

GPS Networks for Atmospheric Sensing

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Biography

Christian Rocken's research focuses on high accuracy applications of the GPS to geodetic surveying and on the development of GPS applications to atmospheric sensing. Presently he manages the GPS Research Group at UCAR, and is chief scientist for the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC). Dr. Rocken received his Ph.D. in geophysics from the University of Colorado, has authored and co-authored over 35 refereed publications, and holds a US patent in atmospheric sensing with GPS.

Abstract

Phase delays induced in GPS signals by the ionosphere and neutral atmosphere can be measured with high precision simultaneously along a dozen or so GPS ray paths in the field of view. These delays can be converted into total electron content (TEC) and integrated water vapor (if surface pressure data or estimates are available) along each GPS ray path. The resulting continuous, accurate, all-weather, real-time GPS moisture data help advance mesoscale modeling and data assimilation, severe weather, precipitation, cloud dynamics, regional climate and hydrology. Several networks are now being established for this purpose. They range from small (10 km) to global scale. We discuss the applications, data communication, and analysis techniques for three GPS networks. The first network consists of 14 low-cost single frequency GPS receivers in a small 8-km diameter area in Oklahoma. Single frequency L1 data are processed, under consideration of good ionospheric models, to determine accurate atmospheric delays and atmospheric water vapor in the directions of the GPS satellites. Use of similar low-cost L1 receivers in larger networks with hundreds of sites is under consideration. The second network is operated by the National Oceanographic and Atmospheric Administration Forecast Systems Laboratory (NOAA/FSL) to compute integrated zenith water vapor in near

real time. The near real time zenith water vapor, daily slant water vapor and vertical ionospheric TEC results from this network are displayed at "gst.ucar.edu/gpsrg/realtime.html". We discuss the importance of near real time orbit improvements (as compared to the use of predicted GPS orbits) for the analysis of such a continental size network. Finally, we describe a global network of high-rate 1-sec GPS tracking stations that is being established in support of satellite missions that profile the atmosphere and ionosphere from low-Earth orbit.

In summary, the proliferation of GPS networks for the primary purpose of atmospheric monitoring shows the importance and maturity that this relatively new application of the GPS has achieved in a very short time.

Introduction

GPS phase data, in combination with surface pressure measurements can be used to compute several atmospheric quantities: (1) The atmospheric total integrated zenith delay (ZD). (2) The zenith delay due to water vapor or zenith wet delay (ZWD). (3) The zenith precipitable water vapor (PWV). (4) The slant delay in the direction of the individual GPS satellites (SD). (5) The slant water vapor or the integrated water vapor in the direction of the individual GPS satellites (SWV).

PWV measurements have been widely demonstrated [i.e. Bevis et al. 1992, 1994, Rocken et al 1993, 1995, Duan et al 1995]. It has been shown that PWV can be measured with an accuracy of ~ 1.5 mm, and that SWV measurements may be achievable with sub-mm accuracy [Ware et al. 1997, Braun et al, 2000]. Primarily because of its ability to measure water vapor, meteorologists have become increasingly interested in using GPS-derived products for weather prediction.

PWV Observations during Hurricane Floyd

GPS 09/15/1999 20 hr UTC GOES 09/15/1999 19 hr UTC

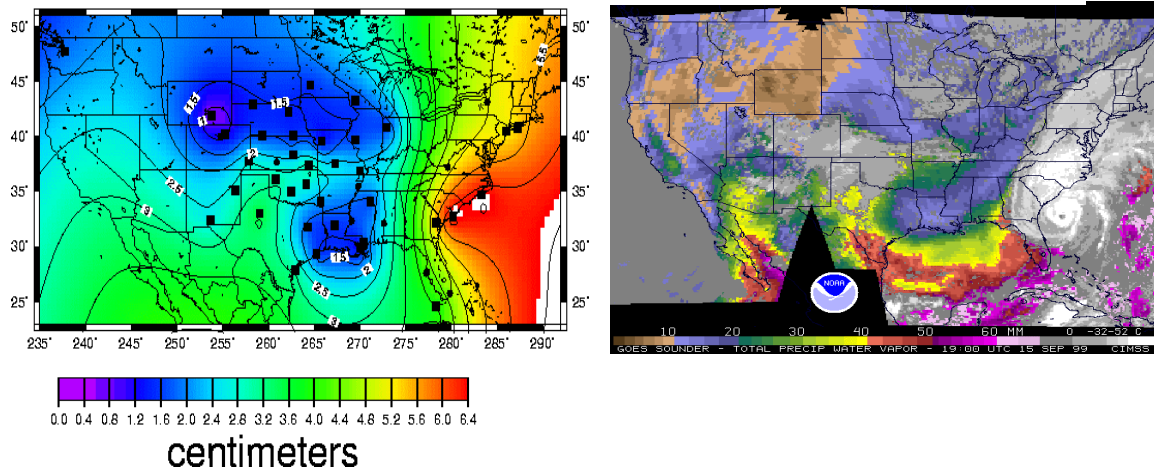


Figure 1 shows a comparison of PWV that was estimated from the NOAA/FSL GPS network during Hurricane Floyd (left panel) in comparison to the GOES satellite data at this time (right panel). Note that all-weather GPS data are available in the cloudy conditions caused by the hurricane.

Figure 1 shows an example of PWV data from the NOAA/FSL GPS network in the U.S. Data in this figure are interpolated and extrapolated from point measurements at the GPS sites. Black squares indicate sites with GPS and surface pressure measurement, black dots indicate sites with GPS only. GPS data are available in all weather conditions and can therefore complement other sensors such as GOES. GPS PWV accuracy of 1-2 mm may also be useful for the calibration of GOES PWV data.

Meteorologists have developed techniques to assimilate PWV measurements into numerical weather models and are presently expanding this technique to also use the slant observations. Initial results indicate that GPS derived PWV values can help improve the prediction reliability of severe precipitation events [Guo et al. 2000], and that that slant water observations from dense networks are useful to recover the vertical structure of atmospheric water vapor (Flores, 1999, S. McDonald pers. com., 1999).

Several GPS networks have been established or are under construction at least in part to support meteorology and ionospheric science (Table 1). GPS networks for meteorology require fast communications to transmit the data to a central analysis facility to compute highly perishable atmospheric or ionospheric information as close to real-time as possible.

Table 1 Some of the largest GPS networks that are operated at least in part for meteorological applications

Network	GPS sites #	Purpose
Japan GSI	1000 +	Tectonics Meteorology
Germany	50 +	Meteorology Geodesy
USA Southern Calif. network	250 +	Tectonics Meteorology
USA CORS +NOAA/FSL	100 +	Meteorology
International GPS Service (IGS)	100 +	Geodesy Meteorology Space Weather
ARM L1-network, USA	~30	Small-scale water vapor Meteorology
Suominet (USA and Intl.)	100 +	Meteorology Space Weather

There are many more GPS networks worldwide that are not listed in Table 1 either because they are small and include only a few stations or because they have no significant atmospheric objectives.

GPS networks of dual frequency receivers can also be used for estimation of ionospheric TEC. In Figure 2 we show an example of TEC computed from the same network used in Figure

1 for the determination of atmospheric water vapor.

Real-time GPS Sensing of Ionospheric TEC 8/30/99, 17:30 UT

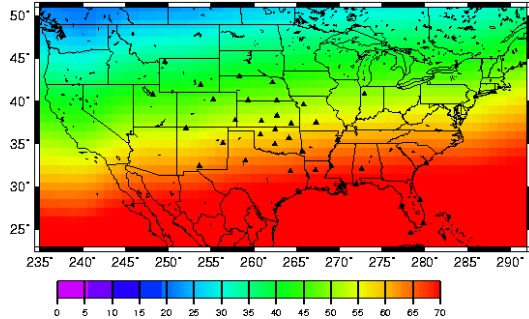


Figure 2 shows ionospheric TEC for the US computed close to real time from data collected by the NOAA/FSL GPS network (www.gst.ucar.edu/gpsrg/realtime.html).

Data from networks as shown in Figure 1 and Figure 2 above have applications in science, and weather and space weather modeling and prediction. The data can also be used for the calibration for satellite radiometry and in delay corrections for navigation.

The following sections of this paper will focus on neutral atmospheric applications of GPS networks.

Dense L1 networks

We are deploying a very dense network of L1 single frequency receivers for measuring atmospheric SWV in north central Oklahoma. The purpose of these measurements is detailed reconstruction of the 3-dimensional (3-D) distribution of atmospheric water vapor. Climate researchers are interested in detailed 3-D measurements of water vapor because of its importance as a green house gas for Earth's radiative balance. Another potential application of such a dense network is the prediction of small storm-scale cells of severe weather e.g. in the vicinity of major airports.

We use single frequency receivers because they are presently about 1 order of magnitude less expensive than dual frequency receivers. Phase data from these low-cost receivers is comparable in quality to the dual frequency counterparts. Thus single frequency receiver boards are at the core of a standalone GPS system that also

features solar power and batteries, a single frequency antenna and ground plane, and a time delay multiple access (TDMA) digital radio to broadcast the GPS data in real time to a central processing site. Data from the entire network are thus broadcast to one central site from where they are forwarded via the Internet for analysis at UCAR in Boulder. The main advantages of the system (one of the sites is shown in Figure 3) is that remote sites can be installed nearly anywhere without power or communications infrastructure. Other advantages are the relatively low cost and the high quality data that can be achieved.



Figure 3 shows a single frequency, standalone GPS site with solar panel, and digital radio, installed in northern Oklahoma.

The single frequency observations of the network are processed to retrieve SD and SWV measurements. The ionospheric delay within the network must be either modeled to high accuracy or it can be assumed to be the same for all sites (remember that the entire network expands only over a few km) and cancel.

Instead of assuming that the ionosphere differences out, one can employ additional ionospheric correction models based on networks of surrounding dual frequency receivers. GPS data from dual frequency receivers can be used to compute ionospheric maps as shown for example in Figure 2 (Schaer et al, 1995, Ho et al., 1996 & 1997, Manucci et al, 1998). However, these global or continental size models only capture the broader, long-wavelength features of the ionosphere. Small-

scale ionospheric fluctuations remain unmodeled as is shown in Figure 4. The red line in Figure 4 shows the L1-L2 (sometimes also called L4) phase residuals for one station (station A) in the direction of one GPS satellite (this example is computed from data collected by the Japanese Geographic Survey Institute (GSI)) after removal of a standard ionospheric model. Thus the red line is a measure of the ionosphere that is *not* corrected by standard ionospheric models.

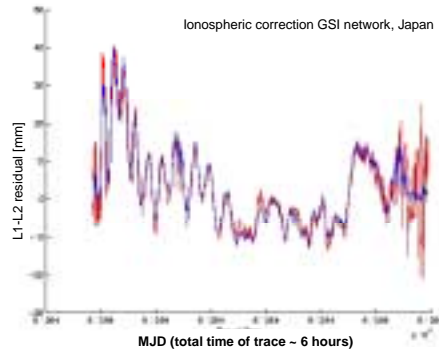


Figure 4 shows in red the unmodeled ionosphere for a dual frequency GPS station in the direction of 1 GPS satellite after a regional ionospheric model has been applied. In blue we show how well this residual site and satellite specific ionospheric delay can be corrected by interpolating the ionospheric delay from surrounding dual frequency sites spaced at about 30-40 km.

Interpolation of similar residuals as seen in Figure 4 from 9 surrounding dual frequency sites, spaced apart by 30-40 km, to station A results in the blue line in Figure 4. Clearly the ionosphere at station A can be well reconstructed from interpolation of the ionospheric delay observed at surrounding stations.

We attempted similar ionospheric interpolation for our L1 GPS network in northern Oklahoma. Here the surrounding dual frequency sites are spaced much wider than for the Japanese example (~150 - 200 km). In this case this ionospheric interpolation technique does not work sufficiently well to allow estimation of residual delay with mm accuracy. Additional research is required to determine the spacing of dual frequency sites to interpolate the ionospheric correction to single frequency sites at the mm level. At this point, based on tests

conducted near solar maximum in mid-latitude locations we know that this spacing is somewhere between 35-150 km.

Below we show example SWV data for a 24-hour time period computed from one of the sites in our L1 network. The time varying PWV values were scaled to the observation elevation angles and subtracted from the observed SWV to yield the +/- 20 mm variation in Figure 5.

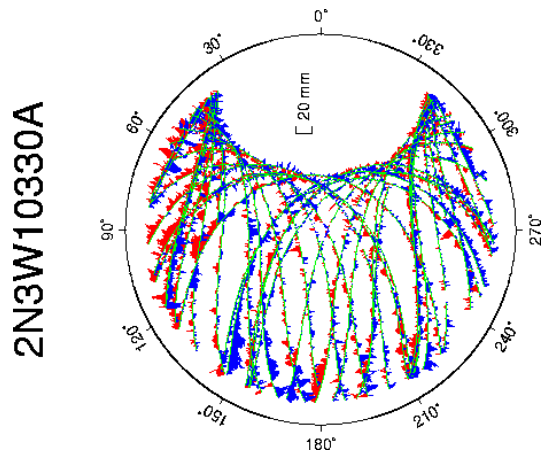


Figure 5 is a sky plot representation of SWV residuals. The directions of the GPS satellites over a 24-hour period are shown in green (zenith is the center of the horizon circle; north is at 0 azimuth, south at 180). Vertically to the green line the SWV residuals are shown. Red indicates that there is less water vapor than the scaled PWV value in a particular direction, blue indicates that there is more water vapor in a direction.

We are still working on the validation of results as shown in Figure 5. Preliminary results from comparisons with water vapor radiometers (WVRs), suggest that low-cost single frequency receivers can be used for the measurement of atmospheric slant delay and slant water vapor. Requirements for this are: (a) The L1 network has to be so dense that the ionosphere can be assumed identical at all sites. Or (b) a surrounding dual frequency network is spaced sufficiently dense (between 35 - 150 km) to interpolate ionospheric corrections at the mm level to each L1 receiver site.

The NOAA GPS Network

The longest operating GPS network for the determination of atmospheric parameters is the

NOAA network (Figure 1) operated by the Forecast Systems Laboratory (FSL) (Gutman, 1995). This is a reliable network of ~50 dual frequency GPS receivers which is steadily being expanded. The main task of this network is to demonstrate the operational feasibility of a GPS network for atmospheric sensing. One of the goals is to achieve reliable estimation of PWV with 30 minute or better temporal resolution at the 2 mm or better accuracy level. The 2 mm accuracy is required by meteorologists in order for the PWV data to have any significant positive impact on weather prediction.

We have analyzed data from the NOAA network in near real time for over 3 years now and have demonstrated (Rocken et al 1997) that real time PWV estimation is possible at the 2.5 mm level. Recently we have also added data from the US Coast Guard Continuously Operating Reference Sites (USCG/CORS), Federal Aviation Administration National Transportation Safety Board (FAA/NTSB) sites, and Department of Transportation (DoT) sites.

GPS-estimated water vapor information is most valuable for forecasting when it is new. The data must therefore be transmitted close to real time. In the case of the NOAA network the data are downloaded every 30 minutes from the field sites. Our analysis process gets the data from the FSL and other data hubs every hour and computes two new PWV values (with 30-minute temporal resolution) for each station in the network. This analysis takes about 20 minutes and requires high accuracy GPS orbits. We use orbits that are propagated into the future by the Center for Orbit Determination in Europe (CODE) at the University of Berne, Switzerland. The quality of these predicted orbits depends on their age but ranges typically from 15-50 cm rms in position.

We noticed time periods when the quality of the predicted orbits of the GPS satellites is significantly worse than the 15-50 cm range. One of the reasons for this is an orbital satellite maneuver that cannot be predicted. These periods strongly affect the quality of the estimated PWV as shown in comparison to radiosondes in Figure 6.

We attempt to detect periods of poor predicted orbit quality by fixing the coordinates of selected stations in the network and checking the fit of the GPS data from these stations to the predicted

orbits. These checks proved to be successful sometimes. Other times this test fails to detect bad quality orbits and the PWV estimates are degraded.

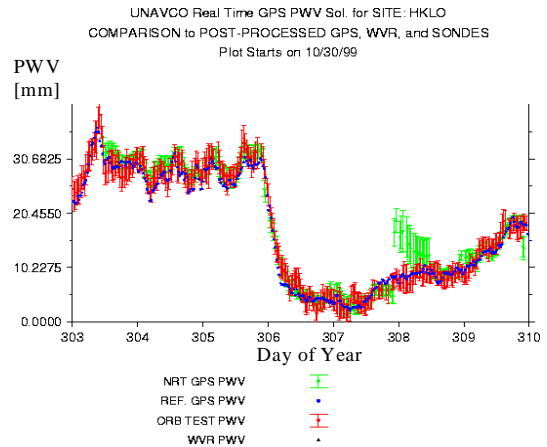


Figure 6 shows estimated PWV for 1 week at site Haskell, OK. PWV estimated with the most precise GPS orbits in post processing is shown in blue, PWV using predicted orbits is green, PWV using predicted orbits that were improved in real time is red.

To reduce the effect of poor orbit quality we have begun to compute orbit improvements using the hourly data from the NOAA network. We estimate corrections to the orbital positions every hour (Figure 7). This process takes slightly longer computing time than computing the tropospheric parameters only, but is clearly feasible in real time. Note that the satellite orbits can be expected to be improved only while in view of the NOAA network. Global orbit improvements in real time are also feasible but require a global real time tracking network.

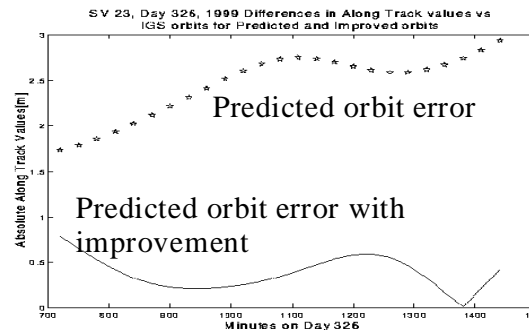


Figure 7 illustrates an example of real-time orbit improvement. Predicted and predicted+improved orbits for SV 22 are compared to IGS final orbits.

Table 2 shows the improvement in quality of the GPS-estimated PWV values if the orbits are improved in real-time. The statistics are based on PWV computations for ~100 days at 14 sites of the network. We compare real-time PWV to post-processed PWV values using the highest quality GPS orbits. These orbits become available about 10 days after real time from the International GPS Service (IGS). It can be seen that real time orbit improvements are important to achieve the 2-mm accuracy required by meteorologists.

Table 2 Comparison of post-processed and near-real time GPS PWV using (a) predicted and (b) real-time improved GPS orbits

predicted orbits rms mm	Bias [mm]	improved orbits rms mm	Bias [mm]	Ave. PWV [mm]
3.45	0.21	1.59	-0.04	23.43

So far the real time PWV data are not used in any operational weather forecast system. Numerical prediction experiments with GPS PWV data collected in the central U.S. (Guo et al., 2000) have shown that the GPS PWV data can have significant impact on rainfall prediction.

The combined network described here is a good example of how GPS sites that are operated for different primary reasons (NOAA meteorology, FAA, USCG, DoT for navigation) can be used for meteorology as long as near real time data and analysis systems are implemented. In addition it is helpful if the GPS sites are also equipped with surface meteorological sensors to measure surface pressure, temperature, and humidity.

NOAA is expanding its network. In addition the National Science Foundation (NSF) has recently funded SuomiNet. SuomiNet, named after satellite meteorology pioneer Verner Suomi, will establish more than 100 GPS sites at Universities in the US and at international partner sites. All these GPS stations will provide data in real time via the Internet to the analysis center at UCAR. UCAR will distribute the raw data and processed results to the atmospheric science community. Together the NOAA network and SuomiNet will provide real time atmospheric and ionospheric data at high temporal and spatial resolution (www.unidata.ucar.edu/suominet/).

A GPS Network to support Space Missions

GPS receivers in low Earth orbit (LEO) can be used to profile the ionosphere and atmosphere with high resolution and accuracy (i.e. Rocken et al, 1997, Kursinski et al. 1996 & 1997, Schreiner et al. 1999).

To compute accurate radio occultation inversions it is necessary to remove the drifts of the GPS transmitter and receiver clocks from the raw phase data. This can be done with common mode double difference viewing of the LEO and ground GPS data as illustrated in Figure 8.

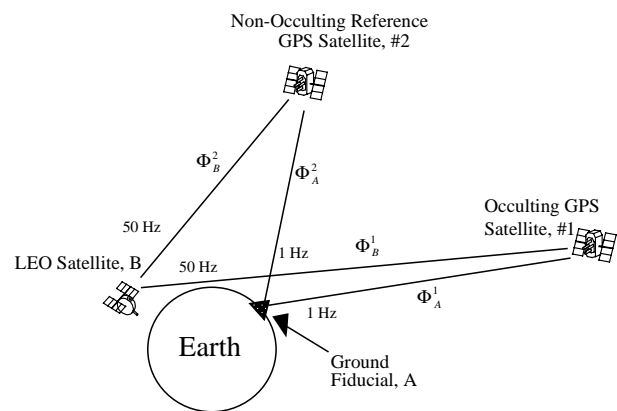


Figure 8 Shows the use of a fiducial site for forming a double difference. The fiducial sites will log GPS data (Φ_A^2 and Φ_A^1) at 1 second while the LEO will track the occulting and reference satellites at 50 Hz or possibly even at a higher rate (Φ_B^2 and Φ_B^1).

Several upcoming satellite missions (including Orsted, SUNSAT, SRTM, CHAMP, SAC-C, GRACE, and COSMIC) plan to carry GPS receivers that will acquire radio occultation measurements of the Earth's atmosphere and ionosphere. During the GPS/MET mission (Ware et al., 1996) a network of 6 sites (in Germany, Alaska, California, Hawaii, Australia, and Antarctica) were operated by the Jet Propulsion Laboratory (JPL). This network is currently expanded and improved to provide reference data for future radio occultation missions.

Data from the support network for occultation missions will be sampled at a rate of 1Hz. Since some of the occultation missions (like CHAMP and later COSMIC) plan to process their data

close to real time the data from this global network will be communicated to the analysis centers worldwide close to real time. Real-time global 1-sec data will also be useful for real-time

1-sec clock estimation and ionosphere monitoring to benefit high precision navigation globally.

JPL/GFZ High Rate Ground Tracking Network

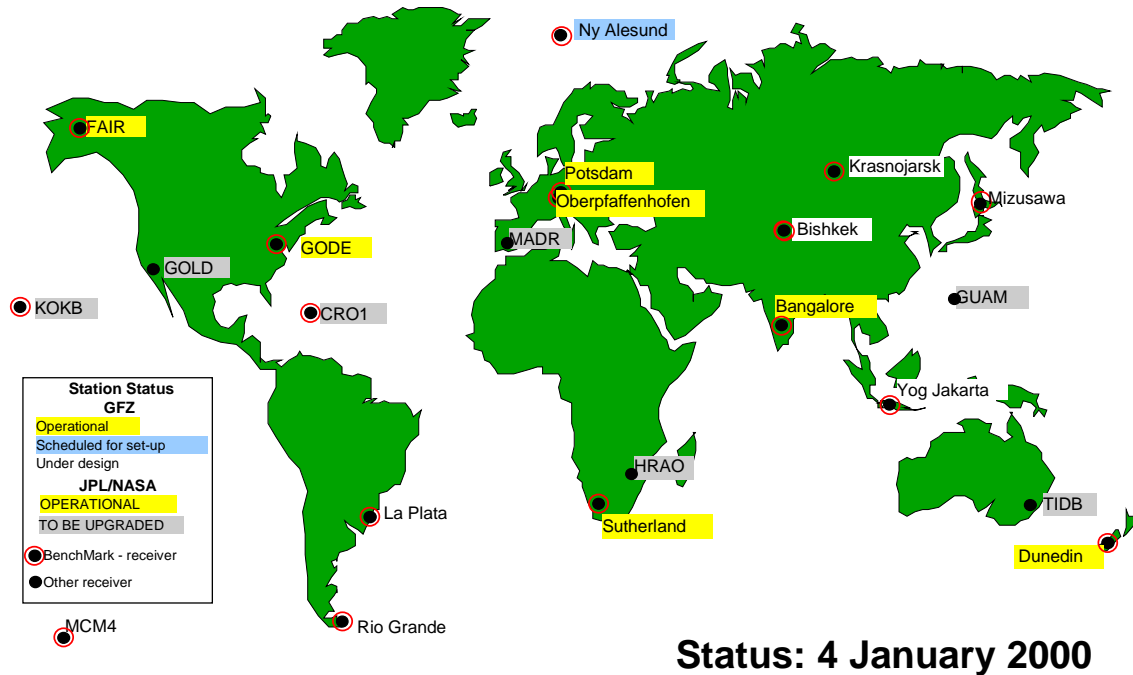


Figure 9 shows the current status of the high rate GPS tracking network. Initially only a subset of these stations will provide data in near real time. Future upgrade to the network for real time 1-sec is expected. (Courtesy J. Wickert, Geoforschungszentrum, Potsdam (GFZ)).

Summary

Presently many new GPS networks are under development. These networks range in scale from a few km to global and utilize new communications and data processing techniques. Just as GPS has already revolutionized geophysics and solid Earth science, it is on the verge to also significantly impact atmospheric science and operational weather and space weather forecasting.

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