Towards New Scientific Observations from GPS Occultations: Advances in Retrieval Methods

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ABSTRACT

Atmospheric soundings using signals received in low Earth orbit from Global Positioning System (GPS) satellite transmissions are widely recognized as important data for establishing a precise climate record of upper-air temperatures, due to their self-calibrating nature and all-weather acquisition. More recently, advances in retrieval methods using the same GPS data have opened the possibility of new scientific studies related to atmospheric processes and climate change. We will present recent innovations in extracting scientifically useful information from the phase and amplitude of received GPS transmissions, and discuss the technical challenges that need to be overcome to achieve new scientific results. Promising areas being pursued include: remote sensing of the planetary boundary layer from space, important for understanding ocean-atmosphere coupling; retrieving tropopause temperature structure at high vertical resolution, important for understanding troposphere-stratosphere exchange mechanisms and the role of convection; high accuracy and precision of upper altitude (25+ km) retrievals in the stratosphere. Using an end-to-end simulator recently developed at JPL, we will investigate in realistic detail the relationship between the atmospheric state and retrieved scientific parameters, and discuss retrieval research needed to address new scientific applications.

Keywords: radio occultations, weather prediction, boundary layer, tropopause, troposphere-stratosphere exchange

1. INTRODUCTION

Global Positioning System radio occultations are active limb soundings that measure the time delay of a GPS signal propagating through the atmosphere. This delay can be related to vertical profiles of atmospheric refractivity from which highly accurate profiles of temperature, pressure, geopotential height, and specific humidity are derived. With their global coverage, self-calibrating nature, penetration through clouds, and high vertical resolution, atmospheric radio occultations are being applied to research in climate monitoring and atmospheric dynamics, and are planned for use in weather prediction with the launch of the COSMIC constellation of low-Earth orbiting GPS receivers expected in 2005.

Data from GPS receivers in low Earth orbit are being used in a number of scientific studies, but it can also be stated that the scientific potential of the data remains to be fully exploited. Given that Global Navigation Satellite Systems, such as GPS, the Russian GLONASS and the future European Galileo system, among others, are planned and will provide signals indefinitely into the future, there is a tremendous potential to exploit these signals for scientific and climate monitoring purposes. Remote sensing and retrieval research that provides information on the geophysical information content of the signals will provide useful scientific benefits for decades to come. It is important to identify the scientific questions that can be answered with the information provided by GNSS occultations, and how this information complements what is available from other observing systems.

In this paper we discuss research in retrieval methods and hardware capabilities for GPS flight receivers, occurring at NASA's Jet Propulsion Laboratory, that addresses key atmospheric science questions. The scientific content of the retrievals naturally varies with the altitude of the raypath. In the lower troposphere, refraction is affected by dry atmospheric density (temperature and pressure) and water vapor, and only marginally affected by clouds (liquid water

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and ice). The cloud penetrating nature of the observations is a unique and powerful feature compared to other remote sensing methods, although other effects such as ducting and horizontal refractivity along the raypath must be addressed to fully utilize the occultation data. In the upper troposphere boundary or tropopause region, high vertical resolution is particularly useful for revealing vertical structure that is important for regulating transport of chemical species into the stratosphere. The refractivity contribution from water vapor is negligible in this region, but under certain circumstances horizontal structure might create ambiguities for interpreting the limb measurements. Finally, in the stratosphere (altitudes 20-50km), an important area of study for climate change research and the impact of greenhouse gases and ozone, retrievals above 30 km altitude are sensitive to an upper boundary initialization that must be used in the standard retrieval process. Work is underway to minimize these dependencies and characterize the measurement errors, as well as understand the use of refractivity (atmospheric density) directly in scientific investigations, instead of temperature or pressure, to minimize the impact of temperature initialization error on retrieved temperature profiles above 30 km altitude.

In the remainder of this paper, we discuss each of these atmospheric regions and recent advances made at JPL to produce useful science products from GPS occultations. We conclude with our estimate of future remote sensing applications of GPS that show the most promise for producing new science that is aligned with the strategic goals of NASA's Science Directorate. We consider the likely contribution of the six-satellite constellation of orbiting GPS receivers, *COSMIC*, that will provide 2-3 times more data per epoch than is currently available.

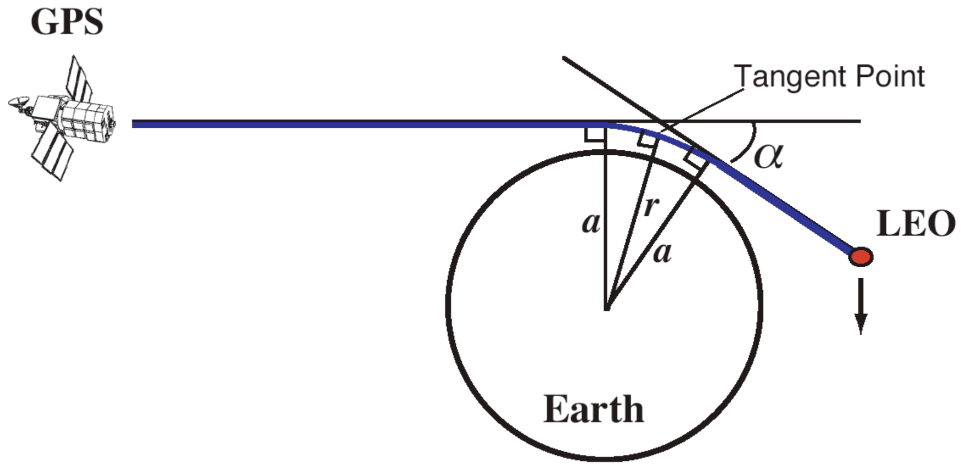

Figure 1. The geometry of GPS occultations. Atmospherically-induced signal bending (α) can be used to infer vertical profiles of temperature and pressure. Each GPS satellite transmits a signal at two frequencies (L1 and L2) to facilitate removal of ionospheric delays. a is the asymptotic miss distance or impact parameter.

2. OVERVIEW OF GPS OCCULTATION REMOTE SENSING

Using signals transmitted by the GPS constellation as the basis for an atmospheric remote sensing technique was first proposed in 1988[1]. A proof of concept experiment GPS/MET was sponsored jointly by NASA and NSF and launched in 1995 under a program run by the University Consortium for Atmospheric Research (UCAR) with receiver technology provided by NASA/JPL[2]. The CHAMP and SAC-C missions are currently operating with a modern BlackJack GPS receiver designed and built at JPL. The GRACE mission contains similar technology with occultation antennas that may be enabled for continuous operation some time in 2005. In late 2005, the COSMIC constellation is planned to launch six satellites carrying GPS receivers as a prototype weather forecasting system (described elsewhere in this issue). Other international efforts are ongoing to place GPS receivers on a variety of scientific and operational satellites, ensuring that scientific uses of Global Satellite Navigation System signals will likely be possible into the indefinite future.

The GPS constellation currently consists of 29 satellites (nominally 24 plus a few spares), distributed in six circular orbital planes at ~55° inclination, 20,200 km altitude and with a 12 hour period. Each GPS satellite continuously transmits two L-band frequencies, L1 at ~1.6 GHz (~19 cm wavelength) and L2 at ~1.2 GHz (~24.4 cm)[3]. From the perspective of the receiver, an occultation occurs whenever a GPS satellite sets behind the Earth's limb as represented schematically in Figure 1. The effect of the atmosphere on the occulted signal can be characterized by refraction-induced bending (α) of the signal which varies as a function of the impact parameter, a. The bending is inferred from the Doppler frequency shifts at the L1 and L2 frequencies, combined to remote the effect of the ionosphere, after removing the contribution of clock errors and geometrical path to the signal delay.

The bending angle profile versus altitude is transformed to yield atmospheric refractivity as a function of altitude using the Abel transform[4]. Let $n(a)$ be the refractivity at the occultation tangent point, corresponding to a trajectory with impact parameter a (see Figure 1), and let α be the bending angle caused by the refractivity variation with a. Assuming spherical symmetry near the tangent point, Bouguer's formula[5] provides the relationship between bending angle and refractivity profile:

$$\alpha(a) = -2a \int_a^\infty \frac{1}{\sqrt{a'^2 - a^2}} \frac{d\ln(n(a'))}{da'} da' \tag{1}$$

which can be inverted via the Abel transform as follows:

$$\ln(n(a)) = \frac{1}{\pi} \int_a^\infty \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} da' \tag{2}$$

Refractivity N (= $(n\text{-}1)\times 10^6$) is related to the pressure P (mbar), temperature T and water vapor partial pressure P_w according to the following formula:

$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} \tag{3}$$

where a_1 and a_2 are constants ($a_1 = 77.6$ K/mbar; $a_2 = 3.73\times 10^5$ K^2/mbar)[6]. Once the refractivity has been determined, separate temperature and pressure profiles can be derived assuming hydrostatic equilibrium (pressure increases towards the surface due to gravity). This procedure has been used for a number of years and originated as a method for interpreting planetary occultation measurements[7,8].

This relatively straightforward retrieval process depends on *a priori* assumptions. First, it requires an extrapolation of measured bending angle to the top of the atmosphere. Second an initialization pressure at an upper altitude height must be used to extract temperature and pressure profiles from the refractivity profile, under the assumption of hydrostatic equilibrium conditions. Fortunately, the exponential increase in atmospheric density with decreasing altitude tends to minimize errors in the *a priori* values at altitudes of ~30 km and below, as discussed further in this paper.

A well-known property of these retrievals is that in the lower troposphere (altitudes < ~ 5km), the contribution from the water vapor partial pressure P_w can become significant, accounting for up to ~30% of the measured refractivity in the lowest 1-2 km of the tropical troposphere. This only diminishes slightly the remote sensing value of these measurements because temperatures are fairly well-determined in this region, and the greater scientific interest is in the distribution of water vapor, to which occultations are quite sensitive. This is discussed further below.

2.1 Penetration of Cloud and Precipitation

To serve its primary function of navigation support for military operations, the GPS frequencies were chosen to provide reliable service under all weather conditions. This property is well exploited in remote sensing applications. We estimate that under extremely adverse conditions of heavy rain and cloud along the signal path, the liquid water contribution to wet refractivity of GPS is at most 10% of the contribution from water vapor[9]. The contribution from ice and other sources is even lower under nearly all conditions. Therefore, contributions to refractivity that are not due to the dry air density are due to water vapor. The physical reason that solid and liquid phases have minimal impact on the signal is the relatively low polarizability per unit mass of water molecules in condensed form, relative to vapor, at the GPS frequencies.

2.2 Requirements for Ground Data Systems

Space-based remote sensing requires the construction and operation of science data systems that transform the raw bits of satellite data into geophysically useful information for science. GPS-based remote sensing places stringent requirements on the velocity determination of the low-Earth orbiter (LEO) carrying the GPS receiver, so that non-atmospheric contributions to the Doppler shift can be calibrated. As discussed by Hajj[4], velocity accuracy of ~0.05 mm/sec is desirable. This can be achieved by using the GPS occultation receiver to provide low-rate (10 second) carrier phase and range navigation data from most GPS satellites in view, provided that precise GPS satellite orbits (cm-level accuracy) are available. Computing precise GPS orbits requires data from a globally-distributed ground network of GPS receivers, which are also used to calibrate the GPS satellite and LEO clocks in a double-differencing scheme. High-rate (one-second) receiver data was necessary to calibrate the GPS satellite clocks when "selective availability" (SA) was implemented on GPS to degrade civilian accuracies before 2001. Such high-rate ground data is probably no longer necessary since SA has been suspended[25]. However, the JPL retrieval system relies on the ground network for GPS clock calibration until the reliability of uncalibrated GPS clocks can be firmly established.

The procedure needed for an occultation ground data system is as follows[4,10]:

1. ***Data acquisition*** from the GPS receiver onboard the Low-Earth orbiter. Occultation data are acquired from the fore/aft occultation antennas and the zenith viewing antenna provides data for precise orbit determination.
2. ***Orbit determination:*** LEO orbital velocities are needed to 0.05 mm/sec accuracy or better, which requires a science-quality GPS geodetic package for orbit determination, and precise GPS orbits, which are widely available from the International GPS Service[11].
3. ***Calibration:*** the contribution of atmospheric delay on the occulting link is determined by calibrating geometrical factors and clocks. To aid this process, the receiver automatically tracks a non-occulting GPS satellite during the occultation, to difference out the receiver clock error.
4. ***Retrieval:*** The atmospheric bending is derived and converted to refractivity and moisture profiles. Information from weather analyses or climatological models are incorporated in this step to satisfy the upper boundary condition between 45-60 km altitude.

3. SOUNDING THE LOWER TROPOSPHERE

The lower 5 km of the troposphere is an important area of study for understanding weather, climate, and the water cycle. GPS retrievals of refractivity can be used to recover the water vapor content of the atmosphere, particularly in the tropics where temperatures available from analyses are generally accurate to 1.5K (1-sigma) or better[12]. Several challenges exist in this region for remote sensing from space: the effect of clouds on radiances, saturation of absorption profiles for certain molecular transitions, and sharp refractive index structures due to the planetary boundary layer or other factors. Clouds and saturation can prevent infrared and microwave radiances from providing accurate vertical profile information down to the surface, and refractivity "kinks" can be difficult to resolve directly from nadir (down-viewing) sounding without adequate *a priori* information. Since L-band radio occultations derive information from bending, not absorption spectra, there is the potential of providing new scientific information on specific humidity not available from other space-based measurements. The 10%-20% accuracy expected from occultations in the altitude range ~0-6 km is competitive with high resolution sounders such as AIRS, and is unaffected by clouds. AIRS can achieve 20% accuracy up to about 12 km altitude and microwave limb sounding (MLS on UARS and Aura) extends the measurements up through the tropopause and beyond[13].

Despite its importance, many technical challenges present themselves with coherent L-band sounding in the lowest 5 km of the atmosphere. The received signal amplitude can drop precipitously, not due to absorption, but because of signal *ducting* which occurs when vertical refractivity gradients cause the raypath bending angle to exceed the Earth's curvature. An example of amplitude reduction is shown in Figure 2, taken from [10]. Work by Hajj *et al* [10], Ao *et al* [14], Sokolovskiy[15] and others, has shown that ducting can cause a negative refractivity bias, generally leading to retrieved temperatures that are too low in the lower troposphere. The existence of this so-called *N-bias* was first detected in statistical comparisons with weather analyses such as ECMWF and NCEP.

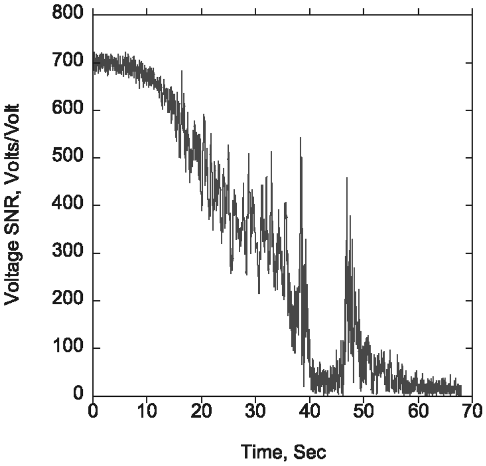

Figure 2: Signal to noise ratio versus time after start of a radio occultation showing amplitude fading the planetary boundary layer (~40 seconds).

The recent work of Ao *et al.*[14] has provided insight into how biases arise relative to the analyses. There are two principal causes: receiver tracking error, and retrieval error from application of the Abel transform to a bending angle profile affected by ducting. In their simulation study, Ao *et al.* computed the retrieved refractivity assuming a perfect receiver that recovers signal phase exactly, and a retrieval assuming the (imperfect) tracking algorithms that are currently implemented on the SAC-C and CHAMP flight receivers. The simulations confirmed that with the current receiver algorithms, a significant fraction of the bias is due to receiver tracking error. JPL is currently developing technology for recovering signal phase that is well suited to the lower troposphere.

3.1 Receiver Tracking Strategies

The different carrier-phase recovery strategies that have been used in the JPL GPS receivers are summarized in Table 1. The strategies differ in how they generate a prediction, or model, of the received signal phase for cross-correlation within the receiver. The simplest method is closed loop tracking, which generates predicted phase based on extrapolating recently measured phase values obtained at a 20 millisecond period or faster, and works well at relatively high signal-to-noise ratio (SNR) such as occurs in the stratosphere and upper troposphere. The receivers also implement "flywheel" tracking, where a phase prediction is generated during periods of low SNR as the signal enters the lower troposphere ducting region. The prediction is based on extrapolating the phase measured just prior to amplitude decrease. Finally, a newer technology known as "open loop" tracking is most robust because it generates an accurate phase model from real-time information about the relative GPS and LEO position, obtained from the zenith viewing antenna. Therefore, the open loop phase model is not affected by low SNR.

Hajj *et al.*[4] discusses how the "open loop" model can predict atmospheric Doppler shifts with better than 10-Hz accuracy based largely on geometrical considerations. Figure 3 shows the strong linear relationship between atmospheric bending angle and GPS to LEO geocentric separation angle. This relationship holds for satellites with nearly circular orbits such as CHAMP and SAC-C, although the slope varies with satellite altitude. Open loop tracking requires real-time computation of the separation angle in the receiver. Initial tests of open-loop tracking have been performed on the SAC-C spacecraft with encouraging results and will be reported in another publication.

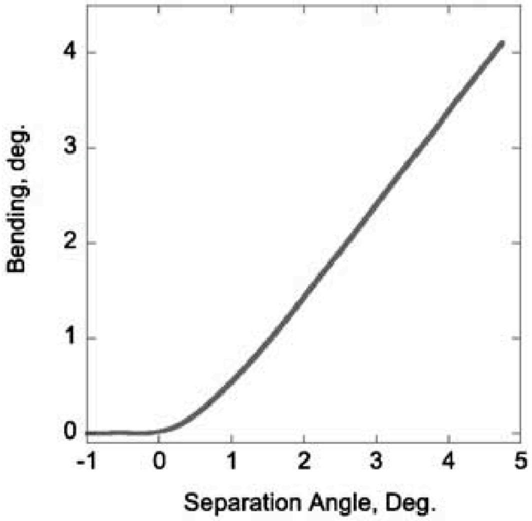

Figure 3: Measured bending angle versus geocentric separation angle between LEO and GPS satellite, showing the strong linear relationship.

The study by Ao *et al.*[14] suggests that open-loop tracking will reduce refractivity biases to about 1%. This is shown in Figure 4 which is derived from a simulation based on 24 occultations. The average refractivity derived from the "flywheeling" tracking approach is indicated by the solid line, and is biased due largely to several "outlier" retrievals where the extrapolated model phase is significantly in error from the simulation ground truth. When receiver error is removed from the simulations (right panel), the bias is reduced to less than 1%. This latter case should correspond closely to the case of open loop. Reducing the bias still further from this level will require retrieval advances that do not use the Abel inversion, which is an area of further research[10].

Table 1: Occultation receiver tracking strategies

Tracking Method	Algorithm	Advantages	Disadvantages
Closed loop	Continuously adjust phase predict based on last few phase measurements	• Low computational burden • Effective over a wide range of altitudes, excepting the lower troposphere	• Might not update rapidly enough under conditions of rapidly varying phase • Ineffective when signal becomes weak in lower troposphere (below ~5 km altitude)
Flywheeling	Extrapolate closed-loop phase predict when signal becomes too weak for loop closure	• Low computational burden • Allows tracking of many lower troposphere signals	• Substantial tracking and retrieval errors occur unpredictably
Open loop	Generate phase predict based on relative receiver/transmitter geometry	• Tracking maintained under low signal conditions • Should work well in lower troposphere	• Somewhat higher computational complexity

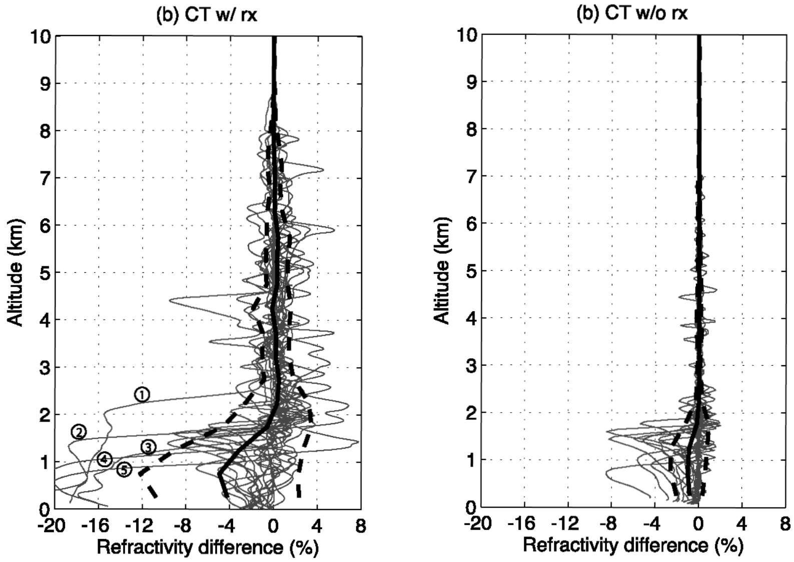

Figure 4: Simulation results for two cases: assuming a receiver implementing "fly-wheel" tracking (left) and for a "perfect" receiver (right).

3.2 Towards Detection of the Planetary Boundary Layer From Space

A strong scientific motivation for lower troposphere tracking is the possibility of extracting water vapor in the lower few km of the atmosphere, entrained within the planetary boundary layer where atmospheric conditions may provide information on ocean-atmosphere coupling[16]. Recent work on lower-troposphere retrievals shows that the amplitude of GPS signals is very sensitive to the large vertical refractivity gradients found in or near the boundary layer. Amplitude variations are caused by diffractive interference, not from absorption or scattering. This sensitivity can be exploited as a remote sensing technique that determines the geometric height of the largest refractivity gradients, which may be related to the specific humidity at the top of the boundary layer.

An example of a lower troposphere retrieval from the CHAMP satellite is shown in Figure 5, from Hajj *et al.*[17]. The rightmost panel shows the decreasing voltage signal-to-noise ratio as the occulting ray descends into the atmosphere. The amplitude recovers after a period of near total signal loss starting at 50 seconds, indicating the presence of strong bending and the onset of signal ducting. In the leftmost figure is plotted retrieved refractivity and its derivative versus altitude, for the GPS measurements and a weather analysis interpolated to the occultation location (ECMWF model). The data capture well the abrupt change in lapse rate associated possibly with the boundary layer, but the height of this change differs markedly from the analysis. This indicates the potential for GPS occultations to better characterize this region of the atmosphere where moisture content plays a major role in large scale climate signatures and the El Nino phenomenon.

Further evidence of the remote sensing possibility of these data are shown in Figure 6. A filter was applied to CHAMP and SAC-C data, and only those retrieval locations are plotted where the refractivity derivative with respect to altitude exceeds a large magnitude ($dN/dz < -70$) at some altitude in the retrieval. Profiles satisfying this criterion are plotted, revealing oceanic coverage almost exclusively, strongly suggesting that occultations can retrieve the properties of moist air in the boundary layer. Research at JPL is ongoing to relate quantitatively the retrieved refractivity profile and physical processes occurring in the boundary layer over oceans.

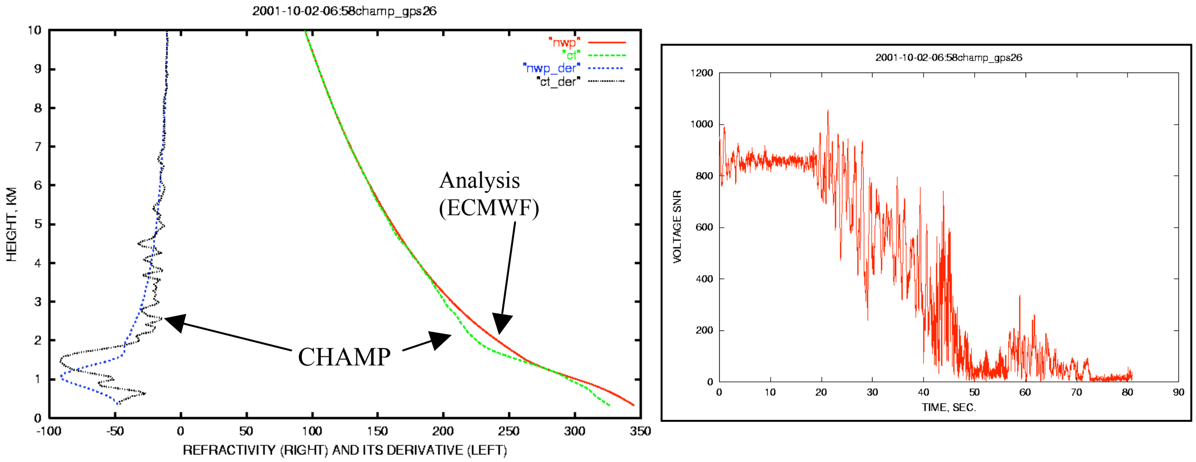

Figure 5: Refractivity and its derivative versus height for a CHAMP occultation on October 2, 2001 and the corresponding analysis values (left); corresponding voltage signal-to-noise ratio versus time. (right).

4. SOUNDING THE TROPOPAUSE

The tropopause, broadly defined, is the region of the atmosphere that bounds the stratosphere from below and the troposphere from above. It is of great interest scientifically because the properties of the tropopause have a large influence on the chemistry of the stratosphere via the mechanism of troposphere-stratosphere exchange. In addition, tropopause properties are affected by the large scale Brewer-Dobson circulation where upwelling of air from the tropical upper troposphere enters the stratosphere and circulates poleward, eventually downwelling in the middle and high latitudes, affecting important stratospheric chemical processes, such as ozone loss. Cold point tropopause temperatures may be a useful diagnostic of vertical transport processes such as deep convection[18].

Remote sensing the tropopause from space is a challenge, because it is a region where temperature lapse rates vary significantly over 1-2 kilometers in altitude, often affecting the accuracy of inversion algorithms from nadir-viewing sounders. GPS, as a diffraction-limited limb sounding measurement, is theoretically capable of vertical resolutions less then 1 km near the tropopause, but interpretation of data at such high resolution is not straightforward due to the possibility of horizontal structure along the raypath. Nevertheless, the following argument can be used that suggests sub-km vertical resolution is easily achieved near the tropopause. Assume that the tropopause is defined based on the World Meteorological Organization's definition: the altitude where the lapse rate decreases to the value of –2 K/km (it is higher at lower altitude and lower in magnitude near the cold-point). Based on the simulation study of Foelsche and Kirchengast using realistic atmospheric structures[19], horizontal structure could result in temperature errors up to 0.3 K at altitudes that typically include the tropopause region. At the lapse rate corresponding to the WMO tropopause definition, this temperature uncertainty corresponds to a height uncertainty of about 150 m, well below the diffraction limit of the observations. Assuming that the tropopause height does not change dramatically along the occultation raypath (~300 km extent), we can expect that under most conditions diffraction-limited resolution can be readily achieved near the tropopause.

Exceptions to this argument will occur when temperature lapse rates near the tropopause are strongly modified by local atmospheric phenomena such as a weather front. In such cases, interpreting the GPS profiles as having sub-km resolution at the occultation tangent point may not be accurate. An interesting GPS retrieval obtained near the location of a tropical storm is shown in Figure 7, along with three radiosondes profiles separated by 390 km obtained at 12-hour intervals (radiosonde temperatures are shifted for clarity). A very sharp tropopause structure is recovered by GPS using the diffraction method (canonical transform), which the last radiosonde appears to be recovering. This example demonstrates the sensitivity of coherent L-band remote sensing to temperature structure near the tropopause, although the interpretation of the measurements in the presence of such sharp, possibly localized features requires further study.

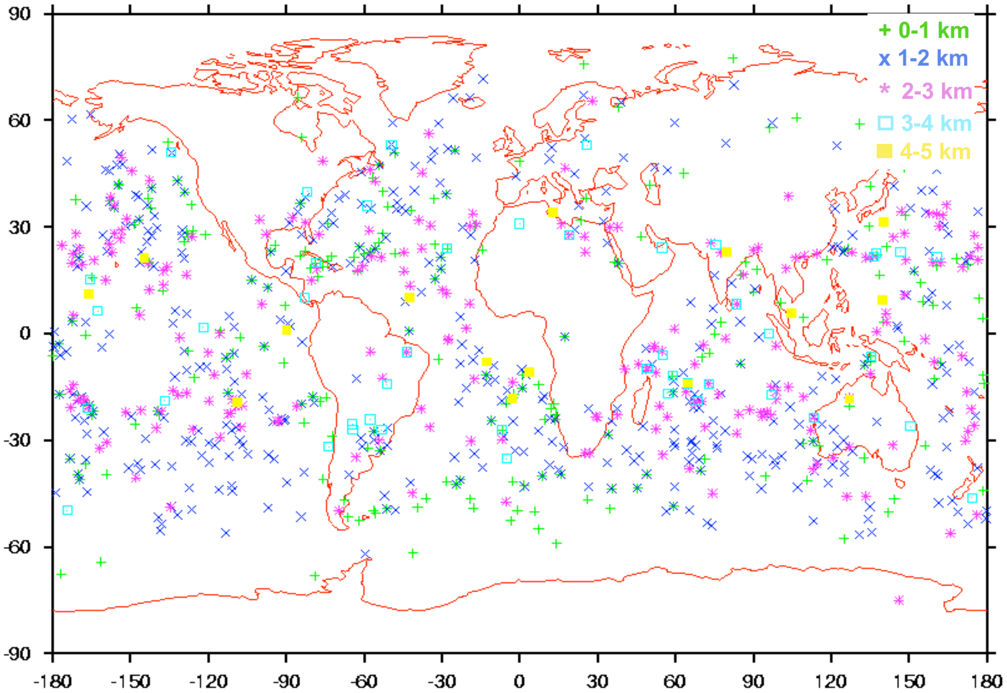

Figure 6 Locations of CHAMP occultations in October 2001 that satisfy the criterion dN/dz < -70, and corresponding altitude where the criterion is satisfied.

It is generally acknowledged that temperature retrievals from nadir sounders have reduced vertical resolution near the tropopause, and recent published research has focused on improving the information content of passive sounding using active temperature sounding[20,21]. A comparison between a GPS occultation and a high-latitude AIRS retrieval is shown in Figure 8, where the high vertical resolution of GPS recovers a tropopause temperature that is lower than a nearby AIRS retrieval by up to 5 K. This example may illustrate that, in situations where tropopause temperature features are particularly sharp, the high vertical resolution of GPS can provide valuable scientific information that augments nadir sounder data, particularly for studies of troposphere-stratosphere exchange and other process studies. Work by Ao *et al.*[22], and others, suggests that cold point tropopause temperatures are often over-estimated by weather analyses such as ECMWF (note this occurs in the example of Figure 7). However, a tendency to overestimate CPT temperatures does not uniformly appear in large scale statistical comparisons between GPS and weather analyses[10,23], possibly because the number of profiles with sharp tropopause features may be insufficient to affect the average. On the other hand, Randel *et al.*[18] report that in an altitude region near the tropical tropopause (100 hPa pressure level) two standard reanalyses tend to underestimate other temperature observations by 1-3K. Further work is needed to resolve the somewhat discrepant nature of these studies, but it is clear that GPS observations are playing an important role in establishing the global behaviour of the tropopause.

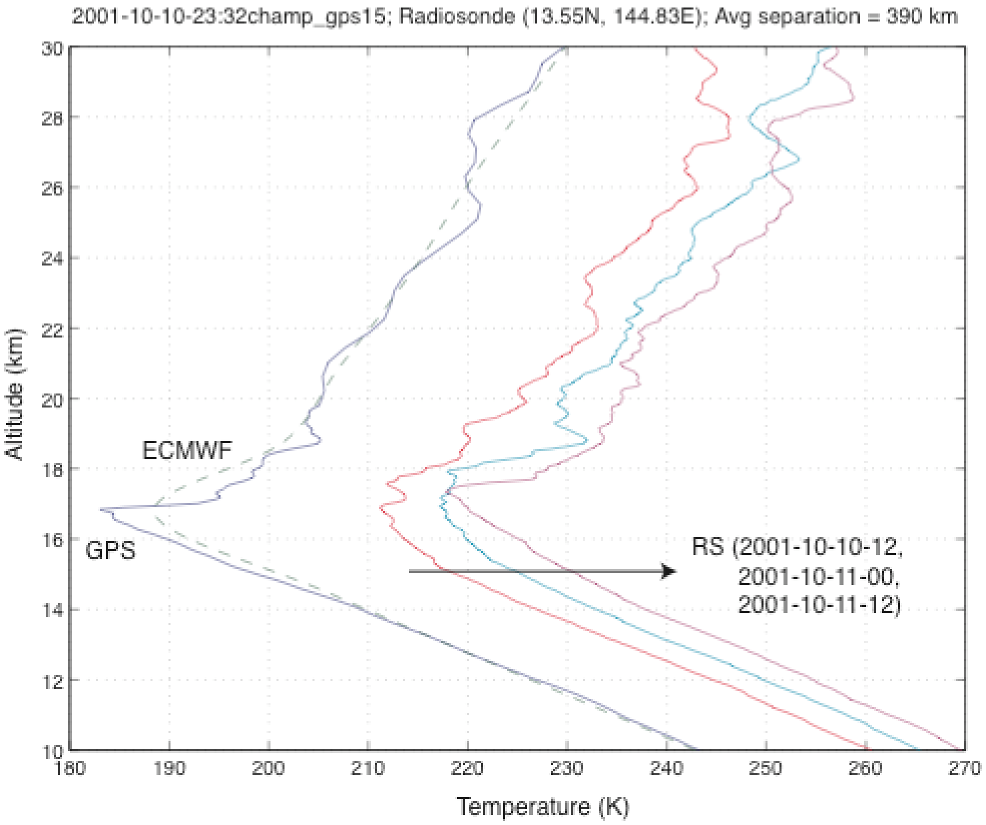

Figure 7: Occultation from the CHAMP satellite on October 10, 2001 obtained near a tropical storm, showing exceptionally sharp temperature structure. Also shown to the right are nearby radiosondes (average separation 390 km), shifted for clarity.

5. SOUNDING THE STRATOSPHERE

GPS occultations can be used to make precise and accurate measurements of the stratospheric temperature and density (refractivity), useful for long-term climate monitoring and detecting temperature trends from greenhouse gas forcing. Stratospheric temperatures in the polar regions are an important determining factor for the formation of polar stratospheric clouds, which regulate the ozone budget.

Accurately extending the retrievals to altitudes greater than 30 km is challenging and requires careful evaluation of the alternative retrieval algorithms. In general, the signal-to-noise ratio (SNR) decreases with altitude as the decreasing atmospheric density produces less bending, so that systematic and thermal noise sources become more dominant. On the other hand, there is generally less horizontal structure at these altitudes and water vapor contributes a negligible amount to the refractivity. Retrievals in the stratosphere are potentially affected by two algorithm choices: 1) an *a priori* bending angle profile that extends the measured bending upward towards the top of the atmosphere, necessary for the Abel transform (Equation 2); and 2) a temperature or pressure initial value defined at an upper altitude level, so that temperature profiles can be retrieved from refractivity by use of the hydrostatic integral. Current research suggests that below 30 km altitude, the retrieved refractivities are nearly insensitive to reasonable choices for upper altitude bending, but temperature profiles near 30 km and higher altitude are affected by temperature initialization error.

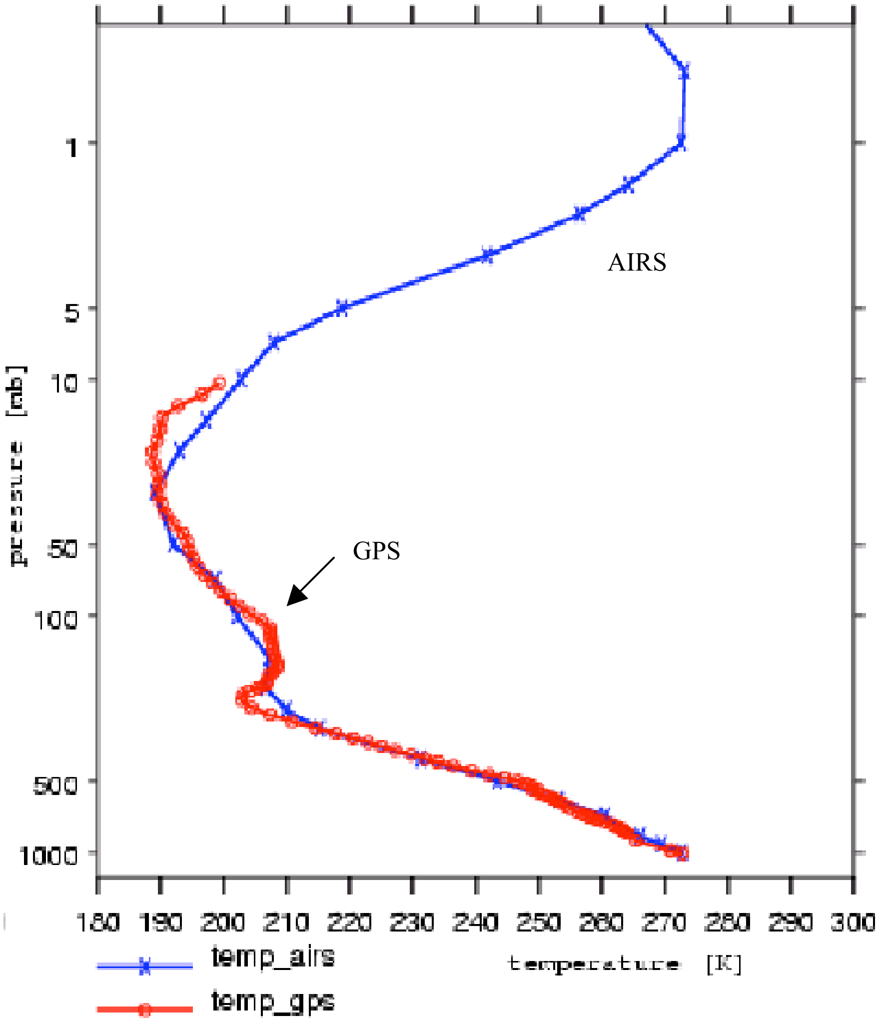

Figure 8: GPS and AIRS temperature retrieval comparison observed at high latitude (68N). The retrievals are separated by 0.5 degrees and 34 minutes.

Ao *et al.*[24] performed a detailed simulation study of the impact of upper boundary conditions on the Abel transform inversion considering two methods for initialization: using a climatological model to initialize the bending at upper altitudes; and extrapolating the bending angle upwards assuming an exponential decay of angle with altitude, which corresponds to an isothermal atmosphere. The ground-truth refractivity and temperature for the simulation was provided by 156 Lidar measurements obtained over Hawaii.

Refractivity results from this study are shown in Figure 9 (see also [10]). Initialization using extrapolation appears somewhat more accurate than climatology in the mean, but with increased scatter (not shown), assuming 60 km initial altitude. A statistical analysis of the data showed climatology-based retrievals are less susceptible to occasional large outliers compared to exponential extrapolation. It is clear that the influence of the initialization procedure decays with altitude so that GPS refractivity retrievals are relatively insensitive to the initialization assumptions below 30 km. For higher altitudes, further research is needed to determine the best way of initializing profiles. For temperature retrievals (not shown), which require an initial temperature value at some height (e.g. 50 km), the errors were still significant at 30 km altitude.

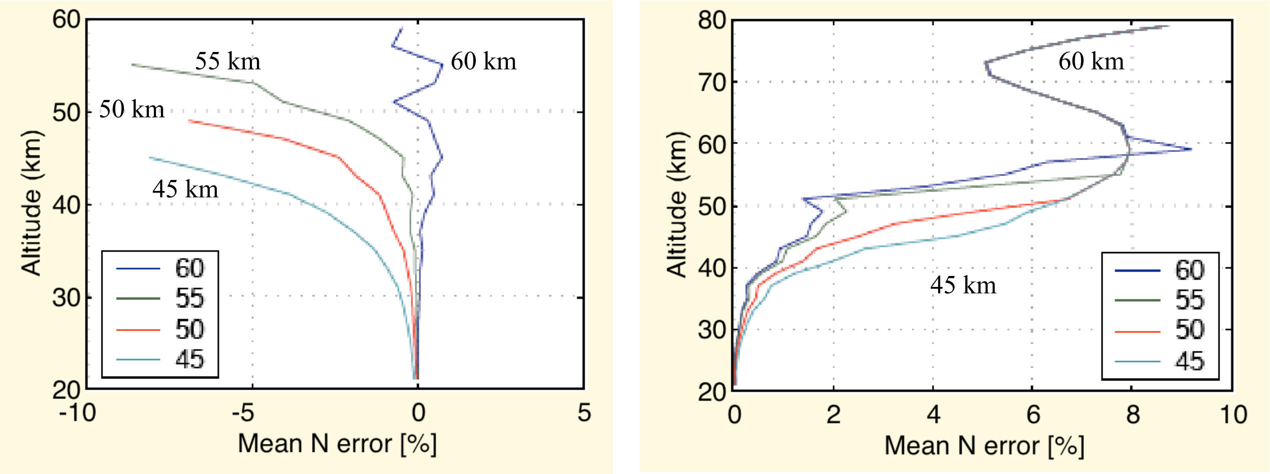

Figure 9: Errors reported in the simulation study of Ao *et al.*[24] for different initialization strategies and altitudes: extrapolation (left) and climatology (right).

Since the stratosphere is an area of study for global warming and climate change, there is scientific benefit to finding the correct initialization procedures for occultation profiles. Although initialization based on climatology may be somewhat more robust, it is worthwhile to pursue model-free approaches because these may be less susceptible to systematic biases that are known to be present in climatologies (e.g. biases may vary seasonally and interannually). A promising approach is a more robust form of extrapolation that relaxes the isothermal assumption. It is worth considering what science can be accomplished using refractivity data directly, without conversion to temperature, since this would eliminate the error due to initializing the hydrostatic integral.

6. CONCLUSIONS AND PROSPECTS

In this paper, we have discussed technologies being developed to improve the scientific return from GPS occultation remote sensing. The unique scientific contribution of GPS must be understood in the context of other space-based measurements, ground-based measurements, and the global weather analyses such as NCEP and ECMWF. At the current time, the following contributions have been identified:

- Lower-troposphere refractivity structure down to the surface and in the presence of clouds, providing information on the oceanic planetary boundary layer that is possibly important for understanding certain aspects of ocean-atmosphere coupling. GPS estimates of water vapor in the presence of clouds and heavy rain will provide important information on feedback mechanisms influencing climate change.
- Accurate tropopause temperature retrievals, for improved understanding of troposphere-stratosphere exchange, variability of the tropopause due to processes such as planetary waves and convection, and how these processes modulate tropopause structure and therefore the humidity and other chemistry of the stratosphere.
- Upper atmosphere temperature or density profiles can be used to develop truly global gravity-wave climatologies, responsible for driving stratospheric circulation patterns and how these change over time.
- Establishing a long-term mid-to-upper atmosphere temperature record free of intersatellite biases.

In the near future, GPS will be used in a prototype operational system for weather prediction based on the COSMIC constellation of six satellites which launches in late 2005 (see Kuo *et al.*, this volume). This constellation will also lead to a wealth of new scientific data that can address the scientific questions mentioned above. With careful planning, a continous series of signal bending data based on GPS could be available as a resource to discern minute, ~0.1 Kelvin trends in atmospheric profiles over time periods of several years to decades. As receiver accommodation costs decrease, it is likely that GPS-based remote sensing in the atmosphere will be a permanent feature of the remote sensing toolkit, useful for tracking atmospheric process changes and climate changes over the coming decades, and for augmenting other sounding techniques, such as passive infrared, to improve their utility.

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REFERENCES

1. T. P. Yunck, G. F. Lindal, and C. H. Liu, "The role of GPS in precise earth observation," paper presented at the *IEEE Position, Location and Navigation Symposium*, Inst. of Electr. and Electron. Eng., Orlando, Fla., 29 Nov. to 2 Dec 1988.
2. R. Ware, (1996), "GPS sounding of the atmosphere from low Earth orbit: Preliminary results," *Bull. Am. Meteorol. Soc*., 77(1), 19– 40, 1996.
3. J. J. Spilker, "GPS signal structure and theoretical performance," in *Global Positioning System: Theory and Applications,* vol. I, B. W. Parkinson, J. J. Spilker Jr., Eds. Washington D.C.: American Institute of Aeronautics and Astronautics**,** pp. 57-119, 1996.
4. G. A. Hajj, E. R. Kursinski, L. J. Romans, W. I. Bertiger, and S. S. Leroy, "A technical description of atmospheric sounding by GPS occultation," *J. of Atmos. and Solar-Terr. Phys.*, **64**, pp. 451-469, May 2002.
5. M. Born and E. Wolf, *Principles of Optics, 6th Edition*, Pergamon Press, Tarrytown, New York, 1980.
6. G.D. Thayer, "Improved Equation for Radio Refractive-Index of Air," *Radio Science*, 9 (10), pp. 803-807, 1974.
7. G. Fjeldbo and V. R. Eshleman, "Atmosphere of Venus as studied with the Mariner 5 dual radio-frequency occultation experiment," *Radio Sci*., **4**, pp. 879-897, 1969.
8. G. Fjeldbo, V. R. Eshleman, and A. J. Kliore, "The neutral atmosphere of Venus as studied with the Mariner V radio occultation experiments," *Astron. J.,* **76***,* pp. 123-140, 1971.
9. F. S. Solheim, J. Vivekanandan, R.H. Ware, and C. Rocken, "Propagation delays induced in GPS signals by dry air, water vapor, hydrometeors, and other particulates," *Journal of Geophysical Research-Atmospheres*, 104 (D8), pp. 9663-9670, 1999.
10. G. A. Hajj, C.O. Ao, B.A. Iijima, D. Kuang, E.R. Kursinski, A.J. Mannucci, T.K. Meehan, L.J. Romans, M.D. Juarez, and T.P. Yunck, "CHAMP and SAC-C atmospheric occultation results and intercomparisons," *Journal of Geophysical Research-Atmospheres*, 109 (D6), art. no.-D06109, 2004.
11. J.F. Zumberge and G. Gendt, "The demise of selective availability and implications for the International GPS Service," *Physics and Chemistry of the Earth Part a-Solid Earth and Geodesy*, 26 (6-8), pp. 637-644, 2001.
12. E.R. Kursinski and G.A. Hajj, "A comparison of water vapor derived from GPS occultations and global weather analyses," *Journal of Geophysical Research-Atmospheres*, 106 (D1), 1113-1138, 2001.
13. W.G. Read, D.L. Wu, J.W. Waters, and H.C. Pumphrey, "A new 147-56 hPa water vapor product from the UARS Microwave Limb Sounder," *Journal of Geophysical Research-Atmospheres*, 109 (D6), 2004.
14. C. O. Ao, T.K. Meehan, G.A. Hajj, A.J. Mannucci, and G. Beyerle, "Lower troposphere refractivity bias in GPS occultation retrievals," *Journal of Geophysical Research-Atmospheres*, 108 (D18), 2003.
15. S. Sokolovskiy, "Effect of superrefraction on inversions of radio occultation signals in the lower troposphere," *Radio Science*, 38 (3), 2003.
16. J.D. Farrara, J.D. and J.Y. Yu, "Interannual variations in the southwest US monsoon and sea surface temperature anomalies: A general circulation model study," *Journal of Climate*, 16 (11), pp. 1703-1720, 2003.
17. G. Hajj, C. Ao, B. Iijima, E.R. Kursinksi, T. Meehan, M. de la Torre-Juarez, "Remote Sensing of the Planetary Boundary Layer by GPS Occultations," Presented at the American Meteorological Society Meeting, Long Beach, California, February 2003.
18. W.J. Randel, F. Wu, S.J. Oltmans, K. Rosenlof, and G.E. Nedoluha, "Interannual changes of stratospheric water vapor and correlations with tropical tropopause temperatures," *Journal of the Atmospheric Sciences*, 61 (17), pp. 2133-2148, 2004.

19. U. Foelsche and G. Kirchengast, "Sensitivity of GNSS radio occultation data to horizontal variability in the troposphere," *Physics and Chemistry of the Earth*, 29 (2-3), pp. 225-240, 2004.
20. E. Borbas, W.P. Menzel, J. Li, and H.M. Woolf, "Combining radio occultation refractivities and IR/MW radiances to derive temperature and moisture profiles: A simulation study plus early results using CHAMP and ATOVS," *Journal of Geophysical Research-Atmospheres*, 108 (D21), art. no.-4676, 2003.
21. A.D. Collard and S.B. Healy, "The combined impact of future space-based atmospheric sounding instruments on numerical weather-prediction analysis fields: A simulation study," *Quarterly Journal of the Royal Meteorological Society*, 129 (593), pp. 2741-2760, 2003.
22. C. Ao, G. A. Hajj, B. A. Iijima, M. de la Torre-Juarez, A. J. Mannucci, *Eos Trans. AGU*, 83 (47),Fall Meet. Suppl., Abstract A71D-0132, 2002.
23. T. J. Schmidt, Wickert, G. Beyerle, and C. Reigber, "Tropical tropopause parameters derived from GPS radio occultation measurements with CHAMP," *Journal of Geophysical Research-Atmospheres*, 109 (D13), 2004.
24. C. Ao, G. A. Hajj, B. A. Iijima, A. J. Mannucci, T. M. Schrøder, M. de la Torre Juarez, S. S. Leroy, "Sensitivity of Stratospheric Retrievals from Radio Occultations on (Abel) Upper Boundary Conditions," Presented at the *2nd International Workshop on Occultations for Probing Atmosphere and Climate (OPAC-2)*, September 13-17, Graz, Austria, 2004.
25. J. Wickert, G. Beyerle, G.A. Hajj, V. Schwieger, and C. Reigber, GPS radio occultation with CHAMP: Atmospheric profiling utilizing the space-based single difference technique, Geophysical Research Letters, 29 (8), art. no.-1187, 2002.