11.5 LOWER-COST GPS MET STATION DESIGN FOR USE IN DENSE NETWORK SLANT PATH GPS-MET ESTIMATES OF TROPOSPHERIC WET DELAY AND PRECIPITABLE WATER VAPOR

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1. Introduction

GPS meteorology (GPS-met) is a technique that uses GPS signals to estimate the amount of precipitable water in the atmosphere (Bevis et al., 1992). In a typical application, this involves combining the slant path signals from the 8-12 GPS satellites in view of a ground-based GPS receiver into an estimate of the zenith precipitable water directly over the GPS station. In combining the multiple slant paths each from a different azimuth and elevation angle into a single zenith value one loses spatial information about how the precipitable water is distributed around the station. Recently there has been growing interest in combining the slant paths from a network of closely spaced GPS stations using tomographic techniques to obtain 3D maps of precipitable water in the atmosphere over a region. This can be done using existing GPS stations, since many of these do provide (in addition to the zenith estimate), the slant path information from which the zenith estimate was obtained. On the other hand, it has been suggested that the ideal spacing for good 3D maps requires a spacing between ground-based GPS stations of no more than 20km (Braun et al. 1999, Bender et al. 2010). Deploying such networks, or adding additional GPS-met stations to “densify” existing networks to achieve such spacing can be prohibitively expensive using existing GPS-met equipment (which can cost upwards of $20K per station for the GPS receiver and antenna alone). To reduce this cost, this paper describes a GPS- met station design based on a low-cost (~$3K), but high performance (dual-frequency), GPS receiver/antenna. The challenge was that, unlike the more expensive equipment, which comes configured for the GPS-met application right out of the box, we had to develop the software and hardware infrastructure to obtain GPS-met capability from the low-cost GPS equipment.

After a background review of the GPS-met technique, we describe the software and hardware design of our low-cost GPS-met station and give results validating its performance. We then describe our plans to develop a 3D atmospheric precipitable water network for the Dallas-Fort-Worth (DFW) metroplex and how we propose to use the network in conjunction with a network of closely spaced polarimetric X-band weather radars that is being deployed in the DFW region to understand relationships between precipitable water observations and subsequent weather radar observations. One ultimate goal is to improve an ability to forecast severe weather, such as the urban flooding events that regularly occur in regions like DFW.

2.GPS-Met Systems

GPS-met is a technique for determining the amount of precipitable water in the atmosphere from the signal propagation delays occurring between a set of signals transmitted by a constellation of GPS satellites and the corresponding set of signals received on the ground by a GPS receiver antenna. For geodists, these propagation delays are a source of error that need to be modeled and compensated for in order to obtain high precision position estimates. For meteorologists, on the other hand, it was found that these propagation delays could be used to determine the water vapor content in the

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atmosphere (Bevis et al., 1992). As a means of measuring water vapor, GPS-met provides an alternative to radiosondes, which though they provide information about water vapor with altitude are only launched once or twice a day from widely spaced locations, and WVR (Water Vapor Radiometry) which provide real-time water vapor information at a location is limited in that it does not work in rain.

GPS signals propagate in two distinctive media, the ionosphere and the troposphere. The ionosphere is a dispersive media. As such the delay in this media are a function of frequency that can be determined from phase differences in the L1, L2 frequencies of a dual-frequency GPS receiver (Spilker, 1980). The delay in the troposphere, termed the neutral delay, consists of two quantities, the hydrostatic delay and the wet delay (Saastamoinen, 1972). Typically the neutral delay is resolved onto a zenith component (the vertical component above the GPS-Met station), referred to as the Zenith Tropospheric delay (ZTD). As shown in Figure 1, this is done by combining the so-called Slant Total Delays (STD) (the S_i in the figure) between the GPS receiver and each of the satellites in its view such that,

$$STD_{\theta} = ZTD \cdot m(\theta) \qquad (1)$$

here STD_{θ} is the slant total delay seen at an elevation angle θ and $m(\theta)$ is a mapping function which is approximately equal to $1/sin(\theta)$. The

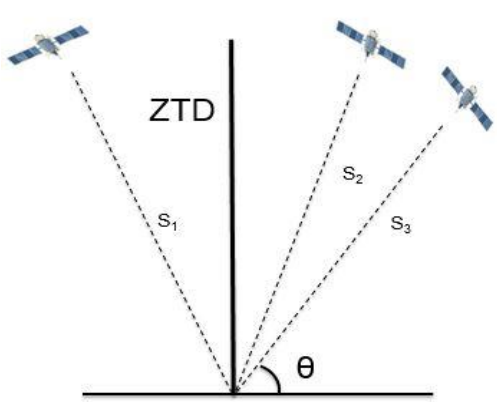

Figure 1. Representation of the signals from various satellites S_i (i=1...32) onto the Zenith component ZTD.

STD_{θ} (and hence the resulting ZTD) are estimated from GPS data using a linear spline method with 30-min knot intervals, and treating the knots as a Gauss-Markov processes (Duan et al., 1996, Tralli et al., 1990).

The ZTD is then decomposed onto its 2 fundamental quantities Zenith Hydrostatic Delay (ZHD) or the delay due to the dry air and Zenith Wet delay (ZWD), or delay due to precipitable water vapor,

$$ZTD = ZHD + ZWD \qquad (2)$$

The ZHD can be estimated using surface meteorological readings of barometric pressure (Saastamoinen, 1972; Davis et al., 1985),

$$ZHD = \frac{(2.2779 \pm 0.0024) * \mathrm{Ps}}{f\,(\lambda, H)} \qquad (3)$$

where P_s is the surface pressure in millibars and,

$$f(\lambda, H) = (1 - 0.00266\cos(2\lambda) - 0.00028H) \qquad (4)$$

λ is the latitude of the GPS antenna and H is elliptical height of the antenna in km. Subtracting the ZHD from the ZTD, one obtains the quantity of meteorological interest, the ZWD. This quantity can be mapped onto the amount of precipitable water given by (Bevis et al., 1994),

$$PW = \Pi * ZWD \qquad (5)$$

where PW or precipitable water is the column of water vapor above the GPS antenna measured in millimeters, and Π is a constant which depends on temperature and partial pressure of water vapor (Davis et al., 1985). This approach of measuring precipitable water vapor has shown an accuracy better than rms 2mm (Duan et al. 1996).

GPS-met has matured in many significant ways since it was first introduced. With the availability of near real time predicted orbits (Springer et al., 2001) and better modeling of antenna phase center variations (PCV) to reduce errors in station position and height estimates, more timely and accurate measurements of precipitable water are produced. Currently there are 600+ GPS-Met stations operating in the

United States by agencies such as Scripps Institute of Oceanography, NOAA and JPL, with near real-time estimates of precipitable water published online every hour from a large number of stations (www.gpsmet.noaa.gov).

2.1Slant path tomography

By not including azimuth angle, mapping function $m(\theta)$ in Equation (1) makes the assumption that the atmosphere is azimuthally isotropic (Bevis et al., 1992). In doing so, the mapping function ignores the spatial distribution of water vapor around the GPS-met station. To overcome this limitation of the zenith GPS-met method, the so called slant path GPS methods have been proposed as a potential way to estimate both the azimuthal and vertical distribution of water vapor over a region.

The slant path methods are based on the idea that, since a typical GPS site sees 8 to 12 satellites, a dense network of GPS-Met stations would thus form a web of intersecting slant paths. Using tomographic or other approaches combined with precise ultra-rapid orbit prediction, it could therefore be possible to obtain a 4D picture of the temporal and spatial evolution of atmospheric water vapor (Flores et al., 2000, Troller et al., 2006, Bender et al., 2010, Shangguan et al., 2012).

In deploying a network of GPS-Met stations for slant path tomography, slant path density over a given domain is a key factor. Slant path density in a given region depends both on the spacing between the GPS-met stations in the network as well as on the orbital paths of the GPS satellites over the region. When using all available GNSS satellites for tomographic slant path analysis; GPS, GLONASS, Galileo and BeiDou (Jones et al., 2014) – 20km between ground based GPS-met stations has been suggested as the ideal spacing (Braun et al., 1999, Bender et al., 2010). Even if one is to incorporate existing GPS-met stations into the network, adding the additional stations to achieve the required 20km inter station spacing density could quickly become cost prohibitive. Reducing station cost is thus a key consideration for slant path research and application.

3.Low cost GPS-Met Station Design

The four main components of a GPS-met station are the GPS receiver, antenna, barometric pressure sensor, and ambient temperature sensor. In selecting and deploying equipment for the GPS-met application, the IGS (International GNSS services) provides a set of guidelines that a continuously operating GPS-station should meet (Moore, 2014). In particular, the GPS receiver should be capable of receiving at least 2 frequencies L1 (1.57542 GHz) and L2 (1.2275 GHz) and should be set to track satellites down to 5º elevation angle. In addition, the GPS antenna should be mounted such that errors due to blockage, multi path and antenna movement are minimized. This means that the antenna needs to be mounted onto a rigid bracket and deployed in a location and at a height such that the antenna field-of-view is clear of foliage, buildings, metal poles, towers, and other objects that might block the GPS signals or produce multi-path reflections.

In general, the cost of a GPS-met station is dominated by the cost of the GPS receiver/antenna equipment. A low-cost GPS-met station, therefore, starts with low-cost GPS equipment. The lowest cost GPS equipment we could find that could potentially meet the IGS requirements were the Hemisphere P320/P306 receiver and the A42/A52 antenna (Hemisphere GNSS), the cost of which was just over $2800 U.S. In researching equipment used at existing GPS-met stations in the U.S. and elsewhere, the equipment closest in cost that we were able to identify comes from Septentrio at a cost of nearly $7,400 U.S. Figure 2 compares the cost of implementing a network of GPS-Met stations using Hemisphere vs. Septentrio equipment. Given that the number of stations and hence the cost increases as the square of the network size, the impact of using a low cost receiver can clearly be seen.

3.1Station Software Design

One advantage of paying more for the GPS equipment is that it can often be obtained configured for the GPS-met application right out of the box. This was not the case for the Hemisphere equipment and a software/hardware system had to be developed.

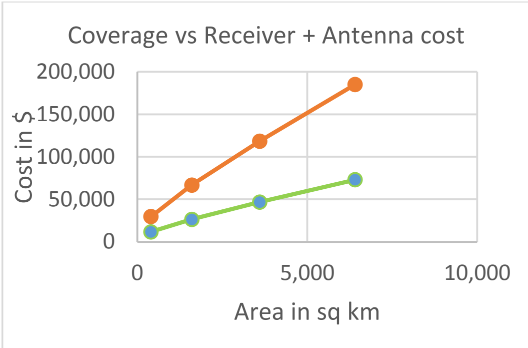

Figure 2. GNSS hardware cost of developing a dense network to cover a given domain, where nodes are placed 20km apart from each other. Orange line shows cost of Septentrio GNSS manufacturer and green line shows Hemisphere.

One of the first things we had to do was select the software for the GPS-met processing. There are three widely accepted software packages for doing this: Bernease, GYPSI-OASIS II, and GAMIT. The GAMIT (King et al., 2005) software is widely used and we were able to obtain it at no cost.[1] The GAMIT software takes three sets of files as input: obs (observation) files which store the pseudo range and carrier phase information from the satellites in view of the GPS receiver over time; nav (navigation) files which store information about the receiver and satellite clock offsets; and met (meteorological) files which store meteorological parameters such as surface pressure ambient temperature and relative humidity.

The standard file format for the obs, nav, and met files, and the format required by GAMIT, is the RINEX (Receiver Independent Exchange) format (Gurtner et al., 2007). For the met data (pressure, temperature and relative humidity) we were able to develop a Python script to sample the instruments (a 5 minute sample interval was used) and store their outputs directly in RINEX format. For the GPS output the RINEX conversion is much more complex and not something easily undertaken with a Python script. A widely used RINEX converter is the teqc software developed by UNAVCO. Because the Hemisphere equipment is not currently compatible with the teqc RINEX converter, we were forced to use the proprietary Hemisphere GNSS pocket max RINEX converter. Since this converter only runs on the Windows OS, whereas GAMIT runs on UNIX, we needed to split the data logging from the processing. The data logging uses a windows OS logger and the processing on a UNIX server.

With the needed GPS and meteorological data in RINEX format Python scripts were developed to place the files in day directories with the correct hour naming convention according to the IGS guidelines. For our first deployment at the Univ. of Texas at Arlington (to be described in the next section), the RINEX files are downloaded from the GPS station every hour via FTP to a UNIX server at the Univ. of Massachusetts, Amherst. There Python scripts organize the data and feed's it to GAMIT from which we obtain near real-time zenith precipitable water estimates. These estimates are published online every hour as a time series (emmy9.casa.umass.edu/gpsmet). The software architecture for our first GPS-met station deployment is summarized in Figure 3.

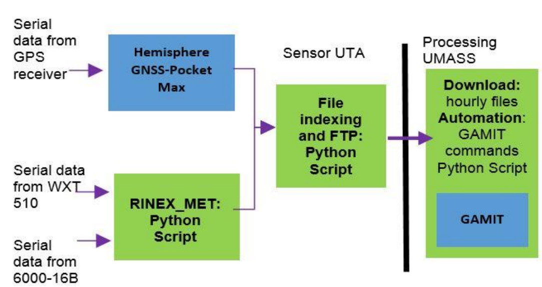

Figure 3. Software architecture, green boxes are software subsystems developed at UMASS, blue boxes are 3rd party software sub systems. RINEX_MET records data from Vaisala WXT-510 and Paroscientific 6000-16B onto RINEX met files. File indexing and FTP gives appropriate hour index and puts them onto respective day folders. Hemisphere GNSS-Pocket Max converts binary files to RINEX. Download and automation script processes all files hourly to produce near real-time tropospheric products using the GAMIT software package.

[1] We did, however, have to have the Hemisphere A42 antenna phase center data added to the GAMIT database.

3.2 Station Hardware Design

Figure 4 shows a block diagram of our first GPS-met station and Figure 5 shows its physical deployment on the top of Nedderman Hall at the Univ. of Texas, Arlington (lat 32 43 56.67, lon -97 06 49.68, alt 196.3 m MSL).

From Figure 4 we see that in addition to the Hemisphere P320 receiver and A42 antenna, other components that make up our GPS-met station are a DC-power supply, IP-Switch, backup power supply, surge protector and an Ethernet switch. For meteorological sensors we use a Vaisala WXT-510 for ambient temperature and relative humidity and a Paroscientific Model 6000-16B barometer for surface pressure. In addition to providing surface pressure, the Paroscientific barometer data is processed for infrasound collection (Pepyne et al., 2015).

From Figure 5 we see that the GPS antenna is mounted on a rigid bracket on the very top of the building for a clear unobstructed field of view. The Vaisala weather station is mounted beside the data logger enclosure. The Paroscientific barometer is mounted inside the enclosure and attached to a microporous wind filtering hose extending out the bottom of the enclosure.

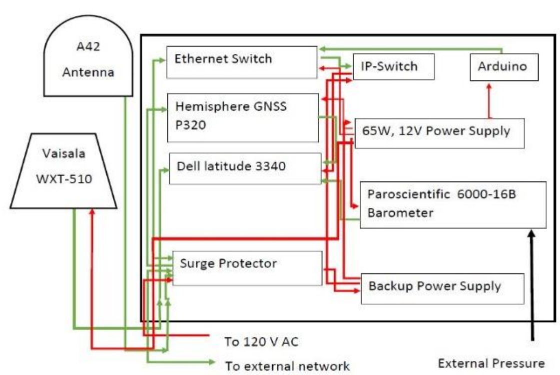

Figure 4. Hardware architecture, green lines represent data connections, red lines represent power connections.

4. System Validation

We have applied to have our GPS-met station included in the national GPS-met network and have given a station designation 'cnvl'. For our own validation we did several studies to compare our system to the closest NOAA GPS-met station 'zfw1' located 11.79km from our site (lat 32 49 50.34, lon -97 03 59.29, alt 155.2m MSL).

The first validation study involved taking the raw GPS data from 'cnvl' and 'zfw1' and processing them identically through GAMIT.

Figure 5. Physical installation on top of Nedderman hall, University of Texas Arlington.

GPS raw observations RINEX files were used from the two sites and the surface meteorological parameters were estimated in GAMIT as described by (Boehm et al., 2006). From the results in Figure 6 top, it can be clearly seen that the two stations produce nearly identical estimates of precipitable water, proving that the two GPS receivers give essentially identical performance.

For a second validation study we compared the precipitable water estimates from 'cnvl' to the "first estimates" reported by NOAA for 'zfw1' on the website (www.gpsmet.noaa.gov). From Figure 6 bottom we see that though the two estimates are close, the 'cnvl' estimates appear much smoother than the 'zfw1' estimates. We attribute the differences here to differences in data processing. The NOAA 'zfw1' station uses the sliding window technique (Foster et al. 2005), whereas our estimates were obtained from the entire days set of RINEX files. The use of the entire 24 hours of data in a single processing not only makes the estimates somewhat different, it also makes the estimates smoother than the near real time "first guess" output of the sliding window method. We are updating our processing to include the sliding window approach.

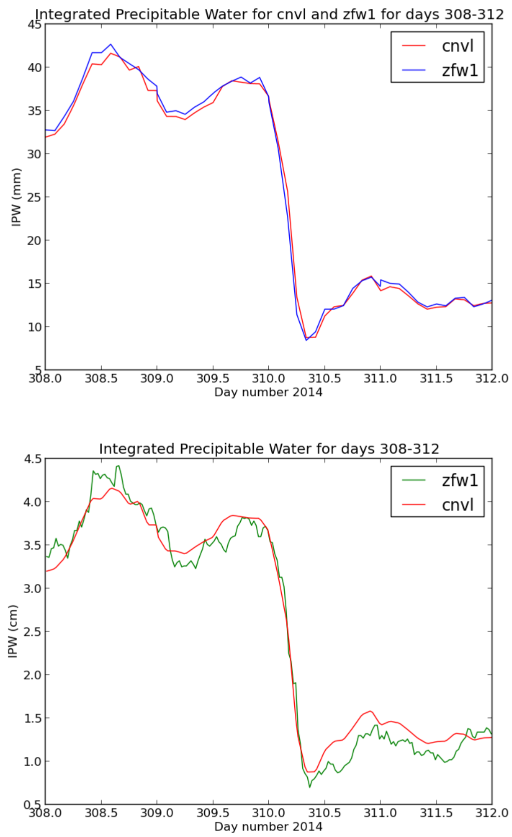

Figure 6. Precipitable water estimates from 'zfw1' and 'cnvl' for UTC 308-312. Top: Precipitable water estimated by running RINEX files in GAMIT, Bottom: precipitable water estimates of cnvl compared with "first guess" of zfw1.

5. Conclusion and Future Work

This paper described the development, deployment, and validation of a low cost GPS-met station. This station, which uses GPS equipment that is less than half the cost of the next nearest competitor, required the development of a custom software. A first iteration of the station was successfully deployed at the University of Texas Arlington on October 28th 2014 and has been publishing near real time estimates of precipitable water every hour at emmy9.casa.umass.edu/gpsmet. The software will be updated soon with the implementation of the sliding window processes (Foster et al. 2005) to replicate the method used by NOAA. Once this update is implemented near real-time estimates of precipitable water will be compared with estimates published in www.gpsmet.noaa.gov.

The purpose of developing a low-cost, high-performance GPS-met station is to allow us to "densify" the existing network of NOAA GPS-met stations in the DFW region in order to research slant path tomography techniques and how the resulting 3D maps of atmospheric water vapor might be used in conjunction with the network of closely spaced X-band, polarimetric weather radars that are being deployed in the DFW region by the CASA organization (www.casa.umass.edu) to better understand storm initiation, rain fall rates and amounts. Figure 7 shows the CASA DFW weather radar network (with 40km range disks), superimposed over our 'cnvl' station at the Univ. of Texas, Arlington and some of the existing NOAA GPS-met stations that we propose to use for our study. To achieve the 20km spacing between stations recommended for good 3D precipitable water recovery, we estimate that we may ultimately need some 16 total stations or the addition of 4 to 12 of our low-cost GPS-met stations.

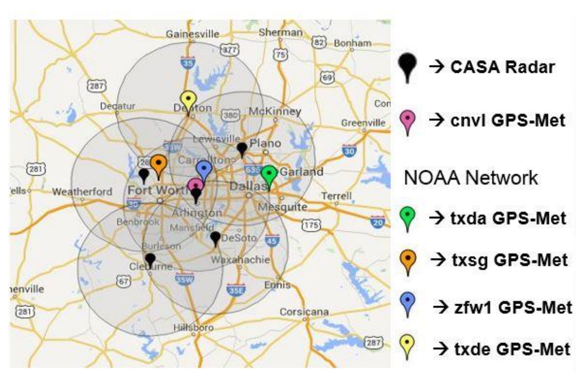

Figure 7. Current locations of operating CASA radars, cnvl GPS-met station and other NOAA GPS-Met stations.

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