 3) we can begin to see IWV fields with a resolution high enough to be useful for nowcasting applications, and as such begin to realise the full potential of NRT GPS IWV. Through the continuing effort with Ordnance Survey we estimate that the network should grow to a similar resolution over the entire UK and by the end of 2005 we estimate to have access to data from about 150 stations in NRT. Furthermore the Met Office is still looking for other sources of GPS data such as accessing data from the Northern Lighthouse Board and from offshore platforms which have a combined total of ~30 stations around the UK and in the North Sea respectively.

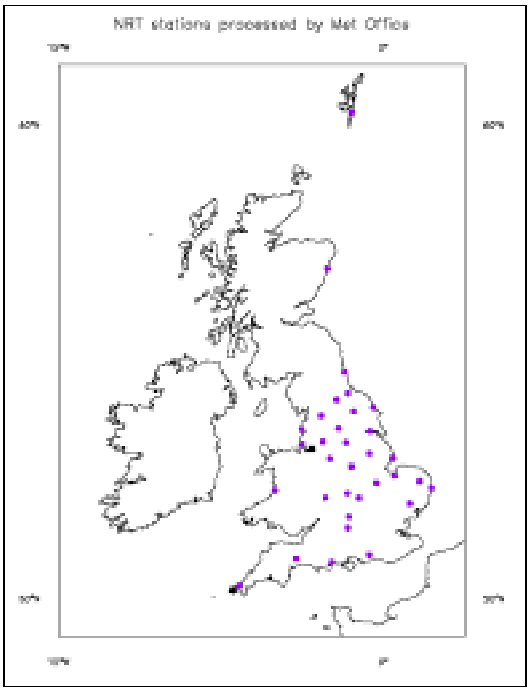

Figure 3 – UK NRT GPS Network – Aug 2004

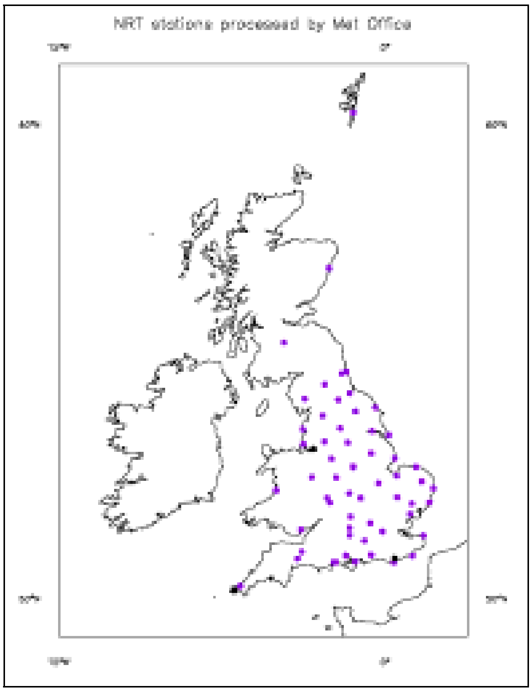

Figure 4 - UK NRT GPS Network - Jan 2005

Processing System - History and Works

Until mid-2004 UK GPS RINEX signals were being processed on behalf of the Met Office by GOPE, Czech Republic. GOPE kindly processed all UK scientific GPS data using Bernese v4.2, on a best effort basis. This arrangement came out of the COST716 Action. Using a single network approach GOPE process data from approx. 50 European stations and as such the time delay between raw data capture and delivery to COST716 takes approx 1:45 hours. The main aims of the Met Office GPS Project was to process GPS data ‘in-house’ to reduce the time delay associated with processing as far as possible. This was required by the customers. To accomplish the tasks required the Met Office purchased 2, dual-processor Linux PC’s to run Bernese GPS processing software, under a Red Hat software environment. Bernese was chosen as the processing software choice due to the significant knowledge and experience held by staff at Nottingham University and also due to the fact that it is the processing software utilised by GOPE. This consistency of processing methods should allow for more accurate comparison and result validation.

For quality control of the NRT solution the decision was taken to produce five different estimates of ZTD, obtained from four different solutions. In this method the NRT solution takes the predicted orbit and uses steps 2 – 5 as quality checks. Some results of comparison between steps 1 and 2 can be seen in the Results section later in this document. Steps 3, 4 and 5 are further quality checks using the more accurate IGS final orbits and thus the most accurate estimate of ZTD may be calculated from this data.

Solution	Orbit Used	Latency	Purpose
NRT	Predicted part of IGU	1 Hour	NRT Solution
IGU12	Observed part of IGU	13 Hours	1st Quality Check
IGU24	Observed part of IGU	25 Hours	2nd QC
DD	IGR	48 Hours	3rd C
PPP	IGR	48 Hours	Independent processing method as 4th QC
Daily_igsPPP	IGS Final	20 Days	Calculates an a-priori coordinate

Table 2 - Initial Processing Solutions

During 2004 UK NRT network size increased greatly and this overloaded the processing power of the PCs. To resolve this issue 3 out of the 6 quality check solutions were removed form the processing cycle only leaving the NRT solution using the predicted part of the IGU orbit, a quality solution using Double Difference processing and the IGR48 orbit and the Daily_igsPPP solution using the IGS final orbit to provide a-priori coordinates for processing.

The initial processing platform (from May '04 to Dec '04) employed a single network approach whereby all available sites were processed in a single national network solution which took approximately 20minutes to be processed. For operational use this time delay was deemed unacceptable and other processing strategies needed to be looked at to find the optimum strategy. IESSG looked at the effect of using smaller network sizes and revealed that processing time may be greatly reduced when a sub-network approach was utilised. The downside of this approach though is that the smaller number of stations used in a sub-network lower the relative data quality. After extensive research on the subject IESSG came to the conclusion that a compromise could be reached where quality was maintained to an acceptable level whilst reducing processing times as far as possible. This was achieved by splitting the network into sub-networks of 7 stations. As such the new processing system currently processes the UK network in approximately 10 sub-networks of 7 stations. This move has significantly reduced processing time from 20 minutes to about 4 minutes for a ~50 station network.

One of the main issues problems encountered during initial trials were software conflicts between the Bernese processing software and the Red Hat 8 environment and Perl scripts used to call the solutions. The conflicts caused the Bernese processing to crash at seemingly unpredictable instances thus preventing reliable stable processing. This software conflict was something which was predicted by IESSG from previous work but with the advent of Bernese v5.0 (written entirely in Perl) these conflicts were predicted to cease. With the implementation of Bernese v5 in December 2004 these conflicts have been resolved.

With the advent of the Met Office system and the resolution of the issues above it has been possible to reduce all times associated with processing as far as is practicable at this point in time. In the future it may be possible to reduce processing time further by the use of sub-hour GPS files, but this is something which is only beginning to be investigated. Under the current system the processing times are as follows:

00:00 – End of hour of GPS data file
00:05 – 00:15 - Raw GPS data sent from GPS sites to BIGF Archive at IESSG, Nottingham
00:16 - Surface Met Data acquired
00:18 – Processing begins using Bernese v5 software in sub-networks of 7
00:23 – ZTD and IWV produced

The outputs are then copied to the Satellite Applications Group at the Met Office for dissemination to the user community and in the near future for assimilation into the mesoscale model.

The main function of the processing software is to provide the user with the highest quality GPS sensor coordinates. In production of the coordinates the ZTD is accurately calculated and used to adjust the coordinates accordingly. As such the user must have a good understanding of global positioning systems and geodetic principles in order to understand the methodology of GPS processing. The principles behind the processing are taught at higher degree level and as such a manager trained to a high level is required to manage the processing system. To maintain the operational software suite, support staff knowledgeable in Bernese, Perl, mysql and Linux must be available.

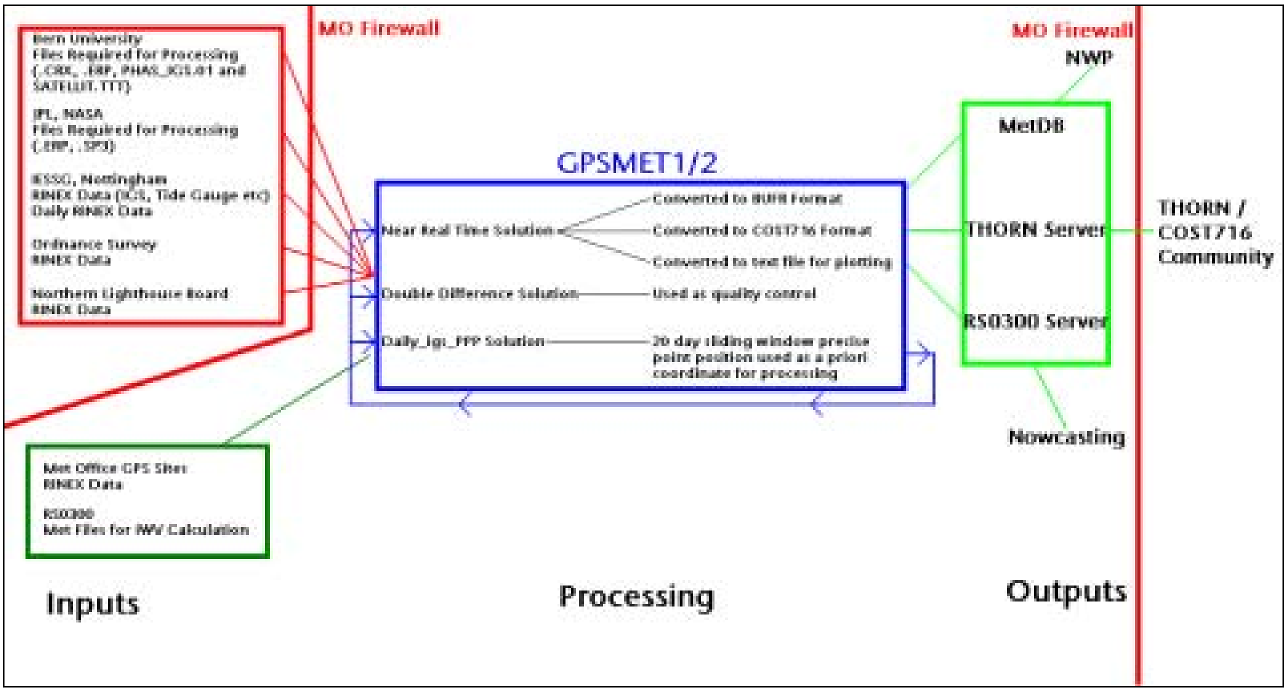

Figure 5 – Met Office Processing System

The costs associated with setting up and running a processing centre is very much dependent on the national costs for both manpower and equipment. In the UK the 2 processing platforms cost in the region of 7k EURO each. Table 2 provides an estimate of the current equipment and staff costs taken from COST716 findings for each of the main European processing centres. These figures should be used as a guideline for what it would cost to set-up and operate a processing centre and are accurate as of 2002. However the UK Met Office believes that the figures estimated are overestimated in most cases and more accurate assessment will be obtained through the development project

Processing Centre	GFZ (Germany)	GOPE (Czech Republic)	IEEC (Spain)	ASI (Italy)	LPT (Switzer-land)	NKG (Norway)	NKGS (Sweden)
Personnel Costs (per year)	1.0 person (split between 3 staff)	1.0 person (split between 2/3 staff)	1.0 person	1.0 person	1.0 person (split between 3 staff)	0.3 person	0.5 person
Hardware Costs (per 3 – 5 years) Processing Backup Archive	6,000 6,000 30,000 (RAID array)	4,500 3,000 estimate below	6,000	6,000 3,000 10,000	30,000 (2 Linux PC plus RAID)	2,000	5,000 3,000 3,000
Comms. pa 1 - Internal 2 - Primary	0 (central Intranet)	0 (academic) 4,800 (primary)	0	0 (ASI) 5,000 (fixed, no limit)	0 (central facility) 100,000 (fixed line)	0	0
Data Archiving (per year)	n/a (central resource)	3,500 (estimate)	n/a	n/a (central resource)	n/a (central resource)	n/a (central resource)	3,000

Table 2. Estimated GPS Processing Costs

In the future more work needs to be carried out to optimise assimilation of GPS ZTD to NWP models. The majority of this work is being carried out as part of the TOUGH Project (Targeting Optimal Use of GPS Humidity Measurements in Meteorology) which is due to continue until 2006 (See http://web.dmi.dk/pub/tough/ for more details). TOUGH is a shared-cost project co-funded by the EU (5th framework programme).

Development of NRT GPS networks for meteorology in Europe will be taken forward by way of a 3 year EUMETNET (E-GVAP) project proposed for initiation in 2005. The main objective of E-GVAP would be to enable and coordinate collection and distribution of European near real time ground based GPS water vapour measurements to EUMETNET members for operational meteorology. As such E-GVAP would facilitate cohesion between European national scale GPS networks and allow for inter-European data transfer and hence bring about standardisation. Also E-GVAP will work to gradually increase quality, amount, and geographical coverage of GPS water vapour data and assist members in utilising GPS water vapour data.

Validation of Results

The first comparisons made were designed to prove the quality of the NRT solution by comparison against the more accurate Double Difference (DD) solution. The DD solution uses the more accurate IGS Rapid orbits (IGR), which are available with a 48 hour delay – see Tables 2 for more details. As can be seen in Figure 5, there is excellent correlation between the two solutions indicating that the NRT solution does not suffer greatly by using the less precise predicted orbits and is satisfactory for meteorological applications.

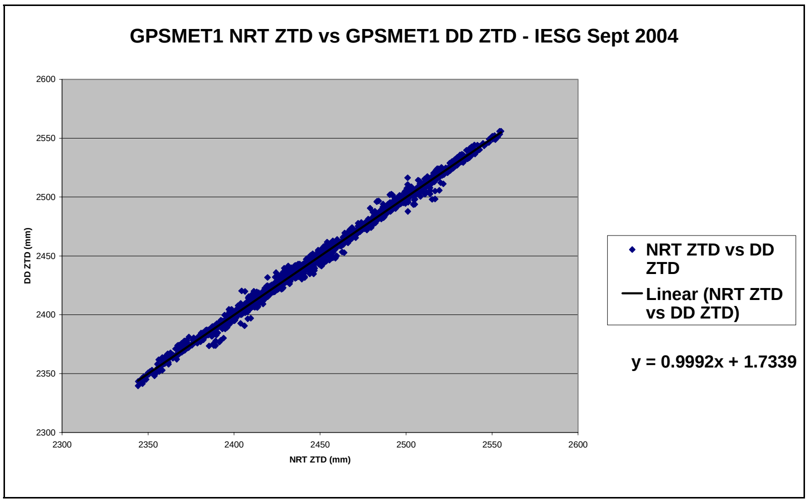

Figure 5 – GPSMET1 NRT vs. DD solutions, Sept 2004

Since 2001 comparisons have been carried out of NRT IWV against operational radiosonde ascents (Vaisala RS80H) at specific sites in the UK where co-located with GPS. At these sites a time series may be produced of GPS against other measurements available. In the case of a recent plot from Lerwick, Shetland Isles (Figure 6) Met Office processing is compared against GOPE GPS, NKG ( ) GPS, radiosonde ascents (x) and against the HiRLAM-22 NWP model data.

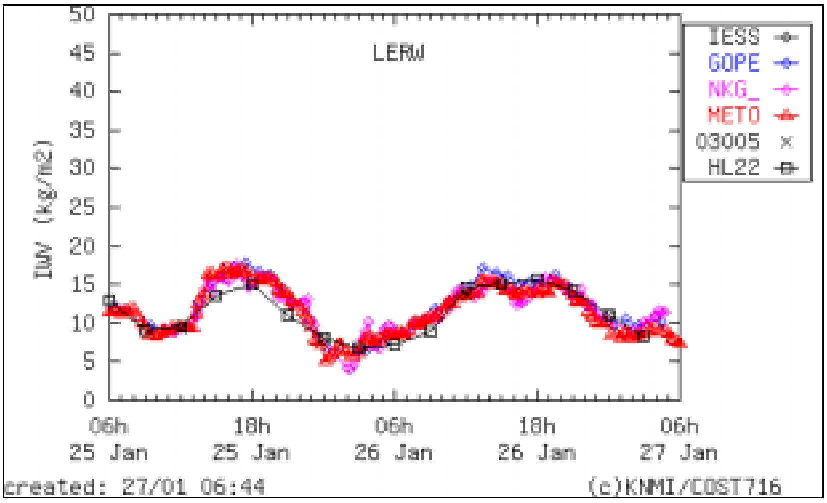

Figure 6 – NRT validation plot of GPS against radiosonde and model IWV

Quality control and quality evaluation procedures require development to check both the short and long term stability of the solutions now that Bernese v5 software has been implemented.

Animated display

In the past there had been relatively poor spatial resolution of NRT GPS sensors in the UK, and as such plotting IWV values in NRT would have had limited impact due to the high amount of interpolation necessary. However, as a result of the resource sharing agreement between the Met Office and OSGB, in the very near future the Met Office should have access to data from a NRT GPS network of 150+ sensors with an average spatial resolution of <50km and as such developing visualisation techniques become a useful tool to very short term forecasting. Since mid-2003 a suite of programs has been developed to plot IWV onto a 2D map, advect +1 and -1 hour IWV values up and downwind according to wind speed and direction and also add secondary relevant information to the plot in an effort to assist forecasting such as wind barbs and ATD info. Wind information is taken from wind profilers, radiosonde ascents as well as from AMDAR sensors. The vast majority of water vapour is located in the lower troposphere, as such winds at 2km are typically chosen which enables the best approximation of IWV advection.

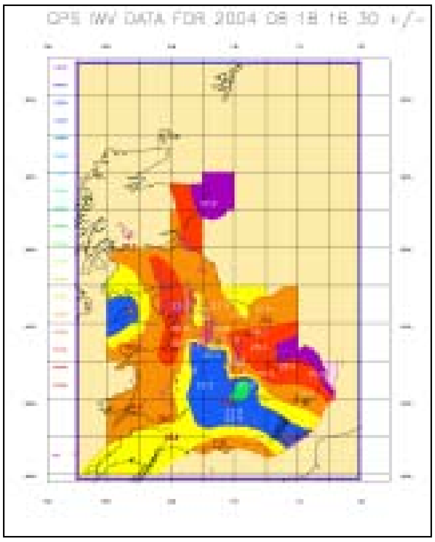

Figure 10 – IWV plot 2004081816

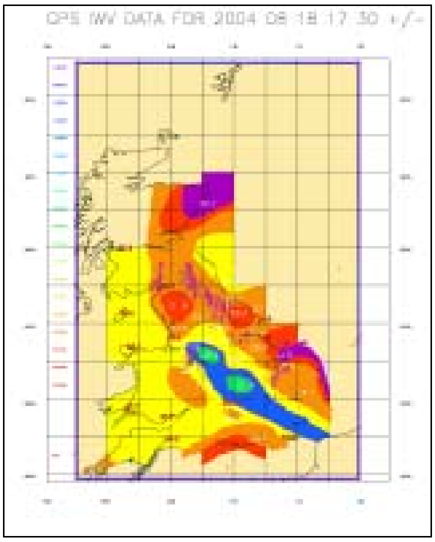

Figure 11 – IWV plot 2004081817

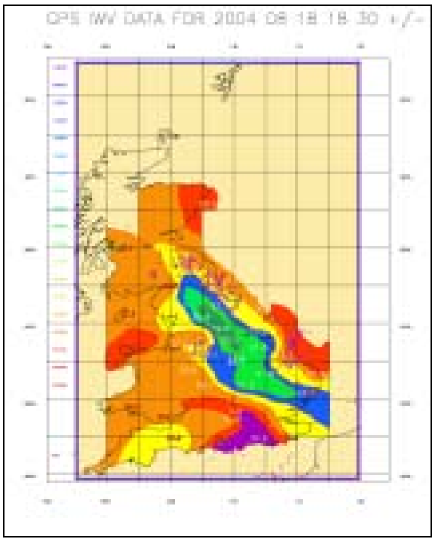

Figure 12 – IWV plot 2004081818

Contouring at 2kgm2, intervals: Green 20 – 22, blue 22 – 24, yellow 24 – 26, orange 26 – 28, red 28 – 30 and purple 30 – 32.

The contoured plots in Figures 10 to 12 demonstrate the current NRT processing and plotting capabilities. From Figures 10 – 12 it can be observed that IWV is a very dynamic quantity which may change rapidly under certain conditions. As such, 1 hour temporal resolution does not appear to be great enough to identify such short term fluctuations of IWV in the horizontal. The current maximum resolution is limited by the hourly RINEX GPS files, however in the near future it may be possible to increase resolution to 30 or even 15 minute files.

Conclusions

The Met Office has successfully demonstrated the capability of a ground based GPS network for the near real time measurement of integrated water vapour. The network has increased in size in a cost effective manner primarily due to collaboration with the UK national mapping agency, Ordnance Survey. Upgrade of the processing software now makes it possible to maintain stable processing but there have been periods using Bernese when processing did crash and further monitoring is necessary before final conclusions are made.