Comparison Between GPS Radio Occultation and Radiosonde Sounding Data

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Academic Affiliation, Fall 2003: Senior University of California, Berkeley

SOARS® Summer 2003

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ABSTRACT

Global Positioning System (GPS) Radio Occultation (RO) is a new technique for obtaining profiles of atmospheric properties, specifically: refractivity, temperature, pressure, water vapor pressure in the neutral atmosphere, and electron density in the ionosphere. The data received from GPS RO contribute significant amounts of information to a range of fields including meteorology, climate, ionospheric research, geodesy, and gravity. Low-Earth orbiting satellites, equipped with a GPS receiver, track GPS radio signals as they set or rise behind the Earth. Since GPS signals are refracted (delayed and bent) by the Earth's atmosphere, these data are used to infer information about atmospheric refractivity. Before the GPS RO data are used for research and operations, it is essential to assess their accuracy. Therefore, this research provided quantitative estimates of the accuracy of GPS RO when compared with measurements of known accuracy. Profile statistics (mean, standard deviation, standard error) were computed as a function of altitude to quantify the errors. Comparing RO data with nearby (300km; 2hr) radiosonde data yielded small mean error for all of the statistical plots generated, affirming that the RO technique is accurate for measuring atmospheric properties. Comparison of RO data with sounding data from different radiosonde systems showed that the RO technique was of high enough accuracy to differentiate differences in performance of various types of radiosonde systems. The results indicated that India’s IM-MK3 radiosonde has the greatest amount of uncertainties and Australia's Vaisala radiosonde has the least amount of uncertainties.

This work was done under the auspices of the Significant Opportunities in Atmospheric Research and Science (SOARS®) program of the University Corporation of Atmospheric Research, with funding from the National Science Foundation, the U.S. Department of Energy, the National Oceanic and Atmospheric Administration, and Goddard Space Flight Center, NASA.

SOARS® 2003, Dione Lee Rossiter, 1
INTRODUCTION

Global Positioning System (GPS) Radio Occultation (RO) is a new technique for obtaining atmospheric properties, specifically: refractivity, temperature, pressure, water vapor, and electron density (Anthes et al., 2003). Because the method is in its primary stage of development, interpreting the accuracy of GPS RO is essential. Therefore, this research provides quantitative estimates of the accuracy of the GPS RO system when compared with traditional measurements of known accuracy. Once the accuracy is determined, the comparisons provide estimates on how different types of radiosondes systems perform. Furthermore, it evaluates the quality of radiosondes produced by different manufactures in different regions.

The GPS constellation, originally developed for the U.S. Department of Defense, consists of 24 operational satellites that transmit radio signals for navigation and positioning purposes (Anthes et al., 2003). However, since GPS signals are refracted (delayed and bent) by the Earth's atmosphere as they travel to the receiver, these data can also be used to infer information about atmospheric refractivity (Rocken et al. 2000). The refractivity of the atmosphere is a function of electron density in the ionosphere and of temperature, pressure, and water vapor in the stratosphere and troposphere (Anthes et al., 2003).

Before analysis of atmospheric properties can take place, measurements obtained from the GPS receiver must first be inverted in order to derive the atmospheric quantities. A GPS satellite will continuously transmit signals in two frequencies, L1 at 1.57542 GHz and L2 at 1.2276 GHz (Anthes et al., 2003). Low-Earth orbit (LEO) satellites, equipped with a GPS receiver, can track GPS radio signals as they set or rise behind the Earth relative to the GPS satellite. A GPS receiver will collect both the amplitude and the phase of the dual frequency signals (Kursinski et al., 2000). From here, a Doppler shift can be computed. The Doppler frequency shift, along with the known positions and velocities of the GPS and LEO receivers, are used to compute the bending angle, $\alpha$, of the radio waves as a function of impact parameter, $a$. This is shown in Figure 1, where impact parameter is the distance from the center of the earth to a point which forms a right angle with the ray (Anthes et al., 2003).

![Figure 1: Occulting geometry for the GPS and LEO satellites](image)

The dual frequency signals allow for separation of the propagation delays due to ionospheric refractivity and propagation delays due to temperature and moisture of the neutral atmosphere (Kursinski et al., 2000). Above 90 km the pressure and water vapor...
terms are negligible and any refractivity seen at this level is due solely to electron density in the ionosphere. Ionospheric bending may then be removed through

\[ \alpha_{\text{free}} = a\alpha_{L1} + b\alpha_{L2} \]  

(1)

where \( \alpha_{L1} \) is the bending due to frequency L1, \( \alpha_{L2} \) is the bending angle due to frequency L2, and \( a \) and \( b \) are constants. Once \( \alpha_{\text{free}} \) is computed, this quantity is used in the Abel transfer function to compute the refractivity of the neutral atmosphere. By assuming spherical symmetry, the Abelian inversion given by

\[ \ln[n(a)] = \frac{1}{\pi} \int_{a}^{\infty} \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} da \]  

(2)

where index of refraction, \( n \), and the bending angle, \( \alpha \), as a function of impact parameter, \( a \), may be used to obtain an index of refraction profile (Anthes et al., 2003). This method is called the radio occultation (RO) technique and was first demonstrated in the 1960s when satellites visiting the outer planets of the solar system experienced delayed signals which were used to successfully extract data on atmospheric properties of the outer planets (Yunck et al. 2000).

According to Rocken et al., 2000, the data from GPS RO contributes significant amounts of information to a wide range of areas including meteorology, climate, ionosphere composition, geodesy, and gravity. The data will provide global coverage in time and space, including regions like the oceans and near the poles where there is a lack of atmospheric measurements (Figure 2). RO provides a data set that allows for a

**Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs**

*Figure 2: COSMIC radio occultation soundings are shown in green and radiosonde sites in red*

SOARS® 2003, Dione Lee Rossiter, 3
fundamentally unbiased temperature study to occur. Furthermore, the technique is mission independent and therefore provides long-term, stable, and globally distributed measurements for climate studies. By probing regions of the ionosphere, GPS RO soundings can also be important for advancements in space weather research that may potentially improve space weather forecasting. Due to its high accuracy in satellite positioning, GPS RO will lead to advancements in the description of the Earth's gravitational field. Most importantly, GPS will provide high-quality soundings at low cost. (Rocken et al., 2000)

The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) is a satellite mission that plans to launch six LEO satellites in 2005 (Anthes et al., 2003). These satellites will collect RO data to measure the refractive properties of the Earth's atmosphere and ionosphere. The COSMIC satellites will each carry a GPS receiver that will collect data and transmit it back to the COSMIC Data Analysis and Archive Center (CDAAC). Figure 2 illustrates the global coverage COSMIC RO will provide with roughly 3000 daily soundings compared to the existing radiosonde network, which has a total of approximately 900 stations (Anthes et al., 2000). In order to use COSMIC data effectively for research and operation when the mission is in progress, it is essential to properly assess the accuracy of the GPS RO soundings (Anthes et al., 2003).

Rocken et al., 1997, describes radiosondes as being the most accurate technique for studying upper air observing systems since the 1940’s. Typically, radiosondes provide data from the surface up to an average altitude of 20 to 30 km. In the upper troposphere and stratosphere, pressure, temperature, and height errors become more common. Although the radiosonde technique is not flawless, it provides data that are the most widely used and accepted for upper air observing systems. (Rocken et al., 1997)

The accuracy of GPS RO soundings is evaluated by comparing their data with the more traditional radiosonde measurements that have known accuracy. Following the evaluation of the GPS RO technique, radiosonde data from different regions and manufacturers were then evaluated by comparing them to both GPS RO data and the European Center for Medium-Range Weather Forecasts (ECMWF) data. The atmospheric properties that were compared are atmospheric refractivity, temperature, pressure, and water vapor.

METHODS

To determine the accuracy of the GPS RO soundings as well as the different regional radiosondes, comparisons were made using CDAAC analysis tools. Radiosonde and global analysis data that have been collected from the NCAR mass store system were used as auxiliary data. The RO sounding data that was evaluated in the study comes from a Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP), one current GPS RO mission. Before analysis of the atmospheric properties can take place, measurements obtained from the RO technique, specifically, the index of refraction, were first inverted in order to derive the remaining atmospheric quantities.

Obtaining Atmospheric Properties from GPS RO

The RO technique is used primarily to derive measurements of refractivity, therefore, refractivity is considered the fundamental atmospheric measurement of RO. Additional analysis is required to obtain temperature, pressure, and water vapor profiles.
The refractivity $N$ (where $N = (n-1) \times 10^6$ in the neutral atmosphere) is related to pressure, $P_{\text{mb}}$, temperature, $T_{\text{k}}$, water vapor partial pressure, $P_w \text{ [mb]}$, and electron density, $n_e \text{ [electrons/m}^3\text{]}$, through

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^4 \frac{P_w}{T^2} - 40.3 \frac{n_e}{f^2}$$  \hspace{1cm} (3)

where $f$ is the frequency of the radio signals in Hz (Kursinski et al., 2000).

Since the dual frequency GPS signals remove the ionospheric contribution to refractivity, Equation 3 becomes

$$N_{\text{ios}} = 77.6 \frac{P}{T} + 3.73 \times 10^3 \frac{P_w}{T^2}$$  \hspace{1cm} (4)

where

$$N = N_{\text{ios}} - 40.3 \frac{n_e}{f^2}$$  \hspace{1cm} (5)

Because only refractivity is obtained from the Abel transform, it is not possible to uniquely determine profiles of $P$, $T$, and $P_w$ without additional information. However, if we assume a dry air case by neglecting the moisture term in Equation 4, the equation of state can be used to write the refractivity as

$$N = 77.6R$$  \hspace{1cm} (6)

where $R$ is the gas constant for dry air (Ware et al., 1996). Next, the pressure can be computed by integrating the equation of hydrostatic equilibrium,

$$\frac{\partial P}{\partial z} = -g(z) \rho(z)$$  \hspace{1cm} (7)

where $P$ is pressure, $g$ is the acceleration of gravity, and $\rho$ is density. Finally, applying the equation of state, and appropriate values for density and pressure, yields temperature for the dry air case. These atmospheric properties that are obtained in a straightforward manner when neglecting moisture provide accurate profiles above the altitude where moisture becomes significant. In contrast, constructing profiles when moisture is considered is more complicated and requires independent estimates of pressure and temperature using models or other sources (Kuo et al., 2000).

**Obtaining Atmospheric Properties from Radiosondes**

The radiosonde data comes from the NCAR’s mass store system (with a mass store file identifier of ds353.4, url: http://www.dss.ucar.edu/datasets/ds353.4). Two issues must be addressed when CDAAC receives its ds353.4 radiosonde data. First, the radiosonde data only report geopotential height, $H$, temperature, $T$, pressure, $P$, and dew point temperature, $T_d$, and do not include measurements of refractivity and partial...
pressure of water. Second, the geopotential height is only a function of pressure and not geometric height as for RO data. The first task is to convert geopotential height, $H$, to geometric height, $Z$, with the equation

$$ Z = \frac{r_H}{g_r - H} $$

(8)

where $G = 9.8 \frac{m}{sec^2}$, $g_r$ is the local acceleration of gravity at the latitude $\Phi$ which is calculated from

$$ g_r = 9.780356(1 + 0.0052885 \sin^2 \Phi - 5.9 \times 10^{-6} \sin^2 2\Phi) $$

(9)

and $r_e$ is the effective earth radius given by

$$ r_e = \frac{2g_r}{3.085462 \times 10^{-6} + 2.27 \times 10^{-9} \cos 2\Phi - 2 \times 10^{-12} \cos 4\Phi} (m) $$

(10)

The second task is to convert dew point temperature to partial pressure of water. The equation

$$ e_v = 6.112 \exp \left[ (17.5027) (240.97 + T)^{-1} \right] $$

(11)

converts dew point temperature, $T_d$, to vapor pressure, $e_v$.

Profiles of pressure, temperature, and partial pressure of water as a function of geometric altitude now exist. These measurements in combination with equation 4 are used to obtain measurements of refractivity. Subsequently, all of the atmospheric property profiles for radiosondes have been calculated for the neutral atmosphere.

### Generating Statistical Graphs

The data-mining interface, developed as part of CDAAC, offers an efficient way to study the available GPS RO data. Profiles of temperature, pressure, humidity, refractivity, and refractive bending angles from previous GPS RO missions can be accessed from CDAAC. When CDAAC obtains the data from the GPS receiver it carefully reviews all of the profiles and removes outliers that may have been affected by a number of error sources. This quality check ensures that the RO data that is accessed is of high standard.

A Perl script was provided in order to access the data-mining interface. The Perl script produced statistical comparisons between the radiosonde data, the GPS RO data taken from the CHAMP mission, and ECMWF data. To determine the best accuracy of the GPS RO soundings in comparison to the auxiliary radiosonde data, GPS RO data was only compared with radiosonde data that were within 300km and 2 hours of each other. For the evaluation of the RO technique, the study period analyzed was of August 2002.
For the evaluation of different types of radiosondes, the study period analyzed was from June 2001 to August 2003. A constraint was also put on latitude and longitude values in order to limit matches to a certain region and therefore a specific manufacturer. Figure 3 shows a map of radiosonde sites and manufacturers. The black squares represent the areas in which constraints were held. The regions/manufacturers and their coordinates being analyzed were Australia/Vaisala; latitude: -40 to -10 degrees longitude: 110 to 155 degrees, India/IM-MK3; latitude: 5 to 30 longitude: 70 to 90, Japan/MEISEI; latitude 30 to 45 longitude 130 to 150, and China/Shang; latitude: 20 to 45 longitude 95 to 130.

The data-mining interface allowed for calculation of the mean and standard deviations (error statistics) of the different data sets. More specifically, once the profiles were completed (matched and plotted together), they were interpolated to a common height grid of 200 m. Then a difference profile was created for each match followed by the combining of all of the difference profiles together. Then, all of the difference points under each 500 m cell were then averaged, meaning the means and standard deviations were produced, at the center of each specified altitude cell (250m). Therefore, the statistic plots both illustrate the standard deviation, the mean, and the number of matched profiles as a function of altitude.

Quantifying Regional Differences

Once the region/manufacturer type has been compared to RO and ECMWF data, quantifying the regional differences was necessary to rate the quality of the different
regions. First the mean of the absolute value of the mean differences in refractivity between radiosonde and CHAMP data was computed over the altitude range between 5 and 25 km.

\[ |\tilde{N}_{CR}| = \frac{1}{40} \sum_{s}^{25} |\Delta N| \]  

(12)

Then, the mean of the absolute value of the differences in refractivity between ECMWF and CHAMP data was computed.

\[ |\tilde{N}_{CE}| = \frac{1}{40} \sum_{s}^{25} |\Delta N| \]  

(13)

A ratio, \( D \), was then computed from these two quantities.

\[ D = \frac{|\tilde{N}_{CR}|}{|\tilde{N}_{CE}|} \]  

(14)

\( \tilde{N}_{CR} \) represents the total mean error between the RO and radiosonde data and \( \tilde{N}_{CE} \) represents the error contributed by the RO only. By dividing \( \tilde{N}_{CR} \) by \( \tilde{N}_{CE} \), \( \tilde{N}_{CE} \) normalizes the error of the RO from the \( D \) value. The equation thus leaves a factor of error caused by the radiosondes alone. For instance, if the radiosonde contained no errors with respect to the ECMWF data, then the \( \tilde{N}_{CR} \) and the \( \tilde{N}_{CE} \) values would be equal and therefore \( D \) would equal 1. Specifically, the value of the radiosonde errors (\( \tilde{N}_{CE} \)) as compared to the ECMWF and the value of the RO errors as compared to the RO (\( \tilde{N}_{CR} \)) would be the same. All \( D \) values greater than 1 indicates radiosonde errors and the greater the \( D \) value the poorer quality of the radiosondes in question.

RESULTS AND DISCUSSION

Results Comparing GPS RO and Radiosondes

Figure 4 shows that of approximately 270 matches, the RO mean refractivity agreed within 0.5 % of the radiosonde data. Figure 5 shows that out approximately 300 matches, the RO mean pressure agreed within about 0.25% of the radiosonde data. Figure 6 shows that out of approximately 270 matches, the RO vapor pressure mean agreed within 0.25 mb of the radiosonde data. Figure 7 shows that also out of approximately 300 matches, the RO temperature mean agreed within 0.5 degrees of the radiosonde data up to 20 km, and 1.5 degrees at 30 km.

In Rocken et al., 1997, a comparison is done with radiosonde data and the GPS/Meteorology (GPS/MET) project similar to that done here with the CHAMP mission. The GPS-MET project was the first mission to launch for the purpose of utilizing the RO technique. The comparison between the GPS-MET and radiosonde data agreed within 1% of the radiosonde data and a RO mean temperature that agreed within.
0.5 degrees of the radiosonde data. This data set is consistent with our findings. Overall, there is very little mean error for all of these plots, affirming that the RO technique is relatively accurate for measuring atmospheric properties. (Rocken et al. 1997)

The count of matched pairs for the refractivity plot decreases considerably and steadily above 7 km. This is due to the fact that when CDAAC detects an error in the radiosonde dew point temperature data, it discards all moisture information above this point and thus cannot compute refractivity. In the rest of the statistical plots (that relate to different radiosonde types) there is a gradual drop-off above 17 km after a peak at approximately 11 km. This is a result of the radiosonde balloons bursting at different altitude ranging from 15 to 30 km. The count is not as substantial near the surface because the RO soundings fail to penetrate in that area, particularly in the tropics. This is mostly due to sharp gradients in atmospheric water vapor. This phenomenon causes large...
signal fluctuations that the current GPS receiver phase locked loops are not able to follow. The COSMIC receivers will track occultations in an open loop mode that will track most occultations to the surface. (Anthes et al., 2003)

**Results Comparing Different Manufacturer Types to GPS RO and ECMWF**

![Chart 1](image1.png)

**Figure 8:** India’s refractivity statistical plot for CHAMP and radiosonde data during July 2000 to present

![Chart 2](image2.png)

**Figure 9:** India’s refractivity statistical plot for ECMWF and radiosonde data during July 2000 to present

![Chart 3](image3.png)

**Figure 10:** India’s refractivity statistical plot for CHAMP and ECMWF data during July 2000 to present

Figures 8 and 9 show that out of approximately 110 matches made in India, the radiosondes mean and standard deviations of the refractivity differences appear similar when compared to CHAMP and ECMWF data. Figure 10 illustrates that the CHAMP
mission and the ECMWF data for India are similar. With approximately 140 matches, the RO refractivity agreed in the mean to within 0.75% of the ECMWF data. From observing Figures 8 and 9 alone it is apparent that the radiosondes carry most of the error because the same errors are found in the comparisons between radiosonde and RO and radiosonde and ECMWF data. Figure 10 confirms that the RO data is more accurate than that of the radiosondes with respect to the ECMWF because both the mean value and standard deviations are considerably smaller and more stable than in Figure 9.

Results for Quantifying Regional Differences

| Region  | Radiosonde Type | Average # of matches | $|\bar{N}_{CR}|$ | $|\bar{N}_{CE}|$ | D   |
|---------|----------------|----------------------|----------------|----------------|-----|
| India   | IM-MK3         | 72                   | 0.88%          | 0.35%          | 2.49|
| Japan   | MEISEI         | 77                   | 0.29%          | 0.15%          | 1.88|
| China   | Shang          | 213                  | 0.31%          | 0.24%          | 1.27|
| Australia| Vaisala       | 213                  | 0.27%          | 0.26%          | 1.03|

Table 1: Table of Regional Differences

In Table 1 all 4 regions and their manufactures are listed with their resulting number of matches, $\bar{N}_{CR}$ values, $\bar{N}_{CE}$ values, and D values. India resulted with the largest D value. Australia using Vaisala had the least amount of radiosonde errors with a D value just over 1.

CONCLUSION

Comparing RO data with radiosonde data yielded very little mean error for all of the statistical plots generated, affirming that the RO technique is relatively accurate for measuring atmospheric properties. The RO technique is also shown to be accurate enough to detect mean radiosonde errors. Quantifying the regional differences showed that India’s IM-MK3 radiosonde had the greatest amount of and Australia’s Vaisala radiosonde had the least amount of error.
REFERENCES


