Climatology of Superrefraction Observed by GPS Radio Occultation

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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, and electron density. Low-Earth orbit (LEO) satellites, equipped with a GPS receiver, track GPS radio signals as they set behind the Earth. The atmosphere refracts GPS signals traveling to the receiver and these data can be used to infer information about atmospheric refractivity. Because GPS RO will be utilized in an array of atmospheric models, attaining the highest level of accuracy is essential. Therefore, this research provides insight to the challenges for GPS RO within the planetary boundary layer (PBL), due to the phenomenon of superrefraction (SR). SR is caused by a sharp decrease in refractivity with an increase of altitude, normally present at the top of the PBL, and results in a loss of the radio signal acquired by a LEO satellite. Consequently, the retrieval technique produces a refractivity profile that is negatively biased compared to global models. By examining the negative refractivity biases (as compared to the European Center for Medium-Range Weather Forecast model) in different seasonal periods, geographic regions, and altitude regimes, this research determined that SR is most probable off the west coast of continents where dry air sinks from above and creates a sharp vertical gradient in water vapor near the top of the PBL. Identifying regions that have a high occurrence of SR was a first step in preventing the use of negatively-biased RO profile data for future missions.

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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 will be utilized in an array of atmospheric studies, attaining the highest level of accuracy for GPS RO is essential. Therefore, this research provides insight to the challenges for GPS RO within the planetary boundary layer (PBL) due to the phenomenon of superrefraction (SR). SR is caused by a sharp decrease in refractivity with an increase of altitude, normally present at the top of the PBL. This results in a loss of the radio signal acquired by a Low Earth Orbit (LEO) satellite that is used to obtain the atmospheric properties (Sokolovskiy 2003). The retrieval technique used in GPS RO attempts to correct for the loss of signal and in turn produces refractivity profiles that are negatively biased. By examining the negative refractivity biases (as compared to models) in different seasonal periods and geographic regions, this research determines the most likely seasonal locations to be affected by SR. This research also studies the nature of SR, by comparing occultations from regions with negative bias to a model profile of moisture, in order to find a correlation between it and the seasonal regions of SR. Identifying the seasons, regions, and moisture characteristics that seem to have a high occurrence of SR will help in the utilization of negatively biased RO profiles in future missions.

GPS Radio Occultation

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 refractivity comparisons can be analyzed, raw measurements obtained from the GPS receiver must first be inverted in order to derive refractivity profiles. GPS satellites continuously transmit signals at two frequencies, L1 at 1.57542 GHz and L2 at 1.2276 GHz (Anthes et al. 2003). LEO satellites, equipped with GPS receivers, can track

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

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GPS radio signals as they set or rise behind the Earth relative to the GPS satellite. The GPS receivers will collect both the amplitude and the phase of the dual frequency signals (Kursinski et al. 2000). Then, a Doppler frequency shift can be computed. The Doppler frequency shift, along with the known positions and velocities of the GPS and LEO satellites, are used to compute the bending angle \( \alpha \) of the radio waves as a function of impact parameter \( a \). This is shown in Fig. 1, where the impact parameter is the distance from the center of the Earth to a point that forms a right angle with the ray and \( r \) is the tangent point radius of the occulting ray (Anthes et al. 2003).

The dual frequency signals allow for separation of the propagation delays due to ionospheric refractivity and the propagation delays due to the 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 the electron density of the ionosphere. Ionospheric bending may then be removed through the relation

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

where \( \alpha_{L1} \) is the bending angle due to frequency \( L1 \), \( \alpha_{L2} \) is the bending angle due to frequency \( L2 \), and \( b \) and \( c \) are constants. To improve the ionospheric calibration of bending angles, the \( \alpha_{L1} \) and \( \alpha_{L2} \) bending angles are combined at the same value of impact parameter (i.e. \( \alpha_{\text{free}} = \alpha_{L1} = \alpha_{L2} \)) as described in Vorob’ev and Krasil’nikova (1994). Once \( \alpha_{\text{free}} \) is computed, this quantity is used in the Abel transfer function to compute the refractivity of the neutral atmosphere. Assuming spherical symmetry, the Abelian inversion is given by

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

where bending angle as a function of the impact parameter and the index of refraction \( n \) (defined as \( n(r) = \frac{a}{r} \)) can be used to obtain a vertical profile of index of refraction \( n(z) \) (Anthes et al. 2003).

Beneath a SR layer, Eq. (2) becomes multi-valued and thus invalid, because the Abel transform is defined only when \( r(a) \) is a single valued function. Also beneath the SR layer, the Abel transform also retrieves the negative bias in \( n(z) \) compared to atmospheric models and radiosonde profiles. Figs. 2 and 3 illustrate the problem of the negative bias and the multi-valued Abel inversion. Fig. 2 shows the retrieved profile as compared to the true radiosonde profile with the numerous subset of profiles filling the space between the two. Fig. 3 also shows the true and Abel retrieved profiles. The bold line in plot A is a model profile of refractivity and the bold lines in the plots B and C are radiosonde profiles of refractivity interpolated by cubic spline. The lighter lines in all three of the plots of Fig. 3 are the Abel retrieved profiles derived from the true profiles. In both Figs. 2 and 3, the Abel retrieved profiles are negatively biased as compared to the model and radiosonde profiles. These two problems that occur, following a SR layer, are the first apparent effects of SR (Sokolovskiy 2003). This inversion method is known as the 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

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successfully extract data about the atmospheric properties of the outer planets (Yunck et al. 2000).

![Figure 2. The true and multi-valued Abel retrieved refractivity profiles.](image)

Motivation

According to Rocken et al. (2000), the data from GPS RO will 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

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time and space, including regions like the oceans and near the poles, where there is a lack of atmospheric measurements (see Fig. 4). RO provides a data set that will allow for a fundamentally unbiased temperature study. Furthermore, the technique is mission independent and therefore provides long-term, stable, and globally distributed measurements for climate studies. 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 Archival Center (CDAAC). Fig. 4 illustrates the global coverage COSMIC RO will provide with roughly 3000 daily soundings compared to the existing radiosonde network that 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 desirable to attain the highest level of accuracy of GPS RO profiles, either by removing the negative bias of SR, or by truncating the RO profile below the SR PBL (Anthes et al. 2003).

**Superrefraction**

As illustrated in Fig. 5, SR is observed when the gradient of the index of refraction of the atmosphere is sufficiently negative such that the curvature of the occulted ray is smaller than the curvature of the atmosphere. This causes the ray to travel into the surface of the Earth and thus results in a temporary extinction of the radio signal (Kursinski et al. 2000). SR that commonly occurs at the top of the PBL, where a large
vertical moisture gradient can be detected, is called an elevated SR layer. In this case, the signal does not bend into the Earth but rather the occulting rays slide along the top of the PBL and remain trapped in the atmosphere (Sokolovskiy 2003). Fig. 6 illustrates the sharp refractivity gradient that appears as a result of the conditions present at the top of the PBL. The meteorological conditions necessary for SR are $\frac{dT}{dz} > 140 K/km$ and $\frac{dP_W}{dz} < -34 mb/km$, for temperature and partial pressure of water vapor (Kursinski et al. 2000), and $\frac{dN}{dz} < -157 N/km$ for refractivity (Sokolovskiy 2003).

The bending angles of rays increase as they approach the surface of the Earth due the increase in refractivity in the troposphere. As the rays approach the point of critical refraction, the bending angle as a function of tangent point tends to bend toward infinity. Within the SR layer $\Delta z$, the rays are internally trapped (i.e., there is a gap in the bending angle versus tangent point function). The corresponding function of bending angle versus impact parameter has only one singularity and is integrated with appropriate interpolation. However, even with perfect interpolation, SR leads to a multivalued function $r(a)$ which invalidates the Abel inversion and leads to a negative N bias below the SR layer. The interval of critical refraction, and therefore the interval of interpolation, is dependent on the magnitude of the refractivity gradient and also the vertical thickness of the layer. As a result, the observed negative bias is also a function of the magnitude and thickness of the gradient. (Kursinski et al. 2000)

According to Sokolovkiy (2003), the depth of the PBL can be anywhere from several tens to several hundreds of meters. Sokolovkiy also states that SR is most probable over oceanic regions where there is a more horizontally homogeneous PBL. It has also been shown that SR causes greater negative errors, or is more probable, over the tropics compared to the rest of the globe. Figs. 7 and 8 are refractivity comparison plots between the Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP), a current GPS RO mission, data and the European Center for Medium-Range Weather Forecasting (ECMWF) model data. Both of these plots show a negative bias in the RO profile at and below ~3km. Fig. 8, constrained to include only the occultations occurring within the tropics, shows a much greater negative bias than does Fig. 7, which incorporates the occultations for the entire globe.
METHODS

To determine the most likely seasons and locations to be affected by SR, comparisons were made using the CDAAC analysis tools. Because COSMIC will not be launched until late 2005, CHAMP RO sounding data were used for this research. The model profiles of refractivity came from the ECMWF, were collected from the NCAR mass store system, and were used as correlative (comparison) data against the RO sounding data.

Generating Binned Refractivity Comparison Plots

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 publicly available is of a high standard.

A Perl script was provided to access the data-mining interface. The Perl script produced refractivity comparisons between the GPS RO data from the CHAMP mission and data from the ECMWF model. All CHAMP data that have been retrieved were reviewed. The regions were established by dividing the globe into 15° latitude sections. These regions were also constrained in time to include only June through August and December through February of 2001, 2002, and 2003. The latitude bands were then divided up into 19° longitude bins. All of the CHAMP occultations that occurred within the bins were combined and the refractivity differences between the CHAMP GPS RO soundings and the ECMWF data were plotted as a function of altitude and longitude after the means were interpolated across the entire latitude bands.

Different mean values were color-coded to easily illustrate areas of positive, negative, or no bias. Plots were generated that cover seasonal grid regions for the entire globe. The data-mining interface also allowed for the calculation of the standard deviation.
deviation of the refractivity comparison data sets. A count of the occultations that occurred in the seasonal latitude band were also shown. Therefore, the comparison plots illustrate the mean of the difference, the standard deviation of the difference, and the number of profiles being compared.

**Generating Refractivity Comparison Scatterplots**

In order to find a better correlation between SR and geography, scatter plots were generated also using the CDAAC data-mining interface. For these plots, the refractivities of individual occultations were compared to the ECMWF model data at 0.5km. This was to better ensure that the biases appearing in the plots were occultations that made it near the surface of the Earth and therefore were less likely due to signal tracking errors. This also ensured that the occultation soundings would experience a significant bias in the presence of SR. Only occultations that differed significantly from the model (did not agree within 4% of the model’s refractivity profiles at 0.5km) were plotted in order to make the SR regions visible in the plot. Again, the different biases were color-coded in order to illustrate areas of greater or lesser bias.

**RESULTS AND DISCUSSION**

**Binned Refractivity Comparison Plots**

Figs. 9 through 12 show several of the binned comparison plots made of the entire globe. All of the figures include plot (a) in 2001, plot (b) in 2002, plot (c) in 2003, with (CHAMP – ECMWF) mean refractivity at the top, standard deviation in refractivity in the middle, and the count of the number of occultations that were considered at the bottom. Fig. 9 incorporates occultations between August through June and 75° through 90° latitude. Fig. 10 incorporates August through June and 0° through 15° latitude. Fig. 11 includes occultations between December through February and -60° through -75° latitude band. Fig. 12 shows the results for December through February and -15° through -30° latitude. In the higher latitude plots (Figs. 9 and 11) there is very little mean error between the RO data and the ECMWF model data. In the lower latitude plots (Figs. 10 and 12) there is a higher occurrence of mean errors. The incompatibility of the Abel inversion is the likely cause for the difference because the error produces a negative bias in the lower altitudes, where a SR layer tends to lie. The negative bias begins at approximately 3km and the degree of that bias increases inversely with altitude. A positive bias is more likely to occur directly above the negative bias in the low latitude figures than in the high latitude figures, where almost no bias is seen at all.

The positive bias is not due to the effects of SR because problems with the Abel inversion do not occur until after the SR layer has caused the temporary extinction of the signal. This positive bias is most likely coming from the model itself, or from interpolation of the model to a common grid. The model may have a hard time in detecting a sharp gradient in refractivity due to its coarse resolution. It therefore might smooth the sharp layer thus causing a positive error as compared to the input data. In all of these figures are definite features that tend to occur yearly throughout plots a through c. The features that only recur yearly are highlighted by rectangles in Fig. 12.

**Refractivity Comparison Scatter plots**

The scatter plots showing refractivity differences at 0.5km altitude are shown in Figs. 13 and 14. These scatter plots were made include similar dates to the binned
Figure 9. August-June, 75° through 90°, 2001-2003 from a to c, with CHAMP – ECMWF mean refractivity at the top, standard deviation in refractivity in the middle, and count at the bottom.

Figure 10. August-June, 0° through 15°, 2001-2003 from a to c, with CHAMP – ECMWF mean refractivity at the top, standard deviation in refractivity in the middle, and count at the bottom.
Figure 11. December-February, -60° through -75°, 2001-2003 from a to c, with CHAMP – ECMWF mean refractivity at the top, standard deviation in refractivity in the middle, and count at the bottom.

Figure 12. December-February, -15° through -30°, 2001-2003 from a to c, with CHAMP – ECMWF mean refractivity at the top, standard deviation in refractivity in the middle, and count at the bottom.
Comparison plots. Fig. 13 incorporates occultations from June through August and Fig. 14 incorporates the occultations from December through February. Both include plot (a) in 2001, plot (b) in 2002, plot (c) in 2003. In these plots the midlatitude regions have the highest occurrence of negative bias. Also, there are many more negatively biased occultations that occurred over oceans than versus land. This is due to the fact that SR requires a very stable PBL and the vast oceans are more likely to meet this requirement.
than the very turbulent lower atmospheres that exist over land topography. There is also a higher occurrence of negative bias in some areas compared to others. There are very few positive biases shown on the scatter plots as compared to the great number of negative biases seen at this altitude.

Soden and Bretherton (1994) compared the ECMWF model total precipitable water (TPW) data with data taken from a Special Sensor Microwave/Imager (SSM/I). They concluded that the model had problems in predicting the dry subtropical ridges off the west coast of continents where marine stratocumulus clouds often occur. This is where dry air sinks from above and creates a sharp vertical gradient in water vapor near the top of the PBL. These are the same conditions needed for SR to occur. Their plots are shown in Figs. 15 along side the scatter plots taken from Fig. 13 c. The areas where Soden and Bretherton find the greatest model TPW bias are correlated with areas likely to have a SR layer, and are high-lighted on the scatter plots with ovals. This research shows that SR most often occurs in mid-latitude regions off the west coast of continents where marine stratocumulus clouds commonly occur.

Figure 15. Areas with a likely hood of a sharp vertical gradient in water vapor near the top of the PBL on the top plots compared to areas with a high occurrence of negative bias on the bottom plot are highlighted with an oval.
CONCLUSIONS

This research provided evidence that there are reoccurring features associated with SR. Yearly and seasonal features of SR can be seen from the binned comparison plots and the scatter plots. A negative bias tends to occur mostly in the midlatitude regions with different concentrations. A positive bias is more likely to occur directly above the negative bias in the low latitude figures than in the high latitude figures, where almost no bias is seen at all. Soden and Bretherton (1994) plots compared very well to the scatterplots that were created with this research. The areas where they find the greatest model TPW bias are correlated with areas likely to have a SR layer. Geographically, it can be concluded that SR occurs off the west coast of continents where marine stratocumulus clouds often form.
REFERENCES


