Broadband Meteorological Sensors Co-located with GPS Receivers for Geophysical and Atmospheric Measurements

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Abstract

Meteorological sensors are successfully used for precise geophysical measurements by correcting for **errors** caused by atmospheric delays of GPS transmissions. These delays also are used as weather-related **signals** to calculate integrated precipitable water vapor in the atmosphere. If the meteorological sensors used with these GPS networks include **broadband** barometers, then it may be possible to detect or forecast a wide range of phenomena such as fog, rainfall, floods, storms, aircraft wake turbulence and wind shear, as well as seismic and nuclear events.

1. Introduction

The Global Positioning System was deployed by the Department of Defense for improved navigation, positioning, and timing purposes. Precise location information of interest to geophysicists required correction of position errors due to atmospheric delays.

In the early 1990's, scientists developed techniques to use these same atmospheric delay errors as signals to determine the amount of Integrated Precipitable Water Vapor (IPWV) in the troposphere. The result of these efforts created a new science, GPS Meteorology.

2. GPS Meteorology

Water vapor is the key element in the hydrological cycle and the main driver of atmospheric events.

Water vapor is not evenly distributed over the earth because of the hydrological cycle and variations of temperature, pressure and geography. The distribution varies both horizontally on earth's surface and vertically as well. Nearly 50% of the water in the atmosphere is between sea level and 1.5 km above sea level. Less than 5% is between 5 to 12 km and less than 1% is in the stratosphere. Horizontally, on earth's surface, average IPWV is less than 5 mm near the poles and greater than 50 mm near the equator. Active weather is strongly correlated to the distribution of water vapor in the atmosphere [1].

The impact of atmospheric events on transportation, safety and agriculture can hardly be overstated. Some weather-related disasters can be prevented or mitigated by improving the weather forecasts.

The ability to improve weather forecasts is currently hindered by the lack of timely and accurate water vapor observations, especially under severe weather conditions. In the USA, Federal agencies like the National Oceanic and Atmospheric Agency (NOAA), Federal Aviation Agency (FAA), Department of Agriculture, and Department of Transportation (DOT) are especially interested in the new developments in GPS Meteorology, since it improves short-term weather forecasts [2].

Current moisture observations in the atmosphere made with weather balloons are inadequate because the balloons are sparsely launched and are not frequent enough to provide reliable, accurate moisture data. Other ground or space-based systems are expensive and have operational limitations. The National Weather Service's (NWS) existing systems measure moisture with 3 mm accuracy inland and 5 mm accuracy along the coasts. For GPS to have a positive impact on weather prediction, GPS moisture measurement accuracy must be better than 2 mm. The target in the GPS Meteorology Community is 1 mm. With appropriate equipment, GPS can easily achieve this.

Ground-based GPS Meteorology utilizes GPS receivers co-located with surface Meteorological sensors to calculate the total precipitable water vapor directly above the site. This surface based system is ready for operational use.

As depicted in Figure 1, the total GPS signal delay (error) in the atmosphere is composed of ionospheric and tropospheric delays [3].

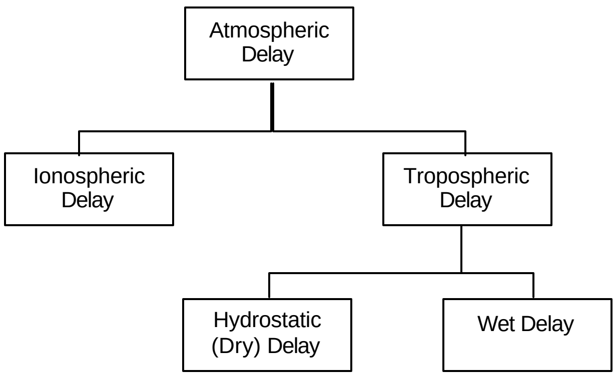

Figure 1. Causes of Atmospheric Delay

The largest atmospheric signal delays come from the ionosphere. These delays can be compensated with dual frequency GPS receivers. GPS satellites send radio signals at two frequencies, L1 (1.6 GHz) and L2 (1.2 GHz). The delay in the ionosphere is inversely proportional to the frequency of the radio-waves. Thus, the delay can be calculated by measuring the difference between the two frequencies. The tropospheric delay cannot be corrected by using the dual frequencies since the electrically neutral atmosphere (troposphere) is nondispersive below 30 GHz.

The tropospheric delay has two components: hydrostatic and wet delay. The water vapor in the atmosphere, which is the main driver of the atmospheric events, bends the radio waves and slows them down. Therefore, GPS signals travel longer distances before they reach surface-based GPS receivers [3].

The troposphere, which contains most of the water vapor (around 95% of the water vapor is below 5 km in the troposphere) delays both the L1 and L2 signal equally, since below 50 kilometers, the atmosphere is electrically neutral. Signal delays in this region are due to changes in pressure, temperature, and water vapor. Therefore, special geodetic algorithms are used to calculate the tropospheric delay. This delay is mapped to the zenith neutral delay to calculate the vertical amount of integrated precipitable water vapor.

The tropospheric delay has dry delay and wet delay components. The dry delay is due to the total mass of the atmosphere, and wet delay is caused by the total amount of water vapor along the GPS signal path. To calculate the delay, first the dry delay (ZHD) is calculated from surface pressure measurements. Then dry delay is subtracted from the tropospheric delay (ZTD), yielding zenith wet delay (ZWD). The wet signal delay maps into IPWV via a mapping function (Pi) that is almost proportional to the mean vapor pressure weighted temperature, (T_m), of the atmosphere.

$$\text{IPWV} = \underbrace{(\text{ZTD} - \text{ZHD})}_{\text{ZWD}} * \text{Pi}$$

The mapping function Pi is mainly proportional to T_m where:

$$T_m = \frac{\int (P_v / T) dz}{\int (P_v / T^2) dz} \qquad \text{(Equation 1) [3]}$$

In Equation 1, Pv is the pressure of water vapor in the atmosphere and T is surface temperature. The accuracy of GPS derived ZWD estimates is dependent upon the accuracy to which the value of T_m can be determined [3].

MET packages co-located with GPS receivers provide the surface pressure and temperature to the GPS receiver at the same time. Data are stored in RINEX format and downloaded periodically for processing from receivers. By using a network of GPS-MET sensors and processing data continuously, the IPWV map for a local area can be generated in almost real time.

3. Current GPS Networks

The promise of GPS-MET to determine the amount of IPWV and improve short-term weather forecasts attracted the attention of groups all around the world. The surface-based GPS networks have grown to hundreds of sites

The initial goal for most of these networks was geodetic applications. Over time, as GPS-MET techniques were refined, most of these networks started co-locating MET packages with the existing GPS receivers to perform IPWV calculations.

NOAA has built a network to show feasibility of improved short-term weather forecasts. This network depicted in Figure 2 will have around 200 stations in 2005. With an experimental network, NOAA has demonstrated that inclusion of GPS observations into numerical weather prediction methods improves forecast accuracy [2].

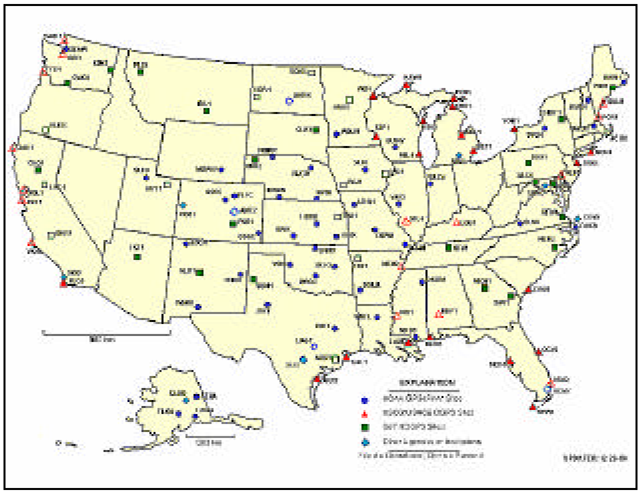

Figure 2. NOAA GPS Network

UNAVCO (University NAVSTAR Consortium) has deployed about 73 stations (SuomiNet) in the USA. This network is a collaboration of different universities and the feasibility phase will be completed by Spring 2002. After that, it is up to the local groups to further develop the concept.

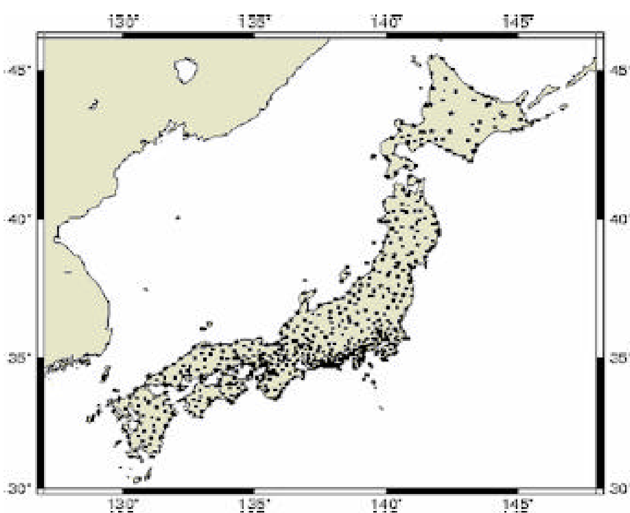

Figure 3. Japanese GPS Networks

Japan has the world's largest and most dense GPS network. The GPS/MET-Japan project was launched in 1997 to use the existing geodetic GPS network for calculating IPWV in the atmosphere. The Japanese GPS networks, shown in Figure 3, have an average spacing of approximately 30 km all over the country. The total number of stations in this network is more than 1000.

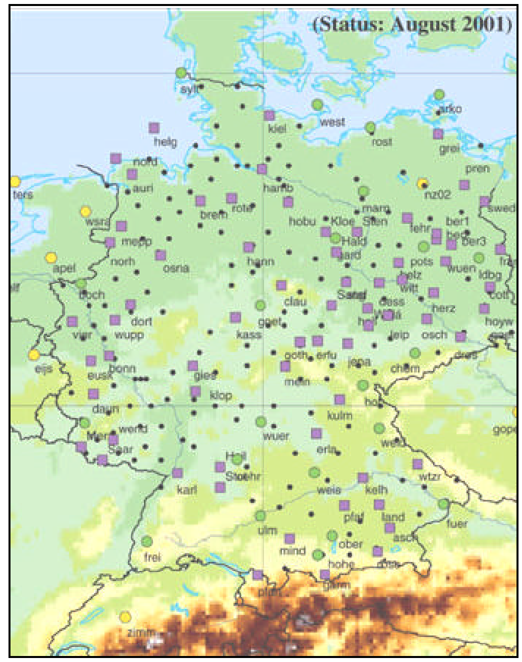

Figure 4. GASP NRT Network in Germany [4]

In Germany, more than 200 government-operated GPS stations with 50 km spacing are used to determine the IPWV for weather forecasting (see Figure 4).

GPS Meteorology has made considerable progress with the work done by these surface-based networks. Scientists are also working on determining ways to determine the spatial distribution of water vapor with the help of slant-path calculations [4].

4. Current GPS Meteorology Applications

The current applications of GPS Meteorology can be categorized as follows:

a) <u>Near-Real-Time Weather Prediction</u>

As described in Sections 2 and 3, the main goal of GPS Meteorology has been to provide improved short-term weather prediction, especially in severe weather. GPS-MET calculations of Integrated Precipitable Water Vapor (IPWV) play an important role in weather prediction.

b) <u>Flash-Flood Monitoring</u>

As part of the hydrological cycle, there is continuous evaporation of water from oceans, rivers, streams and lakes. It stays in the atmosphere as water vapor. Air can hold a certain amount of water vapor for each kilogram of air up to its saturation point that is temperature dependent. At the saturation limit, the excess water vapor comes back to earth as precipitation. Thus knowing the amount of water vapor in the atmosphere helps us to predict the amount of precipitation.

One weakness of the current weather forecast systems is that it does not provide reliable and accurate information under rapidly-changing weather conditions. The GPS-MET system is not limited in this way and continues to provide reliable information-especially when it is most needed. This point makes GPS-MET networks a good candidate for flash-flood monitoring systems.

One example is the GASP NRT network in Germany. During an observation in 2001 in the Westphalia region of Germany, local weather stations underestimated the developing mesoscale convective storm. The IPWV data from GPS receivers showed continuously increasing IPWV amounts which caused the flood. Observing the change in the atmosphere with conventional systems in severe weather conditions was not possible. It was very clear in the IPWV maps that the precipitation in the air was continuously increasing prior to the flooding events. This example demonstrates the potential of GPS IPWV in tracking very rapidly changing weather systems [4].

Another example is the Hawaiian SkyNet system. SkyNet, a development system, is intended to help with flash flood warnings. Its goal is to produce near-real-time PW that can be utilized by the NWS models to look for characteristic signals indicating actual and imminent rainfall. The GPS data may help in predicting the duration and magnitude of a rain event. If it starts to rain and the IPWV is still climbing, we can conclude it is going to continue to rain and probably get more intense. This valuable information is not easily available from other meteorological sources that are sparser spatially and temporally.

c) Long-Term Weather Studies

Knowing the distribution of water vapor in the atmosphere is crucial for understanding climate and climate change. Since GPS Meteorology is a tool to determine the amount of IPWV in the atmosphere, this concept can also be applied to long-term weather studies (climatology).

A study was done by the University of Hawaii and the Jet Propulsion Laboratory in 1998 to determine if the GPS-MET concept was applicable to long-term weather studies. During this study, GPS receivers recorded the influence of El Nino precipitable water vapor in the tropic Pacific Ocean. The IPWV drop from these receivers coincided with the drop in sea-surface temperature. During the mature phase of El Nino, atmospheric drying associated with El Nino was clearly visible from GPS readings [5].

5. Broadband Resonant Quartz Barometers

Accuracy, stability, and reliable performance under difficult environmental conditions are key performance requirements for meteorological instrumentation. Accuracy and stability are required to assure data quality. Instrumentation reliability directly affects data network integrity as well as operating costs.

The current goal of GPS-MET is to measure IPWV with 1 mm accuracy. To achieve this goal, the surface MET package has been allocated an error budget dependent upon pressure accuracy and stability of 0.3 hPa (millibar) and temperature accuracy of ±1 degree C [3]. Achieving 0.3 hPa accuracy and stability with high resolution, broadband capability calls for an inherently digital resonant quartz barometer and careful attention to the pressure port design.

The design and operation of these barometers is given in Reference [6].

Broadband resonant quartz crystal barometers are designed to have resolution better than 0.1 Pa (1 microbar) and a precision of better than 0.08 hPa maintained even under difficult environmental conditions. Thus all calibration and testing must be performed over the full range of pressure, temperature, humidity, and orientation conditions.

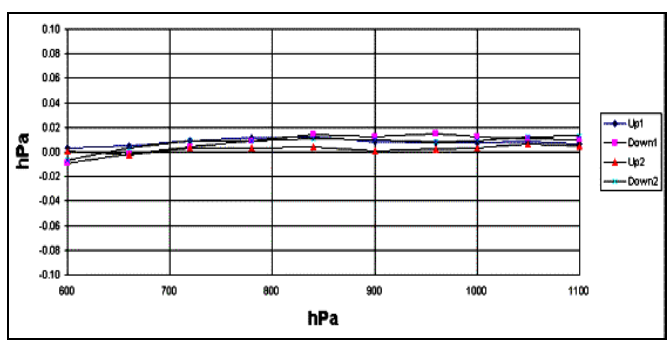

Figure 5. Barometer Repeatability, Hysteresis and Linearity

An example of testing for barometer repeatability, hysteresis, and linearity is shown in Figure 5 This barometer was used as a transfer standard for intercomparison testing of primary standards. After 5 years of travel and testing, its performance was as good as the primary standards used to calibrate the barometer.

Another important consideration that affects integrity of data and cost of ownership is long-term stability. Figure 6 shows the stability results for one of three barometers now in their 12th year of testing. Mean drift is an incredibly low –0.007 hPa per year and reflects not only the care taken in the manufacturing processes but also the fact that all barometers are stability tested prior to shipment and deployment. The barometers must be carefully calibrated and have high resolution to verify stability in a reasonable test time.

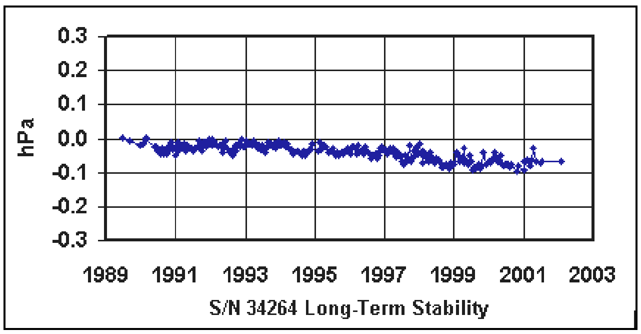

Figure 6. 12-Year Barometer Stability Test

When the Met packages are deployed at the GPS receiver sites, careful attention must be paid to the design of the barometer pressure port because wind-induced errors can consume the entire pressure accuracy budget.

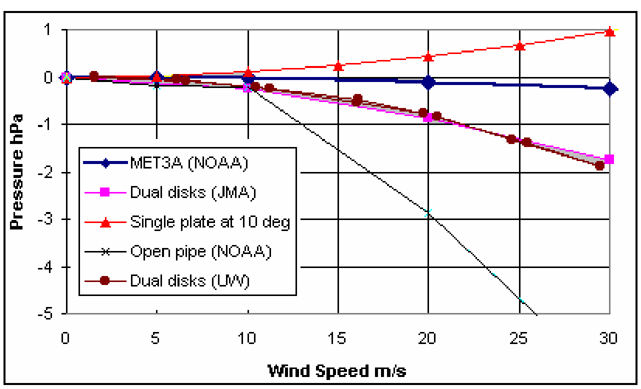

Figure 7. Wind-Induced Errors on Pressure Readings

Figure 7 shows the effects of wind for different types of pressure ports. The dual plate design of the MET3A was the most successful with less than 0.1 hPa errors at wind speeds up to 20 meters per second.

Resolution and speed are important parameters for use in broadband measurements. With a sensor of inadequate resolution, real signals can be obscured by noise, or sensor noise can be misinterpreted as real signals. The resonant quartz crystal barometers operate with a change in frequency of a quartz crystal sensor under pressure-induced loads. The signal is usually measured by gating a high frequency clock and counting the pulses over a sampling period. The resolution is thus inversely proportional to the clock frequency and the sampling time.

The broadband resonant quartz crystal barometer mechanisms, oscillator circuits, and digital interfaces are carefully designed for high resolution. Typical delivered resolution is better than one part per million, and under stabilized laboratory conditions, resolution can approach a few parts per billion [7]. Applications where it is important to measure small pressure changes include infrasound measurements of wind-shear, wake turbulence, and atmospheric waves caused by seismic and nuclear events, as well as Tsunami detection [8].

Data from an evaluation by Hutt, Holcomb, and Agnew of high quality sensors for use in atmospheric seismic studies showed that the broadband resonant quartz barometers had power spectral density noise levels a factor of 100 lower (20 dB) than the next best transducer [9].

Figure 8 shows the average power spectrum relative to 1 Pa2/Hz versus frequency with an observed noise floor of -23 dB.

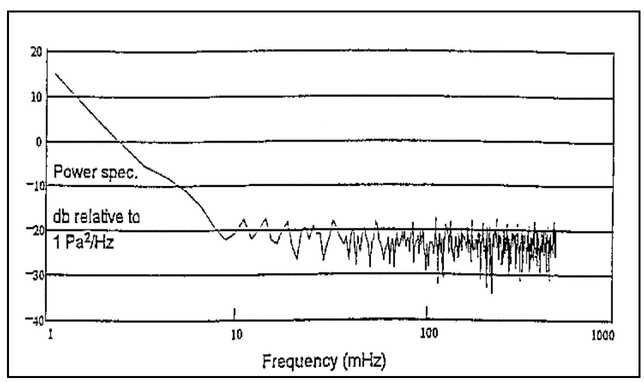

Figure 8. Power Spectrum

Figure 9 depicts the resolution of a broadband barometer versus time from seconds to years of data.

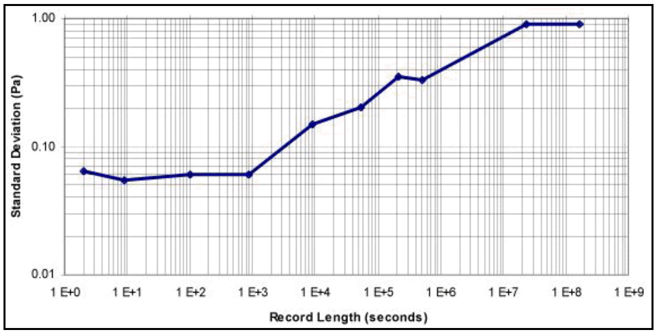

Figure 9. Noise vs. Record Length

6. Expanded GPS-MET Applications

A MET package equipped with a high accuracy, high resolution, digital, reliable, stable, and broadband barometer can be co-located with GPS receivers to detect other signals or atmospheric events.

a) Infrasound Applications

Infrasound is radiated from many geophysical and human-generated sources. Infrasound covers the signal range less than 20 Hz, below the nominal range of human hearing. A variety of phenomena radiate infrasound. Most infrasonic waves are actually a broad range of frequencies and may be generated by events such as avalanches, earthquakes, seismic waves, explosions, missile launches, geomagnetic activity, meteors, space debris, supersonic aircraft, ocean waves, severe weather, tornadoes, turbulence, and volcanoes. Figure 10 shows the amplitude of the pressure difference between acoustic waves and atmospheric pressure versus the infrasonic wave period [10].

The acoustic waves generated by these events may travel a few times around the world. These signals can be detected by broadband barometers that are co-located with GPS receivers. By using different triangulation methods, the location of these signal sources can also be determined.

A barometer with microbar resolution at a 20 Hz sampling rate would be able to detect many of these infrasound events.

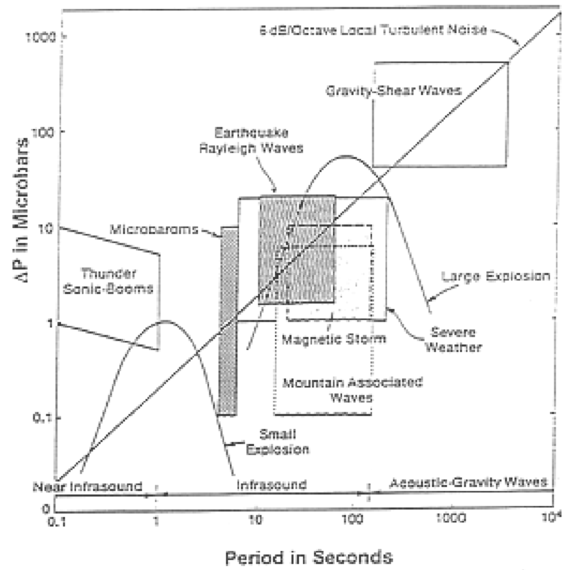

Figure 10. Some Infrasound Signals

b. Fog Forecast

In its simple form, fog is a cloud on the ground. Most common kinds of fog form when air is cooled to condense at its dew point.

Fog reduces visibility and becomes a hazard for travelers, especially at airports. A number of tests have been performed at or near airports to forecast fog using the COBEL numerical weather prediction model.

The important atmospheric parameters for fog forecasting are temperature, humidity, soil temperature and soil humidity, radiation and wind speed.

Because of unreliable humidity measurement sensors, it has always been a challenge to measure humidity correctly for the COBEL model.

With GPS Meteorology, it is possible to accurately measure the IPWV in the atmosphere. With the new slant delay path techniques, it will also be possible to determine the spatial humidity distribution accurately. This capacity will definitely enhance fog forecasting and travel safety [11].

c. Hazardous Materials Detection

Another interesting application for existing GPS-MET systems would be using these networks to track the movements of hazardous material in the atmosphere after a spill or a biological attack.

Hazardous material in the atmosphere is moved around by wind. Wind is a result of pressure, friction and Coriolis effects in the atmosphere. Because of pressure differences, air moves from the high pressure points to low pressure points. For example, a pressure difference of 1 hPa between places 100 kilometers apart can move still air to speeds of up to 10 meters per second.

The pressure data from a network of MET stations co-located with GPS receivers can be fed to a central computer system to map the real-time pressure isobars over an extended area. From the pressure isobars on the map, information about the direction and speed of air movement can be extracted.

Currently, NOAA and the EPA (Environmental Protection Agency) use a software package called ALOHA. The main inputs to this system are temperature, wind speed and direction. Wind speed and direction can be different at the micro level than the actual large-scale movements of the air mass. The transport of air should be monitored at the mesoscale level to track the direction and speed of hazardous materials.

d. Airport Applications

In addition to fog forecasting at airports, GPS network MET packages with broadband barometers may also be used to detect wake vortices. Wake vortices generate acoustic signals and it may be possible to detect these signals in the infrasound region. This capability could be used to enhance airport capacity to enable more parallel landings and take-offs.

A study conducted by the DOT Volpe Research Center at John F. Kennedy Airport used high resolution resonant quartz barometers to demonstrate the pressure-signature relationships generated by different types and weights of airplanes.

The FAA presently uses resonant quartz barometers as portable transfer standards to test and calibrate sensors for the ASOS (Automatic Surface Observing System) and AWOS (Automatic Weather Observing System). These systems are a suite of sensors that provide automated weather related information to pilots at airports. Resonant quartz barometers are also used at many airports as the heart of Digital Altimeter Setting Indicators. A MET package co-located with a GPS receiver can provide multiple cost-effective functions as part of the overall ASOS or AWOS at airports.

7. Conclusions

Broadband Meteorological sensors co-located with GPS receivers can increase the return on investment by enhancing the functionality of GPS networks. Accurate and stable barometers with wind-insensitive pressure ports are key to the GPS-MET calculations of Integrated Precipitable Water Vapor. These sensors are also used as Digital Altimeter Setting Indicators at airports. Work is in process to use GPS-MET for fog detection and flash-flood predictions. In addition, a wide range of phenomena generating atmospheric waves in the infrasound region may be detected with high resolution, broadband barometers.

8. Acknowledgments

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