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Very Long Baseline Interferometry (VLBI) as a means of sensing water vapour

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Contents

1. Abstract

This report investigates the feasibility of using Very Long Baseline Interferometry (VLBI) measurements for determining the amount of precipitable water vapour in the atmosphere above the observing station location. The application of recent and historic VLBI measurements in climate monitoring and numerical weather prediction models is investigated. A comparison is made between the VLBI method and other sources of precipitable water vapour data based on a review of information in the scientific literature. Co-locations of VLBI antennae with radiosonde launch sites are calculated, and other applications of VLBI data are briefly investigated.
This document is based on a report written by Mathew Toll during a summer placement at the Met Office in 2009.

2. Introduction

Water vapour is a key variable for meteorology, impacting forecasts of both weather and climate. As such, measuring its distribution in both time and space, both in the horizontal and the vertical is essential for atmospheric modelling and prediction, especially with regard to global climatic change. Traditionally water vapour measurements are inferred from ground based measurements of humidity, or from radiosonde ascents (Durre et al. 2006), the latter providing vertical profiles through the troposphere. In more recent times, satellite and Global Positioning System (GPS) data collection techniques also now contribute to water vapour measurements. The combined use of satellites, GPS and radiosondes is generally referred to as the Upper Air Network (UAN) within the meteorological community.
The present day UAN is considered inadequate for water vapour measurements (Wang and Zhang 2009). Thus any new technology that could detect atmospheric water vapour is likely to bring benefits to the meteorological community in this regard.
From the perspective of water vapour measurement the UAN aims to provide vertical profiles of water vapour. These can then be integrated vertically to give the precipitable water vapour (PWV). However, the accuracy of PWV measurements is currently limited as radiosondes do not follow vertical trajectories, often suffer from hysteresis in water vapour measurements, and other techniques do not achieve good height assignment of water vapour content. The term PWV is used as it represents the net water vapour stored within an atmospheric column after accounting for its atmospheric budget (Fontaine et al. 2003). Subsequently PWV will be used throughout this report as it is the least ambiguous description of total water vapour in the vertical.
The aim of this report is to assess to what degree Very Long Baseline Interferometry (VLBI), which is a form of radio interferometry, can aid the meteorological observation network, principally the UAN. Utilising the large baseline between radio antennae VLBI was initially developed as an astronomical technique to provide high resolution images and accurate positions of distant radio sources (Goddard1 2009). Nonetheless it has since been used in “reverse” by the geodetic community to make measurements of shifting tectonic plates, the orientation of the Earth in space and to establish the length of the day (Goddard1 2009). However, of significance to the meteorological community, VLBI can also be used to establish the amount of water vapour within the atmospheric column (Behrend et al. 2000; Gradinarsky et al. 2000; Niell et al. 2001; Pacione et al. 2002; Haas et al. 2003; Steigenberger et al. 2007; Jin et al. 2009). Furthermore, with a potential thirty year data record VLBI possibly represents an invaluable resource for climate observations with respect to deriving PWV measurements. The process by which PWV measurements are inferred using VLBI is similar to that of GPS water vapour measurements, and will be outlined in the following sections. For now it is important to note that if VLBI is found to be a feasible means of taking PWV measurements it would be in direct “competition” with the existing components of the UAN.
In this report the feasibility of VLBI is assessed from several viewpoints. Firstly, Section 3 describes the VLBI technique for calculating PWV. Section 4 then gives an overview of VLBI data as well as discussing its future infrastructure. This is followed by a comparison with alternative PWV estimation methods in Section 5. A co-location study concerned with comparative measurements is given in Section 6. Section 7 investigates the possible role of VLBI in the Global Climate Observing System (GCOS), before a similar assessment is given for satellite observation calibration in Section 8. Section 9 deals with a different application of VLBI; observations of El Niño. Finally Sections 10, 11 and 12 contain recommendations for future work regarding the implementation of VLBI within the meteorological community, key outcomes of the report and a summary of the report.

3. Obtaining PWV from VLBI

3.1. How does VLBI work?

Originating from European and Australian Universities the foundations of radio interferometry were laid after the Second World War . However, it was in the 1960s and 70s that very long baseline instrumentation was developed for astronomy, led primarily by universities around the world (see e.g. Broten et al 1967 and Clark et al 1968) and by the National Radio Astronomy Observatory (NRAO) in the USA (Clark 2003). In the late 1970s and the 1980s NASA helped pioneer the use of the NRAO-led VLBI system for geodetic purposes, improving it towards its current capabilities (Goddard1, Ryan and Ma 1998). Geodetic VLBI as a coherent scientific project was not in place however until 1974 under the Pacific Plate Motion Experiment (PPME) (Goddard2 2009). To understand how VLBI can measure astronomical sources consider the following. Using a single radio antenna one can view radio sources from space. By pairing antennae however one can synthesize a much larger instrument aperture (Tubbs 2009, personal communication), where the vector separating the antennae is called a "baseline". The benefit of this undertaking is that from Fourier optics theory the spatial resolution of radio source measurements directly increases with the diameter of the aperture. Thus by increasing the baseline length between antennae large gains in resolution can be found . VLBI represents the ultimate resolution gain currently possible, whereby radio antennae are spread both across the surface of the Earth and in orbit, with baselines of many thousands of kilometres in length. With such gains in resolution, VLBI is able to serve two purposes. Firstly, with greater resolution, the VLBI antennae arrays allow for much more detailed mapping of celestial radio sources. Secondly, with greater resolution available it is possible to distinguish between different radio sources, in order to better assess how stable the sources are. Thirdly, and of greater importance to the geodetic community, the technique is sensitive to changes in the relative positions of the antennae and the astronomical sources, and can thus provide accurate Earth-rotation information from the ground-based antennae, as described below.

VLBI measures the difference in the delay in reception of a given radio signal at different points across the globe . Note that the absolute delay cannot be measured at any one location as the timing of the original radio emission is unknown – so VLBI is a differential technique. Given this measurement, with longer baselines the differential effects from Earth rotation increases, thus producing a larger change in the measured delay. This allows more accurate calculation of the Earth's orientation relative to the astronomical radio sources (Goddard1 2009). Moreover with consistent monitoring of a standard set of radio sources it is possible to establish movements of the VLBI antennas with respect to the rotating Earth (Goddard1 2009). Hence the expansion of VLBI under a project aimed at measuring the movement of the tectonic plates, namely the PPME, superseded by the Crustal Dynamics Project (Goddard1 2009).

Figure 1 shows a schematic diagram of how VLBI operates. Examining Figure 1 there are important points to note. Firstly, when VLBI was first developed simultaneous data collection at sites separated by large distances provided a problem. In the absence of high bandwidth links VLBI measurements were instead recorded on to magnetic tape for inter-comparison at a later date (Goddard1 2009). At this stage measurements from different locations were matched using a correlator which paired their time stamp obtained from an atomic clock. The second point of note is the timing noise highlighted on the diagram. It is this noise associated with the Earth's atmosphere that allows for measurement of PWV, as will be discussed in Section 3.3. Lastly the Mark III labels present on the figure represent a VLBI system introduced by radio astronomers from NRAO in 1979. The introduction of the Mark III system heralded a revolution in VLBI whereby using dual frequency radio antennae the accuracy of measurements was greatly improved, not

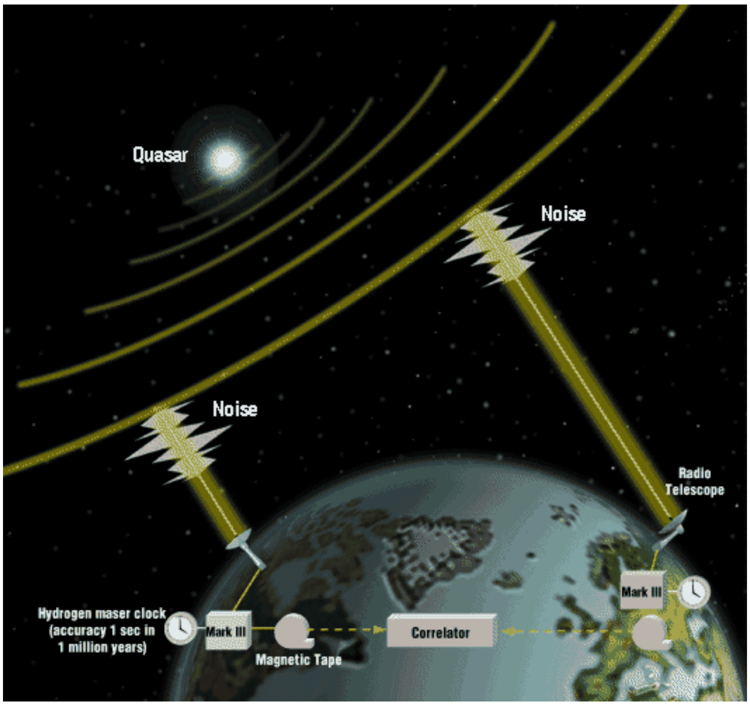

Figure 1: Schematic representation of VLBI radio wave reception (image released into the public domain by NASA in Goddard1 2009).

least because of the removal of timing errors associated with radio waves passing through the ionosphere (Ryan and Ma 1998). A comprehensive overview of the development of VLBI and its applications can be found in Clark (2003). Alternatively a twenty-year retrospective is provided for NASA-led VLBI work by Ryan and Ma (1998).

3.2. VLBI applications

Since the early days of VLBI use for radioastronomy (Broten et al 1967, Clark et al 1968) it was realised that there would be future potential for using this technique for geodesy (see e.g. Gold 1967). Within a decade VLBI was being widely used for Earth sciences, including:

- Obtaining the first measurements of movement in the Earth's tectonic plates (see e.g. Ryan and Ma 1998).
- Establishing the orientation of the Earth relative to objects in space and subsequently the development of the International Terrestrial Reference Frame (ITRF) (see e.g. IVS1 2009).
- Monitoring variations in the length of day (LOD) measurements as well as establishing causal links with large scale mass shift processes, such as El Niño and tropical storms (see e.g. Goddard1 2009).
- Detection of water vapour in the atmosphere (expressed as PWV) (Referred to by multiple sources).

It is the last two points that are of interest to the meteorological community and are the focii of this report.

3.3. Calculating PWV from VLBI measurements

As was alluded to in Section 3.1, the calculation of PWV from VLBI measurements is ascertained from the noise represented in Figure 1. But to what does "noise" refer to in this instance? From Section 3.1 it was explained that VLBI utilises time-delay measurements of radio waves from a known source to determine geodetic variables, including crustal shifts. Such delay measurements would assume that the radio waves propagate through a vacuum (as in space) at all times, at least as a first order approximation. However upon entering the Earth's atmosphere this assumption breaks down. Therefore errors are introduced into the measurement system by the refractive index of air. This is what "noise" refers to. Three major effects can be noted that cause variations in the refractive index, and hence make the propagation of a radio wave differ from propagation in a vacuum. These three effects are: the state of the ionosphere; the density of the neutral atmosphere; and the composition (specifically amount of water vapour) present within the neutral atmosphere (Goddard1 2009). As has already been noted following the introduction of the Mark III VLBI system, the error in VLBI measurements concerned with the ionosphere can be effectively removed using dual-frequency observations (Ryan and Ma 1998). Thus this leaves two neutral atmosphere terms to account for. Both of these terms are responsible for random and systematic error in VLBI time-delay measurements (Goddard1 2009).

The atmospheric density term depends purely on the integrated density along the line of sight. If we assume hydrostatic balance, this density term is proportional to the atmospheric pressure at the antenna, and can be easily (and accurately) subtracted. This delay effect is also referred to as the hydrostatic delay.

The composition term is dominated by the effects of the integrated water vapour content along the line of sight. This integrated water vapour can be converted into the approximate PWV by dividing by the air mass for the observation. This delay term is also referred to as the wet delay.

At this point it is useful to clarify terminology pertinent to PWV calculation from VLBI. If delay measurements are corrected to take account of the Zenith angle of the source (by dividing by the air mass), then the Zenith Total Delay (ZTD) is produced, referring to the total delay caused by all atmospheric effects when looking vertically upwards. The Zenith Wet Delay (ZWD) describes the extra time delay caused by the presence of water vapour in the atmosphere alone, and this leads to estimates of PWV in the atmosphere.

The actual conversion between measurements of ZWD and PWV is undertaken by the use of mapping functions, of which a prominent example is that provided by Niell et al. (1998). Such mapping functions are not discussed here. However it is important to note that although ZTD and ZWD can be thought of as time delays, they are generally expressed in units of millimetres (equal to the time delay multiplied by the speed of light in vacuum). Thus the reported delay simply represents the extra optical path distance travelled by incoming radio waves due to the refractive index variations. Note that optical path difference is given by multiplying the distance travelled by an unperturbed radio wave propagating through space by the refractive index of the neutral atmosphere and integrating along the light path.

By computing differences in ZWD between two VLBI locations (which requires the use of two or more antennae) one can obtain a value for difference in PWV between the two sites. With multiple reporting locations, a more complex map showing variations of PWV both in time and space can be produced. This has significant implications for the meteorological community, and thus for the remainder of this report PWV will refer to all measurements associated with water vapour calculations from VLBI.

4. VLBI data availability and meteorological impacts

4.1. Data availability

Following the development of VLBI from a purely astronomical technique into a geodetic technique under the guidance of a NASA-led research programme (Goddard1 2009), today geodetic VLBI is controlled by over 40 organisations in multiple countries (Goddard1 2009). Thus VLBI has proliferated into a global science. However that has had implications for data availability. In contrast to the meteorological community where freely available datasets are regarded as a necessity and information sharing is widespread, a similar scenario does not appear to exist within the VLBI community. Principally forced by the need to gather global datasets for weather forecast models there is a coherent strategy for meteorological data collection the world over, as overseen by the World Meteorological Organisation (WMO). On the contrary, data products output by VLBI have not been considered necessary on a continual basis. Therefore data collection from VLBI is a more fragmented process, although continual monitoring is now more prevalent, especially with the instigation of a European VLBI network connected by high-speed data links (JIVE 2009).

VLBI data is rarely available in Near Real Time (NRT) in the present day, and certainly not in the past. NRT data access would be a requirement for the weather forecasting field. Such VLBI data access has been considered unfeasible due to logistical issues surrounding the global transport of large quantities of data on magnetic disk or tape . This is combined with a lack of necessity within the geodetic community. Therefore unless this situation changes it would appear that VLBI-derived PWV measurements are unlikely to ever be of use for weather forecasting purposes. In contrast to this, NRT data access is not of concern to the climate community.

4.2. Data reliability

In the case of investigating the use of VLBI data, the term reliability pertains to whether or not the data can be trusted over a long time period. That is to say, is the VLBI data record stable, and have any alterations to the technology been documented? Data stability is crucial in climate work as alterations in a data collection system which impact the observations will have to be accounted for, both in the past and for future work. Such alterations refer to changes in the equipment used, processing software, site location etc. In the past few decades the present atmospheric observing system has not necessarily possessed this quality as stability is not of concern to the short term weather forecasting community. This is especially true for the radiosonde observing network where equipment type alterations in both time and space have introduced systematic biases that have to be corrected for in reconstructing retrospective data time series (Whang and Zhang 2007).

Having been partly funded by the geodetic community, in helping to define the ITRF, VLBI has a partially metrological background. Documentation outlining any alteration to the VLBI data collection method, processing and other information is widely available in the geodetic VLBI community. Such documentation usually accompanies VLBI array group websites and ftp data file directories. Directly quoted from the NASA VLBI group website it is stated that with reference to the VLBI data record: “This historical record provides a long-term database of well-calibrated, stable and consistently measured points to study phenomena that may not be detectable or even recognized over a shorter period.” (Goddard1 2009).

With a reliable data record VLBI opens the opportunity for monitoring the quality and stability of measurements made by other meteorological observational tools. One such employment of past VLBI datasets may be to adjust for biases within the historical radiosonde observation archive provided by the International Global Radiosonde Archive (IGRA) provided by NOAA. A similar process would be to help calibrate water vapour/PWV measurements obtained from polar orbiting satellites. This will be discussed further in later sections of the document.

4.3. VLBI data properties

So far discussion surrounding data collection from VLBI has centred upon the output of PWV. However, as is the case at the United Kingdom Met Office (UKMO) for GPS data, the raw data output is required i.e. zenith time delays. The UKMO require this so that in-house data processing can take place. Subsequently here zenith time delay data is presented as an example of VLBI data output. All of the data shown here is taken from the International VLBI Service (IVS) data archive. Figures 2 and 3 show ZWD over a period of a day

(04/01/2002) and one year (2002) respectively, for Algoquin Park, Canada. Looking at Figure 2 first, one can see that ZWD is calculated at hourly intervals throughout the day. Therefore the temporal resolution is of the order required to detect synoptic and mesoscale induced PWV fluctuations. The data collection pattern shown is typical for VLBI stations present within the IVS dataset. Therefore further investigative work will have to be conducted to see if finer temporal resolution is available. Moreover the IVS dataset only contains archived ZWD values back to 2001. Thus other data sources would have to be exploited for investigative work prior to this date.

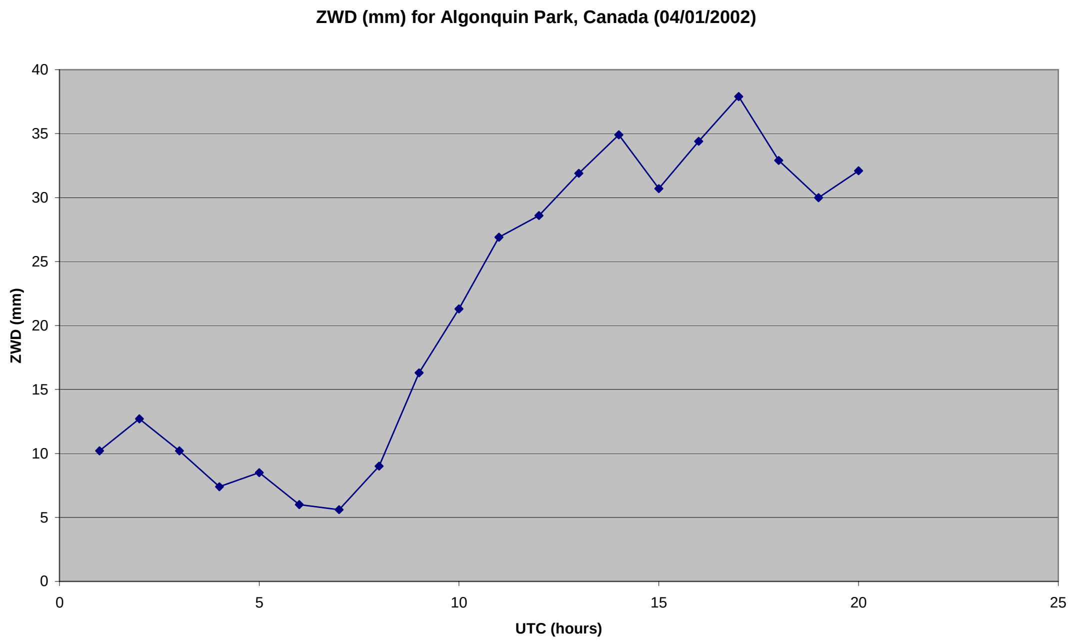

Figure 2: Zenith Wet Delay (ZWD) observations for 04/01/2002, for Algonquin Park, Canada.

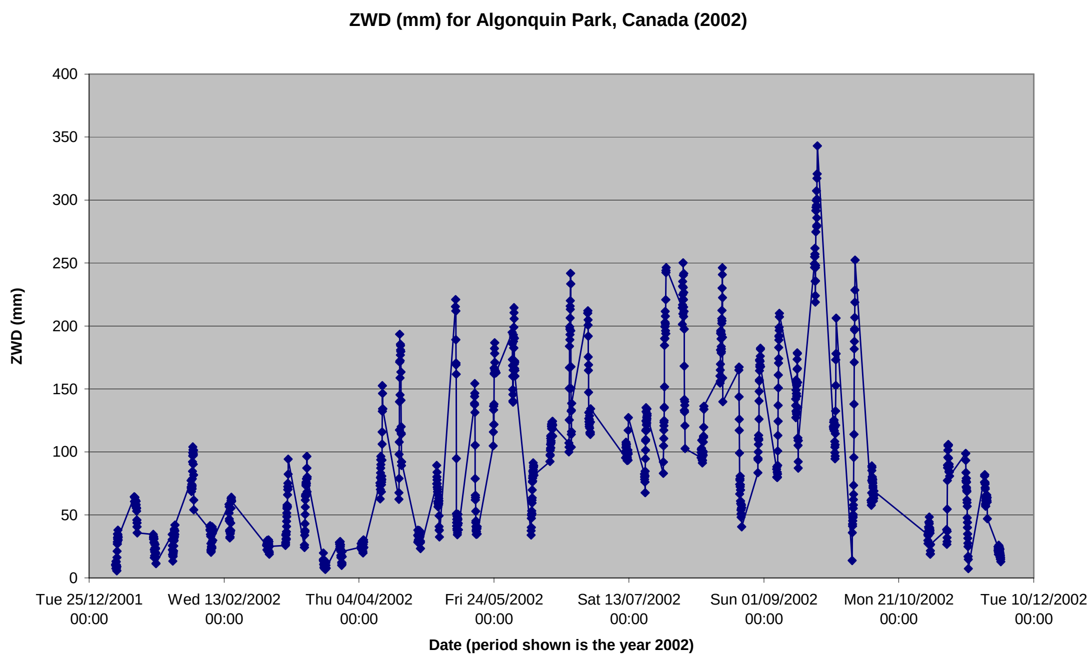

Figure 3: Zenith Wet Delay (ZWD) observations for 2002 for Algonquin Park, Canada

Figure 3 shows ZWD data collected over a year-long period. The first point to note is that the dataset covers the whole of 2002. However note that there are periodic clusters of data points. These clusters are caused by observations only taking place on Thursday and Friday of each week. Moreover Friday observation campaigns also contain the majority of the data. Figure 2 is an example of a Friday observation session. This pattern of data collection would appear typical of the IVS dataset for the initial few years. Nearer to the

present day it would appear that IVS stations have generally increased the number of observations, but the temporal resolution of hourly observations remains unchanged.
Consequently, at least from a temporal perspective the IVS dataset is quite restrictive, however only this source has been investigated fully. It would appear from preliminary research that VLBI data dating back to 1979 is widely available, but would require a collating exercise to provide a central database of VLBI derived data products. Certainly the restrictions on the datasets are prohibitive for weather forecasting observations (as is the lack of NRT data access), but not for climate observation which does not require continual observations.
As a final insight into the available VLBI data, consider the spatial distribution of VLBI stations. Section 6 describes a full co-location study concerning VLBI locations therefore only a brief discussion is given here. Appendix 1 shows the global distribution of IVS monitored VLBI stations. The IVS station list is by no means comprehensive in terms of the total number of VLBI stations worldwide, but Appendix 1 gives an indication of spread. As can be seen the distribution is such that VLBI stations could be described as having quasi-global coverage. Yet the station locations remain sparse. A fuller indication of the actual spread of VLBI stations is given by Figure 5, however not all of the stations shown are monitored by the IVS and thus data collection is likely to become a more arduous process.

4.4. Climate and the VLBI data record

Historically the meteorological community has focused its observational networks on data collection pertinent to the development of weather forecasting (GCOS112 2007). However with the increased interest in climate change and the demand for climate forecasts there is pressure to develop an observing system fit for both weather and climate purposes (GCOS112 2007; Wang and Zhang 2009). Unlike data collection for weather forecasting purposes, data collection pertinent to climate studies does not need to be in NRT. Instead long-term, stable, archived, reliable measurements are required (GCOS112 2007). Therefore stable measurements with a long data record are highly valuable to the climate community. Furthermore, one should also bear in mind that not only temporal availability is of concern. Spatial aspects of any meteorological observation tool are also of importance. For instance, if a new dataset gives measurements (past and present) in a previously unavailable region, this is also of great value to climatologists (Peter Thorne 2009, personal communication). VLBI fits both of these criteria with respect to estimating PWV.

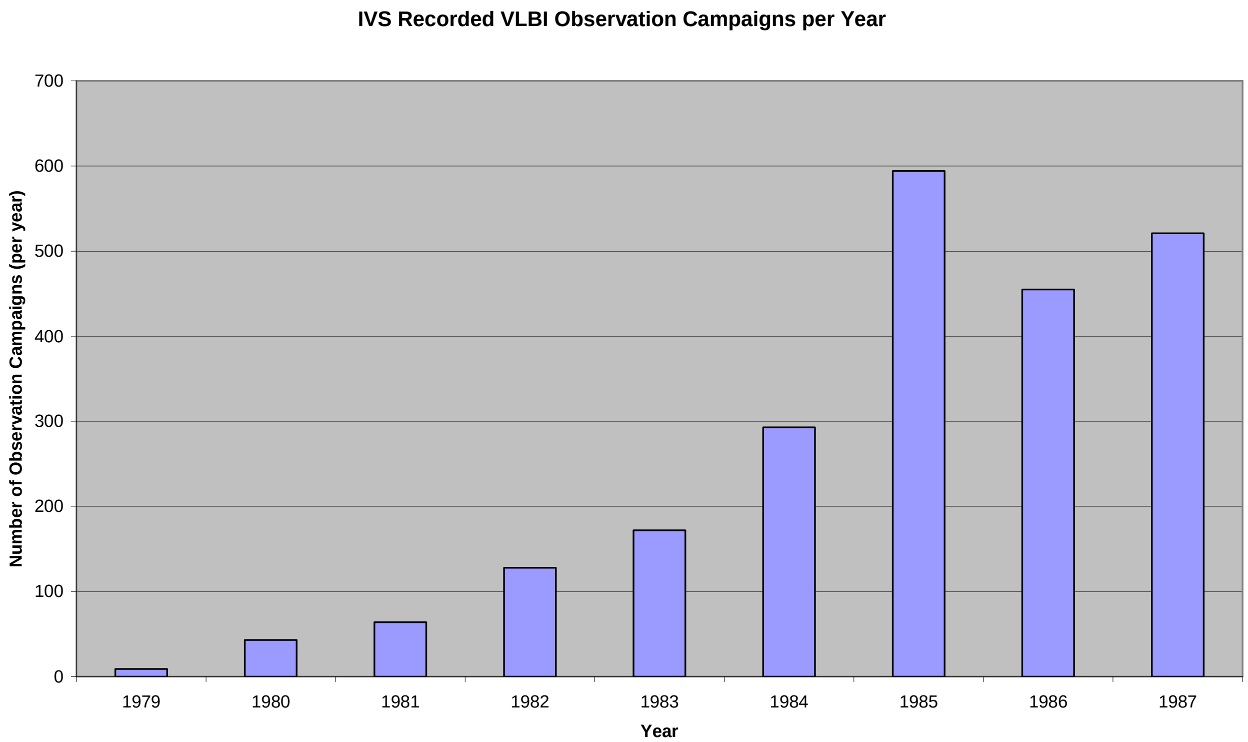

Figure 4: Bar chart showing the number of observation campaigns per year for all stations monitored by the IVS over a nine year period.

First examining the longevity of VLBI data, it was stated in Section 4.2 that VLBI has a long data record. Figure 4 shows the number of observation campaigns per year between 1979 and 1987 as recorded by the

IVS. As is shown, within a 9 year period (note that 1979 is not considered in full) the number of observation campaigns increased dramatically. Furthermore the campaigns plotted are only for those recorded by the IVS, which does not archive information from all of the world's VLBI antenna arrays. Therefore although the number of potential PWV observations was not high in 1979, the first decade of VLBI measurements yielded a large increase in observations. Combining this fact with the reliability of VLBI data, the measurement technique becomes an attractive method of estimating PWV for climate, especially when one considers the recommendations given by the Global Climate Observation Service (GCOS) in Section 7.
Finally with consideration of the spatial distribution of VLBI stations, high density measurements are not of primary importance to the climate community, as is the case with weather forecasting. Moreover with a VLBI stations present on every continent (Appendix 1), VLBI may be able to provide valuable additional observations in sparse measurement regions.

4.5. The future of VLBI observations

As a consequence of the recent upsurge in societal demands for enhanced knowledge of global change and environmental hazards in 2003 the IVS commissioned a working group to investigate the development of next generation VLBI stations (IVS2 2009). The result was a report outlining the development of a new VLBI network by 2010, termed VLBI2010. The criteria for a new network were based primarily on a desire for greater accuracy, data collection and speed of analysis within the geodetic community.
As a consequence of the VLBI2010 report the VLBI community is at the brink of a new era. The next generation VLBI will include the following components, which are outlined in full at http://ivscc.gsfc.nasa.gov/about/wg/wg3/index.html:

1) An increased number of VLBI stations with more even global distribution
2) An increased observation density (in a temporal sense)
3) Near real-time data output
4) Central management and archiving of data

Such improvements will lead to greatly enhanced opportunities for calculating PWV across the globe. This then has possibly significant ramifications for global climate observations in the future. The VLBI2010 programme may have implications for the weather forecasting observation network, especially in regions with sparse measurements of PWV.
Many of the improvements outlined for the VLBI community in the VLBI2010 report were brought about by the advances in comparative technologies such as GPS, which represents the greatest competition for VLBI with regard to its use within the meteorological and climatological fields. Such comparative techniques are discussed presently.

5. Comparison with other observational tools

5.1. VLBI and GPS

In terms of water vapour detection and the calculation of PWV, the present day GPS network has proliferated over and above VLBI due to its greater practicality and lower operating cost (Goddard1 2009). This is perhaps best demonstrated by the global distribution of GPS stations as provided by the International GNSS Service (IGS) as shown at http://igs.org/network/netindex.html (where GNSS is the acronym for a Global Navigation Satellite System). Compare this to Appendix 1 showing the current IVS network.
Ironically however, one should bear in mind that the GPS network is dependent upon the VLBI community to provide the fiducial reference frame in which the former operates (Goddard1 2009), and VLBI is essential to the successful operation of GPS.
Aside from their respective station locations, the calculation of PWV from GPS and VLBI is remarkably similar. Both methods derive measurements of PWV from the calculation of zenith delays from incoming radio waves. However in contrast to VLBI, the radio emission sources for GPS are non-celestial, rather emitted at known times by satellites at known locations in Earth orbit.
Currently GPS is in use for both weather forecasting and climatological purposes. The UKMO has incorporated ground-based GPS ZWD measurements since 2007 into its weather forecast observations

(Gemma Bennittt, personal communication). This is made possible by NRT data access to GPS ZWD measurements. Furthermore Wang and Zhang (2009) have recently compiled a global archive of GPS PWV data to be used in climate studies. So, what room is there for VLBI?

As has been alluded to previously, with no current NRT data access VLBI has no application in weather forecasting observations. However in terms of past climate observations, the VLBI dataset extends over a decade beyond the first GPS measurements, taken in 1993 (NPS 2009). Wang and Zhang (2009) note such data availability from the IGS from as late as 1997. Furthermore, for VLBI its stability and accuracy make it an attractive option for climate studies concerned with the previous few decades and for future observations. Still, such climate applications are now possible for GPS ZWD measurements (Wang and Zhang 2009). Therefore how do VLBI and GPS measurements of ZWD/PWV or similar compare? Note that from this point PWV will be used as an umbrella term for PWV related variables derived from different technologies with the aim of calculating PWV.

Numerous studies have been conducted comparing VLBI and GPS derived measurements of PWV. These include Behrend et al. (2000); Gradinarsky et al. (2000); Niell et al. (2001); Pacione et al. (2002), Haas et al. (2003); Steigenberger et al. (2007) and Jin et al. (2009). References to the listed studies are given in Appendix 2. Instead here the outcome of these studies is discussed. This discussion is two fold. Firstly one must consider the agreement in measurements between VLBI and GPS estimates of PWV. Secondly the recommendations from comparative studies should be highlighted.

Addressing the agreement between VLBI and GPS measurements, the general consensus of comparative studies between the two methods of estimating PWV are that both techniques show close agreement within acceptable error bounds. However systematic bias between the two estimation methods appears in most studies irrespective of the comparative time window. Consequently it would seem apparent that VLBI represents a plausible observational tool for PWV, and could be used to help diagnose biases in GPS observations. Yet, attention should be paid to the uncertainties surrounding both methods, which will not be expanded upon here, as each comparison study includes corrections for each technique to allow for comparison. Such corrections may exist within the raw data, processing, or comparative procedures.

As for stated recommendations from the considered studies, these have important implications for any future use of VLBI. Applicable to VLBI and GPS as well as other techniques of estimating PWV it is stressed that VLBI stations should be collocated with other measurement methods. Results from comparative studies of VLBI with other measurement methods highlight that the most robust estimates of PWV are produced by a combination of measurement techniques, principally VLBI and GPS, which show the closest agreement. Besides collocation the use of VLBI stations as a verification tool for other PWV observation methods is also distinguished. This is akin to the findings of Wang and Zhang (2009), where radiosonde bias correction is given as an application of the newly formed GPS data archive.

5.2. VLBI and other alternative observational methods

Other than GPS, existing methods of estimating PWV estimates include the radiosonde network, satellite radiometers and ground-based water vapour radiometers (WVR). Historically the radiosonde network is the yardstick by which new additions to the upper air sensing network are judged (Niell et al. 2001). In terms of comparison between VLBI and multiple existing PWV estimation methods, there are several studies that breach this subject. Notably works by Haas et al. (2003) and Niell et al. (2001) have drawn conclusions concerning the comparison of multiple methods used for inferring PWV.

Firstly Haas et al. (2003) found that VLBI, GPS, WVR and satellite derived measurements of PWV agree well when their sampling epochs are synchronised. This is especially true for the agreement between GPS and VLBI. Niell et al. (2001) draws the same conclusions, also highlighting the use of multiple sources of PWV data as the prime method of providing robust water vapour measurements. Moreover both studies stress the importance of combinative methods of deriving PWV for long term water vapour trends, important to climate work. Significantly however, both Haas et al. (2003) and Niell et al. (2001) also highlight the idiosyncrasies in each method that must be accounted for upon comparison.

It must be understood that each technique of estimating PWV has advantages and disadvantages (Haas et al. 2003). This may relate to spatial and temporal resolution, reliability, cost etc. Furthermore one should consider that each technique for measuring PWV may measure a different raw variable, from which PWV is derived (Niell et al. 2001). For example radiosondes measure relative humidity along a convoluted ascent path whereas WVR measure integrated brightness temperature along a direct line of sight. Thus error will be induced in deriving variables to give a comparable parameter, namely PWV. Nevertheless, with a greater number of observations of the same variable from multiple sources one should be able to derive the most accurate estimate possible. Hence VLBI has a role to play in helping to verify and more accurately define PWV measurements, regardless of its application.

5.3. Distribution of measurement locations

In order to assess the distribution of VLBI stations globally, the locations of VLBI stations are plotted on a map in Figure 5, using the stations listed in Appendix 3. Note that this list of stations may be incomplete, but hopefully gives a good idea of the overall distribution. It should be noted that away from the IVS station inventory the VLBI community appears to have no standard for reporting station location, and many organisations name the same station differently. This can be compared with the locations of IGRA launch sites in Figure 6. The IGRA location data used was obtained from the United States National Oceanographic and Atmospheric Organisation (NOAA), available at http://www.ncdc.noaa.gov/oa/climate/igra/index.php. An overview of the IGRA list is given by Durre et al. (2006). This list of radiosondes launch sites would appear to be the most comprehensive of its kind. However stations are omitted from the list, for example the radiosonde launch site at Chilbolton, UK. Figure 7 shows a similar comparisons with GPS stations taken from an IGS tracking network list (available at http://igs.org/network/netindex.html). The GPS stations listed on this site are used for water vapour measurements (Wang and Zhang 2009), however the list does not include the national GPS networks that are used by weather forecasting agencies for NRT water vapour observations (Gemma Bennitt 2009, personal communication). Thus the GPS dataset used in this study has been chosen to give an indication of the spread of GPS stations and is not to be considered comprehensive. All of the data used is for IGRA and GPS locations is for stations which have been active at some point since 1979, in line with the development of VLBI. Therefore some of the locations plotted in the following results section may represent disused observation points for the respective measurement techniques. Such data however remains useful for climate studies, where historical records may be of use in replicating the Earth’s past climate.

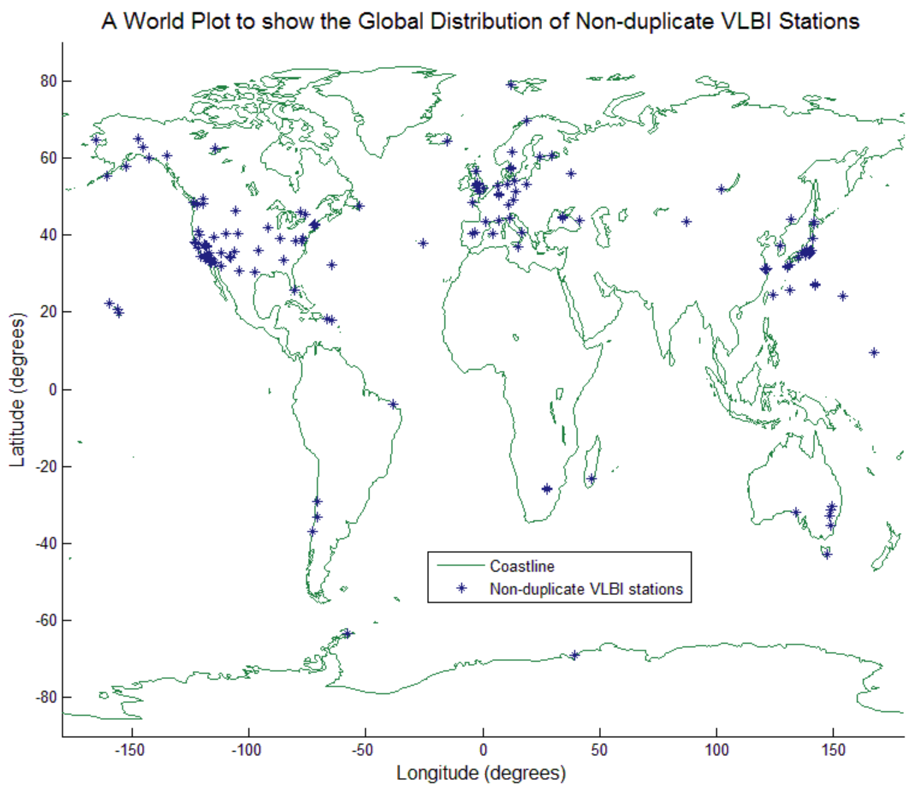

Figure 5: World plot of 164 non-duplicate VLBI stations, where station location data has been obtained from sources given in Appendix 4.

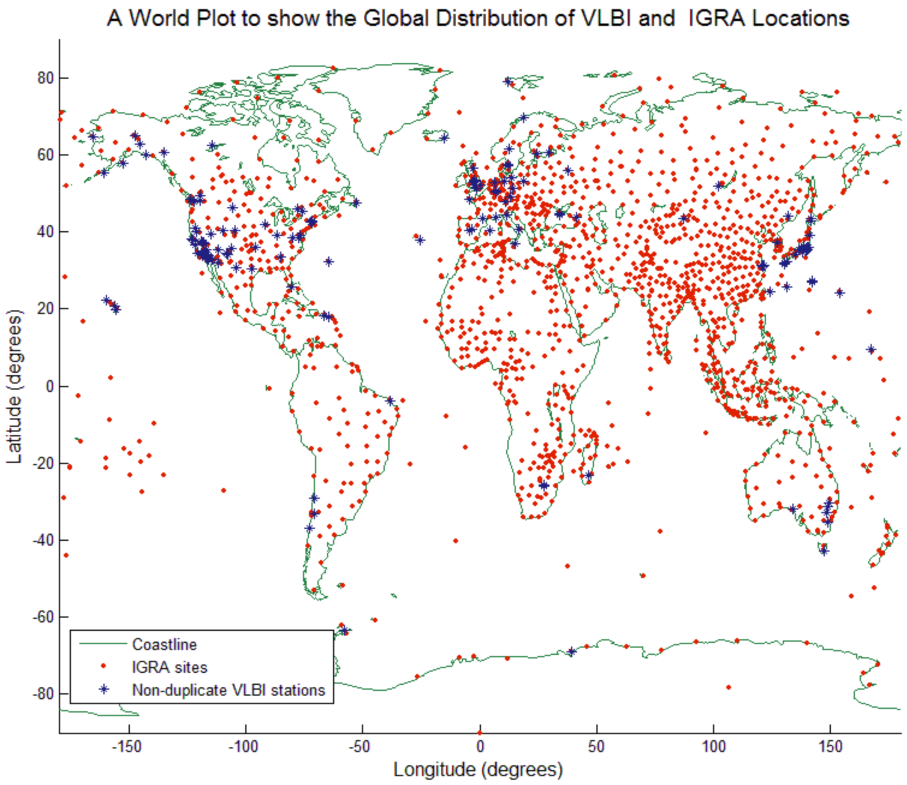

Figure 6: World plot of non-duplicate VLBI stations and IGRA locations shown as a means to compare the global distributions of both.

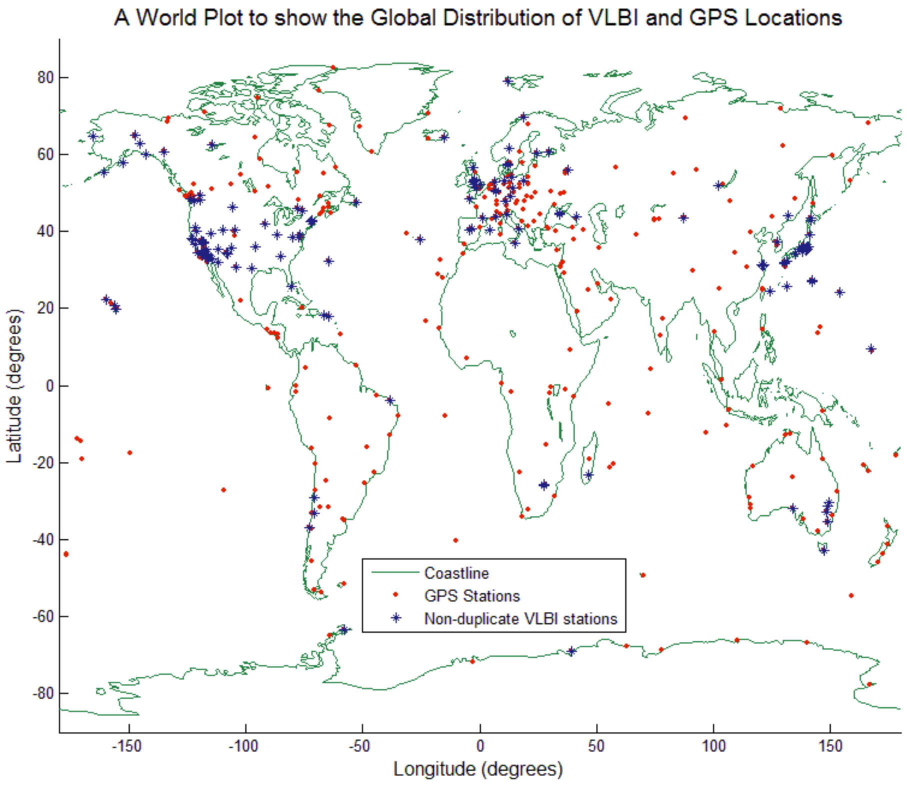

Figure 7: World plot of non-duplicate VLBI stations and IGS tracking locations shown as a means to compare the global distributions of both.

6. VLBI collocation study

6.1. Overview

In order to do intercomparisons between VLBI PWV measurements and other types of PWV measurement, pairs of observation stations must be found which are sufficiently close that there is useful correlation between PWV measurements at the two locations. In order to assist any future analyses of this, the separations of VLBI stations from IGRS launch sites was assessed in a co-location study. Note that other techniques of measuring PWV such as GPS or water-vapour radiometers have not been included due to time constraints.

6.2. Results

A study was performed of the co-location of VLBI stations and the IGRA locations. This first involved plotting the distance to the closest IGRA station for each of the VLBI stations. The separations were calculated using the Cartesian station location vectors with origin at the Earth's centre. The result of this process is given by Figure 8, where VLBI stations are plotted according to their separation from the nearest radiosonde launch site. Three categories are used, corresponding to separations of 30, 100 and 200 km. Importantly, most of the VLBI stations lie within 200km of the nearest radiosonde launch site. The outcome of the co-location study is presented as map plots of the separations of VLBI and IGRA locations (Figure 8) and as histograms of the separations (Figures 9 and 10). It should be noted that a VLBI station may lay within 200 km separation of multiple radiosonde launch sites, hence the depiction of nearly 400 VLBI-radiosonde pairs in Figures 9 and 10.

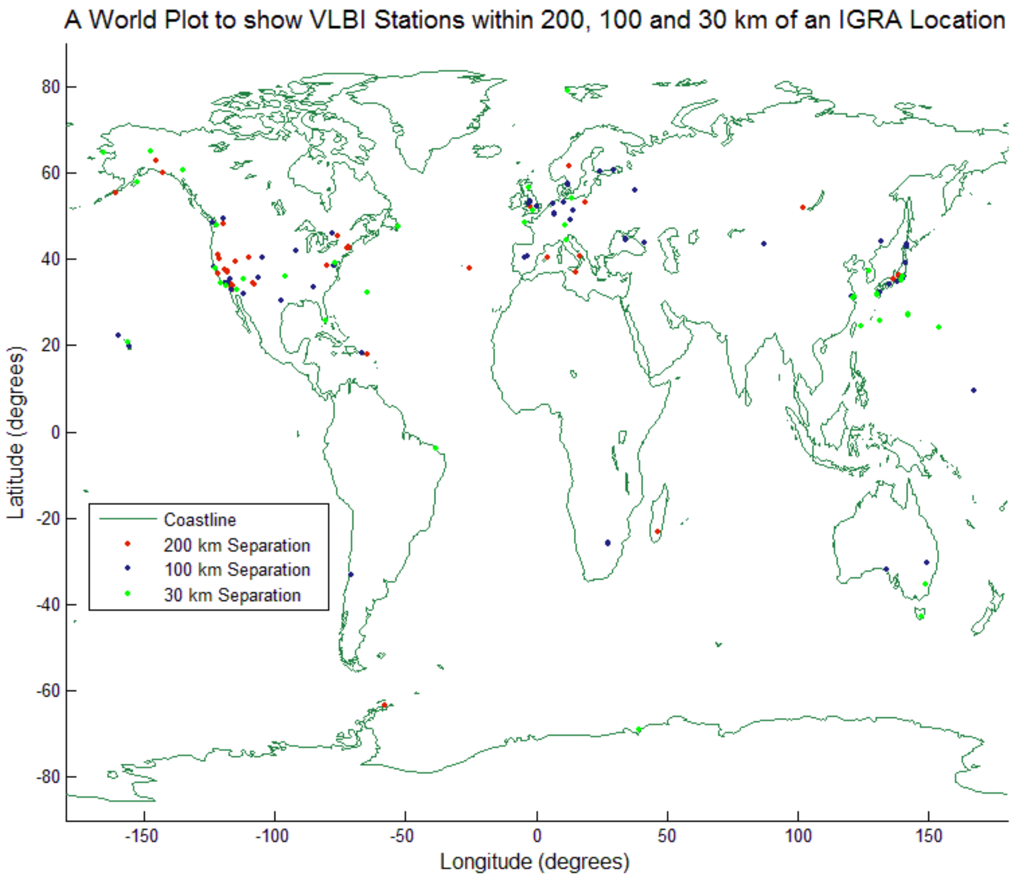

Figure 8: World plot to show the separation of the nearest IGRA radiosonde site from each VLBI station within three range categories of 30,100 and 200 km.

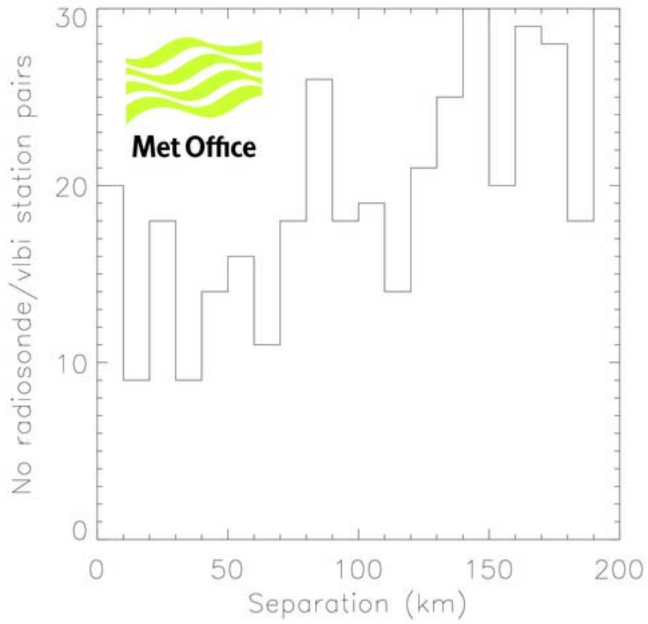

Figure 9: Histogram showing the number of VLBI-radiosonde location pairs separated by incremental distances.

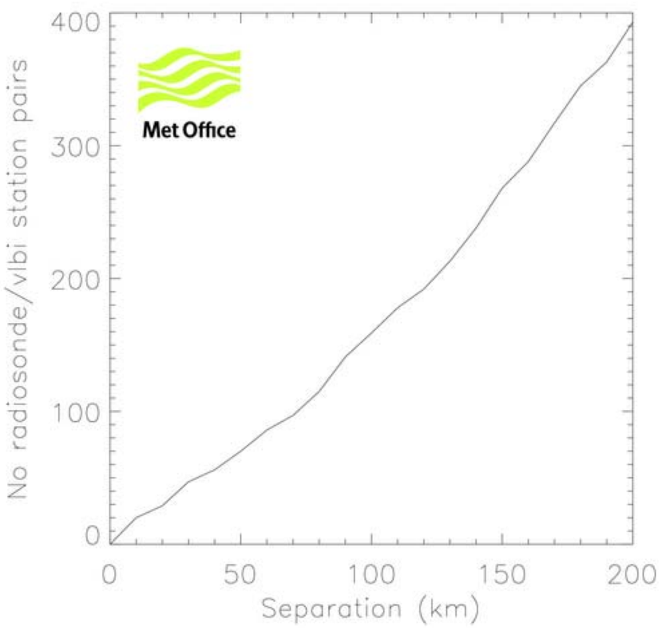

Figure 10: Cumulative histogram showing the increasing number of VLBI-radiosonde pairs with an increase in separation distance.

6.3. Discussion

The map plots of VLBI station locations (Figure 5) and the comparisons of VLBI, IGRA and GPS locations (Figures 6 and 7) highlight the variations in station density across the globe. As can be seen there are large swathes of the Earth without VLBI coverage including parts of Africa, South America, Central Asia, Southeast Asia and Australasia.

In contrast, the IGS and radiosonde (IGRA) network are more dense and more uniform, as shown in Figures 6 and 7. This may be partly exaggerated in Figure 6 as it includes all operational radiosonde launch sites since 1979, even if they are no longer in use. Despite the density of launch sites, the radiosonde network is still considered inadequate for upper air water vapour observations, both from a temporal and spatial perspective (Wang and Zhang 2009). National GPS networks have not been plotted in Figure 7, thus the density of GPS stations is underrepresented. Note that there is a correlation between areas which have a high density of VLBI stations and areas with high densities of GPS or IGRA sites, which will increase the likelihood of co-locations.
The histograms of Figures 9 and 10 show that (for example) 47 VLBI stations lie within 30 km of a radiosonde launch site, and 72 stations lie with 50 km. The number of these stations which can be used will depend on how strongly PWV decorrelates with horizontal separation – this would allow one to decide at which point the separation distance becomes too large to consider comparisons of PWV measurements.

7. VLBI, GUAN and GRUAN

7.1. GUAN and GRUAN

This section is primarily concerned with the findings of the GCOS 112 Report, referred to elsewhere as (GCOS112 2007). Thus references will not be given unless concerned with alternative materials.
Concerned with a sub-division of the World Meteorological Organization (WMO), GCOS represents a meteorological working group aimed at providing a global network of observation stations fit for inferring climate change from long-term, stable meteorological datasets (GOSIC 2009). Currently in operation is the GCOS Upper Air Network (GUAN), with the remit of sensing meteorological properties throughout the depth of the atmosphere. This network comprises 164 radiosonde launch sites, aimed at providing long-term datasets that are able to detect hemispheric alterations in temperature, humidity and momentum. However building on the work conducted under GUAN a new generation of climate observations is currently being formed. The following information and discussion has been disseminated from the GCOS 112 Report document.
The GCOS Reference Upper Air Network (GRUAN) aims to build on the work conducted by the GUAN, but not replace it. GUAN locations have been spatially organised to provide global coverage with consistent, homogeneous observations from radiosondes. The GRUAN in contrast has the aim of providing a stable reference network of the upper air comprised of multiple measurement techniques. The key properties of the GRUAN are that it should be a comprehensively documented network allowing for equipment bias corrections with time; it should comprehensively characterise the atmospheric column; and comprise the best possible measurements available at any given time. Not yet in operation, if the GRUAN is to exhaustively measure the atmospheric column in a stable manner a combination of VLBI with other techniques of measuring PWV may have a role to play, as illustrated in Section 5.2. Not cited by the GCOS 112 report for considered instrument options for the GRUAN, it is stressed here that VLBI, with long-term stable measurements and planned proliferation under the VLBI2010 scheme is likely to be of interest to the global climate community.

7.2. Possible role of VLBI under GRUAN

Building on points already covered in this report, it is prudent to investigate the possible role that VLBI could play in the GRUAN network. With information again taken from the GCOS 112 Report document the bullet points below emphasise how VLBI would fit into the GRUAN programme:

Firstly VLBI already represents a long term, stable measurement method for PWV, which is in harmony with the GRUAN basis.
The GRUAN, employing multiple measurement methods requires that redundant measurements be incorporated into the observation scheme for each meteorological variable. This is significant given the good agreement between VLBI and alternative PWV measurement techniques (see Section 5).
VLBI remains a relatively un-tested technology by the climate community, and therefore would represent a new technology that could be tested for its validity (encouraged by the GRUAN) in sensing PWV at proposed GRUAN sites, given the necessary co-location.
The GRUAN aims to sample a variety of climate regimes, surface types, latitudes and altitudes. This compliments the distribution of VLBI stations which despite being low in density are spread across the

globe. Furthermore with the astronomical grounding of VLBI many VLBI stations are located at high altitude, and thus represent an alternative to measurements that are not.
Ocean locations are scarce within the GRUAN programme consideration, and with a need for maritime climate observation the numerous VLBI sites located on tropical and non-tropical islands represent an opportunity.

The outlined points show that VLBI has the capability of significantly aiding the climate community. However the discussion given here is only preliminary. A full investigation into the role that VLBI could play would be required. In the short term a key recommendation for future work would pertain to a co-location study showing the position of VLBI stations (current and planned) relative to proposed GRUAN locations.

8. VLBI and Satellite Verification

The role of VLBI in satellite observation verification is explored in this section. One of the aims of the GRUAN is to improve observing satellite calibration and validation (GCOS112 2007). In this instance calibration and validation refer to correcting for drift in satellite radiances. Achieved via reference to a ground-truth, this represents another opportunity for VLBI implementation into the climate sphere.
For VLBI to be implemented as a calibration and validation tool for satellite PWV measurements would require incorporation into a relevant calibration project, such as the proposed Global Space-Based Intercalibration System (GSICS). This project is discussed as working in tandem with the GCOS as part of GRUAN (GCOS112 2007), which incorporates the criterion of satellite calibration.
From a UK perspective, incorporation of VLBI could take place in the form of the HadIR project. HadIR represents a project conducted by the UKMO Hadley Centre, concerned with infrared (IR) radiances for climate monitoring purposes (Saunders 2009). The basis of the HadIR project is to achieve a 40-year dataset of homogenised IR radiances measuring multiple atmospheric variables for numerous objectives. Most pertinent to VLBI is the aim of quantifying the alterations in the upper air humidity record since the inception of satellite IR radiometer measurement. To achieve homogenisation it is necessary to correct for several factors (Saunders 2009), including:

1) Uncertainty estimation
2) Degradation of hardware
3) Data processing

However, regardless of the source of uncertainty, any verification using VLBI would ultimately utilise VLBI's stability and long term data record to assess alterations in measurements provided by other instruments. The main requirement of this process being that the VLBI observations are sufficiently close in space and time to satellite overpasses to correct for satellite drift in the past, and subsequently in the future. This final point represents a new opportunity for investigative work that is not conducted here, but is recommended as future work.

9. VLBI and El Niño

Unrelated to the detection of atmospheric water vapour, this section is included due to a large amount of literature being dedicated to the topic. In detecting the shifting plates on the Earth as well as helping to define the ITRF, VLBI is sensitive to momentum exchanges throughout the Earth-atmosphere system (Goddard1 2009). In particular VLBI measurements are sensitive to the irregular oceanic oscillations related to El Niño (IVS3 2009). Related to shifts in ocean currents, the transfer in angular momentum between the ocean and the solid Earth causes the Length of Day (LOD) to alter, as measured by VLBI (IVS3 2009). The literature contains several studies pertinent to this topic, where time series of LOD measurements and El Niño indices have been correlated to show the causal link in Earth-rotation parameters. For example, the IVS 2003 Annual Report included a graph of the correlation between the state of the El Niño Southern Oscillation (ENSO) and LOD measurements – this can be seen at:
http://ivs.nict.go.jp/mirror/publications/ar2003/acoso/ . Note that high-temporal frequency variations in Earth rotation due to earthquakes and other sudden events are also superimposed on the signal.

Further to detecting large moment of inertia changes such as ENSO, VLBI can also detect momentum exchanges and low density atmospheric mass movements (Gipson 1998). Thus the question posed here is, if small mass shifts in the atmosphere (relative to the ocean) can be detected by VLBI LOD measurements, can initial oceanic current shifts related to the onset of El Niño and La Niña be detected? This question is highly speculative, and only basic research has been conducted on this topic for the purpose of this report. The need for detection is evident in that, despite the comprehensive ENSO observation network (described by http://www.elnino.noaa.gov/observ.html) predictability of the event is hindered by, amongst other processes, the spring predictability barrier (Wu et al. 2008). Thus any benefit VLBI could bring to the prediction of the ENSO is surely of interest to the seasonal and decadal forecasting community. Consequently it is recommended that a preliminary study into the detective capability of VLBI in relation to mass shifts be conducted. Only from that standpoint could one infer the use of VLBI in the prediction of the ENSO.

10. Recommendations for Future Work

Proposals for future work can be broken down into distinct segments. Recommendations can be categorised under VLBI data availability, data quality, further co-location work and other future developments. Each of the listed categories will be dealt with in turn.

10.1. VLBI data availability

This report has highlighted the need for coordinated VLBI data collation with regard to PWV estimation. This issue was primarily raised due to the difficulty in locating VLBI station location data whilst undertaking the co-location study given in Section 6. However there is a need for collation of VLBI data as a whole. Instigated in 1997, the IVS represents the the most coherent international VLBI organisation. Prior to its conception it would appear that the VLBI community was disjointed such that international collaboration was on an adhoc basis, from a data access standpoint. Yet, even under the IVS there would appear to be a large disparity between the number of monitored stations as indicated by Appendix 1 and Figure 5. So, there is a need for communication such that any loss of data is prevented and that a central archive is generated for international use. The IVS does of course provide centralised data archives, but only for the stations monitored by the IVS. It is therefore suggested that a similar protocol be employed internationally. Furthermore, if such a project were undertaken a uniform data formatting procedure should be applied for PWV data.

The previous recommendations are pertinent both to meteorology and the VLBI community. From a meteorological perspective the need for a coherent data scheme is still necessary, however the availability of meteorologically available products is of importance also. From Section 3.3 it is most likely that the zenith delay outputs from VLBI observations are of greatest interest, akin to the meteorologists in the GPS community. Such data was found to be readily available from the IVS, however investigation into other VLBI stations monitored by separate organisations was not considered. If there were concerns about second-order effects from the source elevation, it might be necessary to go back to raw delays rather than using the processed zenith delays. A full investigation would be necessary to discover the true potential of an archive of VLBI-derived zenith delays, i.e. its potential use as an international verification tool for radiosonde and satellite water vapour observations. The envisaged investigation would ideally establish a data-record timeline, citing the development of VLBI observations. A timeline of available data would be of particular use to the climate observing community to assess whether the data record from VLBI was long enough and available in the correct locations for applications such as retrospective radiosonde corrections.

Lastly, it is recommended that a full investigation into the plans and progress of VLBI2010 be undertaken. In doing so one would be able to assess the future of VLBI as a climate observing tool (with respect to future station distribution), and to determine whether costs would be prohibitive for its use in weather forecasting (in comparison to cheap GPS data).

10.2. VLBI data quality

This report has not fully considered the quality of VLBI measurements. Assessment of data quality has been made only with reference to a limited number of studies and has been qualitative in nature. Subsequently, as with data availability a comprehensive international assessment of data reliability, accuracy and properties will have to be conducted in order to gain a fuller picture of the possible future use of VLBI for PWV estimates. Of course this would entail the same pitfalls as were made evident in Section 10.1. That is to say, it is likely that considerable work will have to be undertaken to obtain information relevant to data attributes at each VLBI location due to the disjointed nature of the VLBI data services.

10.3. Further co-location studies

The co-location study presented in Section 6 was in no way comprehensive and only represented a preliminary overview highlighting the possible uses of VLBI. The study considered the distribution of VLBI stations; comparison of this distribution with international locations of radiosonde launch sites and GPS; as well as a consideration of radiosonde-VLBI location separations. As noted in Section 6.1, the data included for all three estimation techniques within the study were for measurement locations that had been operational since 1979, but that may have since ceased to be in use. Thus, one enhancement would be a study the time overlap of station operation. Another would be to ensure that all known VLBI stations were included, however this process is constrained by limited data access as outlined in Section 10.1.
With the removal of time constraints, a much more comprehensive co-location study is suggested. This would include the following components:

1) A full list of global VLBI stations
2) Comparison of distributions of stations with all alternative PWV estimation methods, including the radiosonde network, the GPS network, ground-based water vapour radiometers and satellite radiometers.
3) Separation calculation between each station under each method
4) Production of time series showing the temporal overlap of observations from different methods.
5) A sub-study concerned with VLBI station locations as proposed GRUAN sites.
6) A sub-study addressing the previous bullet points, but relative to VLBI station locations and temporal resolution given under the VLBI2010 plan.

By fulfilling the listed objectives a more comprehensive co-location study will be realised that investigates the co-location of VLBI station with other PWV estimation techniques to the fullest extent. Assuming that there are frequent co-locations with the alternative methods of estimating PWV, then VLBI could give substantial benefits for PWV climate monitoring (see Section 5), as well as for its incorporation into operational programmes such as the GRUAN. Moreover with the inclusion of observation overlap time series it would be much easier to establish the use of VLBI as a verification tool for the radiosonde network, satellite drift etc.

10.4. Other future developments

The focus of this report is the use of VLBI as a measurement tool for estimating PWV. However, in doing so this incurs applications of correcting for, and comparison with, other methods of estimating PWV.
In terms of corrections, the stability of VLBI discussed in Section 4.2 and its potentially long data record makes VLBI a candidate for correcting errors within other measurement techniques, namely the radiosonde and satellite networks. To carry out such procedures, however, it would be required that the data quality and stability of VLBI were sufficient for the task (see Section 10.2). Only then would work regarding corrections be possible. With respect to the radiosonde network, one is mostly concerned with accounting for alterations in radiosonde type, both in a temporal and spatial sense (Wang and Zhang 2009), or differentiating between regions where different radiosonde types are used. This would be possible through comparison of water vapour measurements inferred from both VLBI and radiosondes and assigning step changes (type alterations) or data trends (possible hysteris or climatic effects). This process of course being reliant upon availability of the necessary radiosonde data.
With respect the satellite network it has been proposed that VLBI measurements could be used to correct for satellite drift, with respect to water vapour estimates. Such a procedure would again be dependent on data quality assurances with respect to VLBI, but would require sufficient observation co-location, both in space and time, and therefore any future work would be reliant upon the results of a co-location study such as that outlined in Section 10.3. Moreover there is a question of what program the VLBI verification scheme would operate under. From a UK perspective the possibility of incorporation into the UKMO HadIR project is emphasised as one such avenue.
Aside from correction applications, comparison of VLBI and with other PWV estimation techniques has been shown to provide robust combinative estimates of PWV. With the development of robust results any trends found in PWV with time would perhaps be reliable climatic indicators. Consequently it is encouraged here that further studies, building on the work of Haas et al (2003) and alike, take place to demonstrate further the use of VLBI for climate monitoring. Any proposed study of this nature could bring greater benefits by

considering a broader perspective than those already in the literature. For example it would be prudent to consider several VLBI stations co-located with other measurement instrumentation over a large region. This could establish a stronger climate signal, and minimise erroneous effects from individual sites.
With respect to Section 7, the speculative inclusion of VLBI estimates of PWV into the GRUAN network would seem plausible given the rhetoric outlined by the GCOS. However a full assessment of the likelihood of such a development would be required before any steps towards this were taken. This would most likely need to involve communication and collaboration between the GCOS and the various VLBI organisations, with the IVS considered as an initial starting point. The primary objective of any such study would be the need to establish any co-location between existing or proposed VLBI locations and proposed GRUAN locations. If co-location was found at multiple sites this would enhance the likelihood of VLBI's incorporation into GRUAN.
Finally, we consider future work relating to the relationship between ENSO and LOD measurements made by VLBI. Section 9 gave a very basic overview of the causal link between ENSO and alterations in the LOD. However the speculative question posed in Section 9 is the focus for the suggestion of future work pertaining to this topic. The question being can VLBI aid the climate community in predicting the ENSO? This postulation has been based on the ability of VLBI derived LOD measurements to detect relatively small momentum alterations in the atmosphere or oceans. It is stressed here that any suggestion at this stage is purely speculative.

10.5. Summary

The following is simply a bullet-pointed summary of prior information concerning future work, which may be of use for those with little reading time. **Points highlighted in bold are of greater immediate importance to the future consideration of VLBI use within meteorology.**

Future work suggestions and requirements:

1) Requirement for closer collaboration with the VLBI community leading to a true international data collation exercise. This would aid all scientific efforts concerned with VLBI.
2) From a meteorological perspective there remains a need to assess the potential dataset availability for tropospheric products relevant to deriving PWV.
3) The temporal overlap of VLBI measurements with other modes of estimating PWV needs to be established in order to assess the full potential of VLBI as an observation verification tool.
4) Ideally a data record timeline would be established for all VLBI stations, aiding the assessment of the historical VLBI data record.
5) A full investigation is needed into the quality of VLBI data for inferring PWV for meteorological applications i.e. its reliability, accuracy and properties. Ideally this would establish any heterogeneities between VLBI observation campaigns, both in time, space and by organisation.
6) Key to the impact of this report, a future co-location study of VLBI with other PWV estimation techniques is considered imperative. Such a study would lay the foundations for many of the other future work objectives in highlighting the potential for comparison between techniques. For further details see Section 10.3.

Given the necessary assurances regarding the quality and longevity of the VLBI data record a comparative study between VLBI and radiosonde derived PWV measurements is suggested. This would ideally establish errors in the radiosonde data archive, as well as helping to establish climatic trends. A study with a similar basis to the recent work of Wang and Zhang (2009) for the GPS record is envisaged.
Similar in nature to the previous point, given the same data assurances for VLBI, correction for satellite drift would be a possibility.
This report has reviewed comparative studies relating to PWV estimates derived from VLBI and "competing" techniques. The agreement between these techniques and VLBI has been shown to be close. Based on this knowledge studies have addressed the issue of establishing climatic trends from VLBI. Given the completion of a full co-location study a subsequent proposal is a co-location investigation between VLBI stations and the proposed GRUAN. This work would shed light on another avenue in which VLBI could perhaps contribute to the future of climate observations and ties together comparative work between VLBI and other techniques.
Finally, aside from PWV measurements it has been speculatively suggested in this report that VLBI might have the potential to aid the ENSO prediction effort.

11. Key Outcomes and correspondence

The following represents key points that should be taken from this report as well as important correspondence that has taken place.

VLBI would appear to represent a potential technology for monitoring climate, providing verification for current climate observation as well as other meteorological applications.
Future work has been suggested that should aid in developing the prominence of VLBI within the meteorological community, which should provide the impetus for its proper consideration as a genuine observation tool.
Interest has been shown in international collaboration with the UKMO to assess the use of VLBI in observing PWV. It is suggested here that a possible visiting scientist programme be considered for someone involved within the VLBI community and who is willing to help asses the development of its meteorological uses.
Interest has also been shown in the development of a possible postgraduate research project investigating the future use of VLBI in climate observations.
Furthermore from literature concerning VLBI, as well as communication with members of the VLBI community, the potential impacts of VLBI in the meteorological fields are yet to be fully realised.

With consideration of the above the following action points are noted:

Communication with the VLBI community is considered with a view to investigating the use of VLBI within the meteorological sphere.
Future work highlighted in bold within 9e is carried out in order to assess any meteorological use of PWV derived from VLBI.
Communication takes place with the GCOS coordinators in order to implement an investigation in whether VLBI as a technology fit for climate observation with respect to PWV.
Discussion regarding the implementation of a postgraduate research project is undertaken whereby suggested future work is incorporated into the project agenda.

12. Summary

This report has investigated the use of VLBI as a measurement technique for PWV. Following an overview of the how PWV can be derived from VLBI zenith delay measurements the future use of VLBI within the meteorological community has been considered.
Beginning with an assessment of the VLBI data availability it has been shown that there is a need for an international effort to collate VLBI data (past and present) into a central location. Further to this, greater international integration is suggested between different facets of the VLBI community. Considering data from the IVS, a preliminary descriptive assessment of the reliability, longevity, impacts and future infrastructure of VLBI has been conducted. Importantly it has been established that the use of VLBI-derived PWV measurements for weather forecasting purposes is unlikely, at least with respect to the present day VLBI network. However VLBI's application in climate observations is much more likely, with its use as a verification tool for other techniques in a retrospective sense, and as a climate observing tool in its own right.
Following this, a literature review pertaining to the comparison of VLBI derived estimates of PWV with alternative techniques has been given. The conclusions from this show that VLBI agrees very well with GPS observations, and also relatively well with traditional radiosonde observations.
Given the potential for VLBI as a means of observing climate, the results of a co-location study conducted for this report were presented. Although limited in its extent and impact the study has highlighted the global distribution of the present VLBI network and its co-location with radiosonde launch sites over the last four decades. This of course has impacts both for verification of the radiosonde observations and the use of VLBI as a climate observing tool.
Having recognised the global distribution of the present day VLBI network as well as taking the planned VLB12010 expansion into consideration, possible operational uses of VLBI have been given. Firstly with an overview of the GRUAN, it would appear that PWV measurements from VLBI may be of interest to the GCOS. Secondly, a very brief outline of the possible application of VLBI in satellite drift correction has been presented. However the only output from this discussion has been the possible incorporation of past VLBI PWV measurements into the UKMO HadIR project.

The application of VLBI LOD measurements were discussed in terms of helping to overcome the ENSO spring predictability barrier. The discussion included in this report is stressed to be purely speculative and serves only to stimulate interest of further investigation of the topic.
Finally, future work stemming from open questions from this report has been outlined. This includes the need for global collaboration to ensure a comprehensive effort aimed at the collation of VLBI data; a further more comprehensive VLBI co-location study with regard to other PWV measurement techniques; as well as possible future communication with organisational bodies, with a view to implementing VLBI as an operational tool for measuring PWV. It is acknowledged that this report has only scratched the surface of any possible VLBI involvement within meteorology, but it should at least provide the momentum to instigate further works towards this aim.

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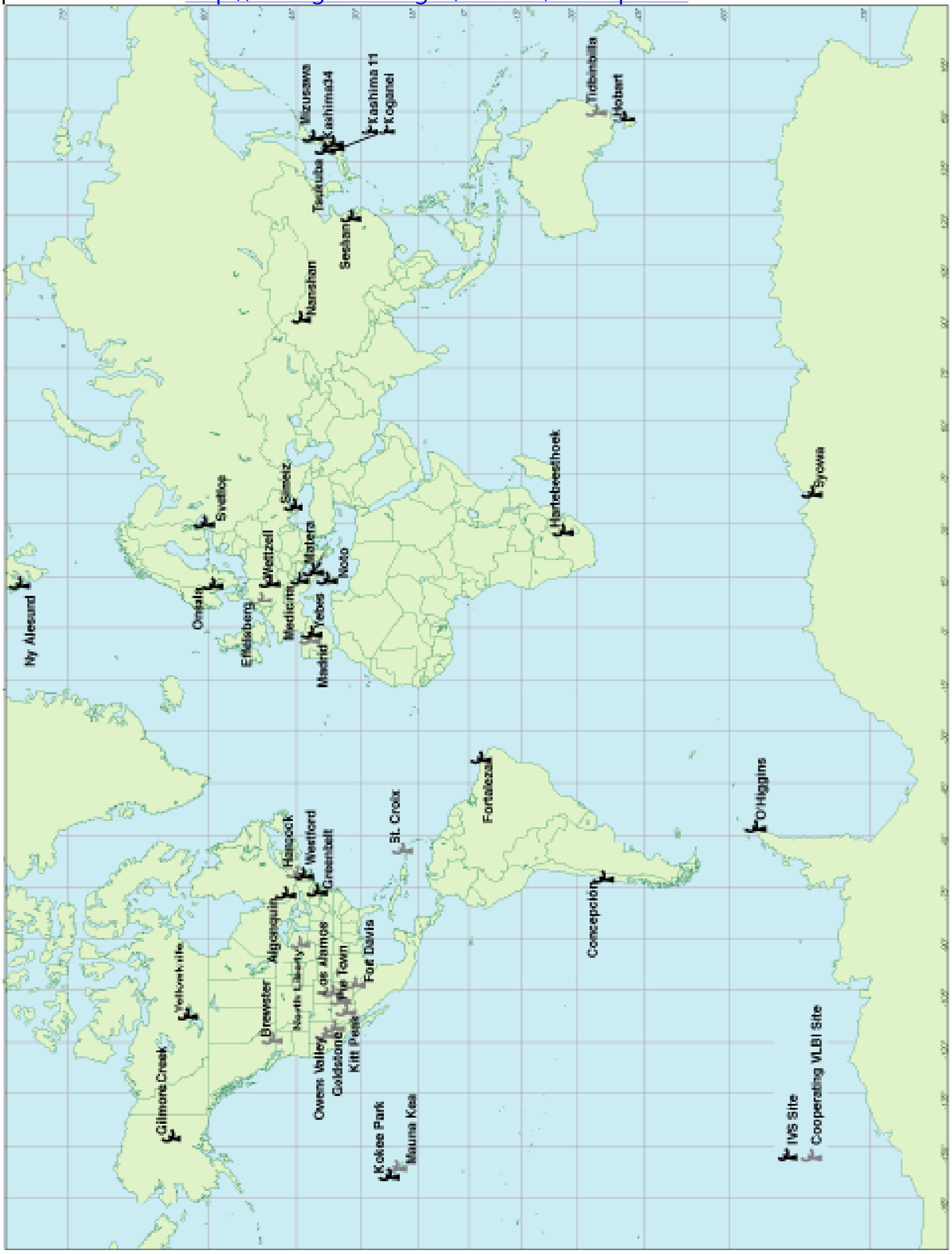
Wu, R., B.P. Kirtman, and H. van den Dool, 2009: An Analysis of ENSO Prediction Skill in the CFS Retrospective Forecasts. J. Climate, 22, 1801–1818.

Appendix 1

The map below indicates that global positions of IVS monitored VLBI stations. This map is released to the public domain at http://ivscc.gsfc.nasa.gov/stations/ns-map.html.



14. Appendix 2

Below is the list of references for comparative studies concerning VLBI and other methods of estimating PWV:

Behrend,. D, Cucurull, L., Vila, J., and Rudiger Haas, 2000: An inter-comparison study to estimate zenith wet delays using VLBI, GPS, and NWP models. *Earth Planets Space,* 52**, pp.** 691-694.

Gradinarsky, L. P., Haas, R., Elgered, G., and Jan M. Johansson, 2000: Wet path delay and delay gradients inferred from microwave radiometer, GPS and VLBI observations. *Earth Planets Space,* 52, pp. 695-698.

Haas, R., Elgered, G., Gradinarsky, L., and J. Johanssen, 2003: Assessing Long Term Trends in the Atmospheric Water Vapor Content by Combining Data from VLBI, GPS, Radiosondes and Microwave Radiometry, in Proceedings of the 16th Working Meeting on European VLBI for Geodesy and Astrometry, eds. W. Schwegmann and V. Thorandt, Bundesamt für Kartographie und Geodäsie, Frankfurt/Leipzig, pp 279-288.

Jin, S., Luo, O. F., and J. Cho, 2009. Systematic errors between VLBI and GPS precipitable water vapour estimations from 5-year co-located measurements. *Journal of Atmospheric and Solar-Terrestrial Physics*, 71, pp.264-272.

Niell, A. E., Coster, A. J., Solheim, F. S., Mendes, V. B., Toor, P . C., Langley, R. B., and C. A. Upham, 2001: Comparison of measurements of atmospheric wet delay by radiosonde, water vapour radiometer, GPS, and VLBI. *J. Atmospheric and Oceanic Technology*, 18, pp. 830-849.

Pacione, R., Fionda, E., Ferrara, R., Lanotte, R., Sciarretta, C., and F. Vespe, 2002: Comparison of atmospheric parameters derived from GPS, VLBI, and a ground-based microwave radiometer in Italy. *Phys. Chem. Earth,* 27, pp. 309-316.

Steigenerberger, p., Tesmer, V., Krugel, M., Thaller, D., Schmid, R., Vey, S., and M. Rothacher (2007): Comparisons of homogeneously reprocessed GPS and VLBI long time series of troposphere zenith delays and gradients. Journal of Geodesy, 81 (6-8), pp. 503-514.

One should note as a caveat to this list, that the comparative studies shown here represent only a selection of such studies within the literature.

15. Appendix 3

Shown here is the list of non-duplicate VLBI stations used for the co-location study. Following the list reference is made to the data sources the list was compiled from. The VLBI station name is given along with its Cartesian vector coordinates from the centre of the Earth. X, Y and Z are in units of metres. For the purposes of the co-location study these vector coordinates were converted into latitude and longitude via Matlab, assuming the WGS84 ellipsoid model to convert between coordinates. Latitude was calculated by geodetic rather then geocentric means.

VLBI Station:	X:	Y:	Z:
HOHNBERG	0.661752	0.128846	0.738568
DAITO	-0.594032	0.677760	0.433320
SYOWA	0.277722	0.229640	-0.932811
WHTHORSE	-0.348160	-0.347224	0.870758
KODIAK	-0.475714	-0.247670	0.844012
BERMUDA	0.362084	-0.764940	0.532693
NYALES20	0.189136	0.0397527	0.981146
MARCUS	-0.820044	0.400242	0.409065
SHANGHAI	-0.446875	0.731251	0.515339
TITIJIMA	-0.704342	0.546451	0.453094
CHICHI10	-0.704593	0.546576	0.452553
VERAOGSW	-0.704591	0.546210	0.452996
TATEYAMA	-0.628025	0.529748	0.570045
HOBART26	-0.620288	0.396073	-0.677029
TSUKUBA	-0.621139	0.519593	0.586694
NOME	-0.417877	-0.109073	0.901932
CARNUSTY	0.554172	-0.0269387	0.831966
BREST	0.664255	-0.0523227	0.745672
VERAISGK	-0.512033	0.754255	0.411000
ST JOHN'S	0.410347	-0.538252	0.736139
VNDNBERG	-0.420338	-0.710287	0.564631
YUMA	-0.344749	-0.766990	0.541179

MEDICINA	0.700619	0.144415	0.698768
RICHMOND	0.150805	-0.890171	0.429947
FLAGSTAF	-0.301887	-0.761131	0.574059
SYOWA	0.279527	0.227436	-0.932811
KARLBURG	0.574016	0.138967	0.806966
SUWON	-0.480663	0.636607	0.603070
VERAIRIK	-0.552615	0.648405	0.523629
KAGOSIMA	-0.555048	0.649714	0.519417
SUWON	-0.480565	0.636575	0.603182
PVERDES	-0.396357	-0.732939	0.552903
AIRA	-0.554020	0.646335	0.524703
TIDBIN64	-0.700111	0.420980	-0.576733
PRESIDIO	-0.425063	-0.668371	0.610411
FORTLEZA	0.781643	-0.620097	-0.0671795
SESHAN25	-0.444360	0.733735	0.513981
GILCREEK	-0.358679	-0.228526	0.905055
GORF7102	0.177509	-0.758486	0.627049
CHLBOLTN	0.629705	-0.0158121	0.776674
LEONRDOK	-0.0819695	-0.807664	0.583918
SEATTLE1	-0.360536	-0.571434	0.737209
HALEAKAL	-0.856934	-0.376952	0.351527
MIURA	-0.624135	0.530174	0.573908
CEDUNA	-0.589023	0.614017	-0.525390
SANPAULA	-0.400919	-0.723314	0.562211
KANOZAN	-0.626508	0.526579	0.574632
PUSCHINO	0.443186	0.345218	0.827292
KOKEE	-0.869443	-0.322219	0.374490
JPL MV1	-0.391300	-0.730588	0.559576
MK-VLBA	-0.856510	-0.391138	0.336753
YEBES	0.761173	-0.0410826	0.647247
PBLOSSOM	-0.386690	-0.729641	0.563999
TA	0.599950	-0.0256173	0.799627
KIRSBERG	0.609512	0.155207	0.777435
HOHENFRG	0.593621	0.109769	0.797223
SAGARA	-0.614218	0.549505	0.566375
ONSALA60	0.529713	0.111883	0.840766
TOMAKOMAI	-0.577941	0.458120	0.675359
PLATTVIL	-0.194749	-0.740953	0.642699
KOGANEI	-0.618730	0.528668	0.581106
KASHIMA	-0.627524	0.514305	0.584555
EFLSBERG	0.633683	0.0765002	0.769801
DA	0.601788	-0.0267586	0.798208
EB_VLBA	0.636200	0.0768134	0.767691
URUMQI	0.0358409	0.727134	0.685559
HARTRAO	0.797653	0.418518	-0.434273
LO	0.600607	-0.0241979	0.799178
SIMEIZ	0.592775	0.400088	0.698962
CARROLGA	0.0711746	-0.831851	0.550417
KOGANEI	-0.618060	0.529498	0.581062
MARPOINT	0.173727	-0.766555	0.618234
ROBLED32	0.761258	-0.0565583	0.645978
KAINAN	-0.588722	0.584016	0.558867
ALGOPARK	0.144178	-0.682563	0.716464
ONSALA85	0.532277	0.112362	0.839080
MON PEAK	-0.374395	-0.753461	0.540485
WSTRBORK	0.602007	0.0675259	0.795630
SINTOTU3	-0.571929	0.449343	0.686286
KP-VLBA	-0.313092	-0.790280	0.526717
CRIMEA	0.594435	0.400643	0.697232
PENTICTN	-0.323390	-0.568810	0.756224
PENTICTO	-0.323539	-0.569068	0.755965
PT REYES	-0.428934	-0.662104	0.614519
DSS15	-0.369358	-0.728447	0.577009
WETTZELL	0.640141	0.146347	0.754190

KN	0.606640	-0.0319093	0.794336
KWAJAL26	-0.963295	0.213872	0.162241
ARECIBO	0.374883	-0.872703	0.312815
HART	0.800438	0.415629	-0.431916
METSHOVI	0.454352	0.205952	0.866688
MOJAVE12	-0.369773	-0.729252	0.575725
SVETLOE	0.429135	0.245588	0.869212
METSAHOV	0.454656	0.206175	0.866476
NL-VLBA	-0.0205486	-0.747742	0.663671
USSURISK	-0.480482	0.538197	0.692445
GOLDMARS	-0.370192	-0.730019	0.574482
LA-VLBA	-0.227489	-0.780704	0.582023
CA	0.615908	0.000427746	0.787818
SANTIA12	0.277707	-0.791603	-0.544283
VICTORIA	-0.367768	-0.555912	0.745459
AUSTINTX	-0.115770	-0.856734	0.502597
GOLDVENU	-0.368971	-0.730600	0.574529
SHANG_S2	-0.434033	0.738945	0.515340
ZELENCHK	0.541866	0.480502	0.689564
ATCA	-0.745653	0.437997	-0.502156
MIZUSGSI	-0.606358	0.487454	0.628266
MIYAZAKI	-0.562245	0.635887	0.528704
MIZNAO10	-0.605552	0.488054	0.628578
DE	0.616546	-0.0229957	0.786983
PINFLATS	-0.371832	-0.747124	0.550950
MATERA	0.728757	0.218694	0.648911
QUINCY	-0.395140	-0.659071	0.639913
CTVASBAY	0.171412	-0.683370	0.709664
OHIGGINS	0.239867	-0.382393	-0.892323
GIFU3	-0.594490	0.559445	0.577585
MAMMOTHL	-0.384188	-0.694661	0.608150
NOTOX	0.774580	0.207389	0.597508
OCOTILLO	-0.366549	-0.758371	0.538996
FORT ORD	-0.423356	-0.683515	0.594623
QUAB	0.224675	-0.705898	0.671736
OVRO	-0.379095	-0.704573	0.599887
FORTORDS	-0.423781	-0.684231	0.593497
BADARY	-0.131672	0.607268	0.783510
OVR 7853	-0.378311	-0.702782	0.602477
OV-VLBA	-0.378110	-0.702901	0.602464
ITA	0.632764	0.667961	-0.391712
TORUN	0.571681	0.191991	0.797696
NOBEY 6M	-0.607508	0.538004	0.584368
VLA	-0.251222	-0.791074	0.557753
SNDPOINT	-0.538271	-0.190871	0.820873
WIDE85 3	0.138497	-0.773090	0.618991
NRAO 140	0.138584	-0.772984	0.619104
NRAO85 1	0.138690	-0.772986	0.619078
SOURDOGH	-0.380379	-0.261586	0.887065
HN-VLBA	0.227111	-0.698420	0.678697
TRYSILNO	0.469637	0.103099	0.876819
USUDA64	-0.605019	0.537865	0.587072
BLKBUTTE	-0.361938	-0.751387	0.551742
SC-VLBA	0.409000	-0.860718	0.303122
MADRID64	0.763360	0.0567007	0.643480
PIETOWN	-0.257455	-0.786791	0.560960
VERNAL	-0.256085	-0.720335	0.644622
BR-VLBA	-0.331742	-0.582000	0.742444
WESTFORD	0.234311	-0.700030	0.674578
HAYSTACK	0.234341	-0.699892	0.674712
AZORES	0.714600	-0.343263	0.609522
DEADMANL	-0.366719	-0.742688	0.560297
YAKATAGA	-0.397624	-0.305257	0.865282
ELY	-0.326020	-0.704185	0.630742

HATCREEK	-0.396224	-0.647326	0.651135
GRASSE	0.719342	0.0873136	0.689147
MILESMON	-0.189148	-0.665738	0.721814
MOPRA	-0.734274	0.439976	-0.516975
HRAS 085	-0.207745	-0.836498	0.507063
TOULOUSE	0.726724	0.0188191	0.686672
MCD 7850	-0.208641	-0.835877	0.507719
BLOOMIND	0.0474710	-0.775792	0.629201
PARKES	-0.714697	0.442035	-0.542046
YLOW7296	-0.192469	-0.422738	0.885578
TROMSONO	0.330670	0.113468	0.936900
HOFN	0.421268	-0.114436	0.899688
CONCEPCION	0.234207	-0.767261	-0.597040
SEST	0.288329	-0.824832	-0.486332

VLBI station data sources used in this report:

NASA VLBI data directory: ftp://igscb.jpl.nasa.gov/

US Naval Oceanography Portal: http://www.usno.navy.mil/USNO/astrometry/vlbi-products/reference-frames/earth-orientation/earth-orientation-parameters
International Terrestrial Reference Frame (ITRF) website:
http://itrf.ensg.ign.fr/ITRF_solutions/2005/more_ITRF2005.php

e-MERLIN / VLBI National Radio Astronomy Facility (UK): http://www.e-merlin.ac.uk/

16. Appendix 5

This final appendix is dedicated to the reader who wishes to find out more about VLBI. Listed below are data resources that may prove useful in any future work conducted concerning the use of VLBI in meteorology.

http://ivscc.gsfc.nasa.gov/ - Website of the International VLBI Service

http://lupus.gsfc.nasa.gov/ - Goddard Space Flight Center (VLBI section)

http://www.evlbi.org/ - Website for the Consortium of VLBI in Europe

http://www.vlba.nrao.edu/ - Website for Very Long Baseline Array (US)

http://vldb.gsi.go.jp/sokuchi/vlbi/en/index.html - Website for the Geographical Survey Institute, Japan (VLBI section)

http://www.jb.man.ac.uk/vlbi/ - Merlin/VLBI National Facility Homepage (UK)

http://www.merlin.ac.uk/ - Merlin Array Homepage (UK)

http://www.iers.org/MainDisp.csl?pid=86-65 - Website for the International Earth Rotation and Reference Systems Service.

http://hpiers.obspm.fr/icrs-pc/ - Website for the International Celestial Reference System (ICRF)

http://itrf.ensg.ign.fr/ - Website for the International Terrestrial Reference Frame (ITRF)

http://www.gosic.org/ - Website for the Global Observing Systems Information Center. Includes information elating to GCOS and subsequently GRUAN