Atmospheric sounding using GPS radio occultation

RICHARD A. ANTHES, YING-HWA KUO, CHRISTIAN ROCKEN

and

WILLIAM S. SCHREINER

University Corporation for Atmospheric Research,
Boulder, Colorado, 80307, U.S.A.

email: anthes@ucar.edu

ABSTRACT. This paper summarizes the radio occultation (RO) technique for remote sounding of the Earth’s atmosphere using the Global Positioning System (GPS) satellites and GPS receivers on low-Earth orbiting (LEO) satellites. As the LEO satellites rise and set with respect to the GPS satellites, the radio waves from the GPS satellites are refracted by the Earth’s atmosphere. Precise measurements of the bending angle of the radio waves are used to derive vertical profiles of atmospheric refractivity, which is a function of electron density in the ionosphere and temperature and water vapor in the stratosphere and troposphere.

Results from the GPS/MET, CHAMP, and SAC-C RO missions are summarized, and examples of soundings are presented. Analysis of the CHAMP and SAC-C data indicates that approximately 45% of CHAMP and SAC-C retrieved radio occultation profiles reach below 1 km altitude, compared to only 35% for GPS/MET. All missions exhibit a negative refractivity bias in the lower troposphere of between 1% and 2% compared to NWP models. When constrained to the tropics, only about 20% of the CHAMP occultation profiles reach 1 km from the surface.

Taiwan’s National Space Program Office (NSPO), the University Corporation for Atmospheric Research (UCAR), the Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), and many partners in the university community are developing COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate), a
follow-on project for weather and climate, space weather, and geodetic science. COSMIC plans to launch six satellites in 2005. Each satellite will retrieve 400-500 daily profiles of key ionospheric and atmospheric properties from the tracked GPS radio signals as they are occulted behind the Earth limb. The radio occultation sounding data from COSMIC will contribute significantly to atmospheric research, weather forecasting, and climate modeling.

Key words – Radio occultation, Remote sensing, Atmospheric sounding, Global Positioning System, COSMIC.

1. Introduction

The Global Positioning System (GPS) satellite constellation was developed for precise navigation and positioning. The GPS today consists of 24 operational satellites that transmit L-band radio signals to a wide variety of users in navigation, time transfer, and relative positioning and for an ever-increasing number of scientists in geodesy, atmospheric sciences, oceanography, and hydrology.

Atmospheric soundings are obtained using GPS through the radio occultation (RO) technique, in which satellites in low-Earth orbit (LEO), as they rise and set relative to the GPS satellites, measure the phase of the GPS dual-frequency signals. From this phase the Doppler frequency is computed. The Doppler shifted frequency measurements are used to compute the bending angles of the radio waves, which are a function of atmospheric refraction. The refractivity is a function of electron density in the ionosphere and temperature, pressure, and water vapor in the stratosphere and troposphere.

This paper summarizes the RO technique and the results from the GPS/MET experiment, which was carried out in 1995-1997 and demonstrated for the first time the successful application of the RO method for sounding the Earth’s atmosphere (Ware et al., 1996). The recent CHAMP (Kramer, 2002; Reigber et al., 2001) and SAC-C (Kramer, 2002) missions have extended the successful results of GPS/MET. We show statistical results from the CHAMP and SAC-C missions and compare them to the statistics from the GPS/MET mission. We also show some individual soundings from CHAMP and SAC-C through a typhoon near Taiwan, gravity waves in the tropics, and a monsoon depression over India.

2. The GPS RO technique

A detailed discussion of the GPS RO observations and data processing may be found in a number of papers. See, for example, Melbourne et al. (1994), Hocke (1997), Hoeg et al. (1996), Kursinski et al. (1996,1997), Rocken et al. (1997), and Hajj et al. (2002). The March 2000 special issue of Terrestrial, Atmospheric and Oceanic Sciences (TAO, 2000) contains a number of articles describing the history of GPS sounding and the RO technique. Therefore, we only provide a brief summary here. Each of the GPS satellites continuously transmits signals at two frequencies, L1 at 1.57542 GHz (~19 cm) and L2 at 1.2276 GHz (~24.4 cm). In a GPS occultation, the GPS receiver on a LEO satellite tracks the occulted signals from a GPS satellite whenever a GPS satellite rises or sets behind the Earth (Fig. 1). Atmospheric refractivity affects the phase and amplitude of the radio waves. If we consider wave propagation in terms of rays (Fig. 1), then the effect of the atmosphere can be characterized by the total bending angle \( \alpha \) as a function of the impact parameter, \( a \), which are derived from the measurements of the phase and amplitude of the received signal and precise knowledge of the LEO and GPS positions and velocities.

The vertical profile of \( \alpha \) as a function of the impact parameter \( a \) is inverted into a refractivity profile by assumption of spherical symmetry and use of an Abelian transformation (Fjeldbo et al., 1971) given by:

\[
\ln[n(a)] = \frac{1}{\pi a} \int_0^a \frac{a'(a')}{\sqrt{a'^2 - a^2}} da'
\]

(1)

Refractivity \( [N = (n-1) \times 10^6] \) is related to atmospheric pressure, \( P \), temperature, \( T \), water vapor partial pressure, \( P_v \) and electron density, \( n_e \), through

\[
N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \left( \frac{P_v}{T^2} \right) - 40.3 \frac{n_e}{f^2}
\]

(2)

where \( f \) is the signal frequency. At altitudes of 90 km and above, the pressure and water vapor terms are negligible, and the observed refractivity is directly proportional to the electron density in the ionosphere. In the stratosphere and the upper regions of the troposphere where \( T < 240K \), the water vapor contribution to refractivity is negligible, and refractivity is proportional to density via the ideal gas law (after removal of the ionospheric contribution using the dual GPS frequencies).

† The number of soundings depends on the LEO orbit, the number of GPS satellites, and the field of view and gain of the RO occultation antennas that are flown. For COSMIC we expect about ~400 soundings per day per satellite to fall within the high-gain field of view of the antennas. Additional, lower quality soundings and ionospheric soundings will be tracked outside this field of view.
Density, in turn, yields pressure through the assumption of hydrostatic equilibrium and a boundary condition on pressure at an initial height (~60 km). Applying the gas law once more, density and pressure yield temperature. In the warmer regions of the troposphere, water vapor can contribute as much as 30% to refractivity and can locally dominate the vertical refractivity gradients and bending near the surface, particularly at low latitudes.

3. Summary of results from GPS/MET

The GPS/MET program (Ware et al., 1996) was established by UCAR in 1993, jointly with the University of Arizona and the JPL, to demonstrate for the first time active limb sounding of the Earth’s neutral atmosphere and ionosphere using the RO technique. Launched on a LEO satellite MicroLab-1 on April 3, 1995, the GPS/MET program collected soundings for two years. GPS/MET demonstrated the high accuracy (~1 °C) and high vertical resolution (~500m) of the RO technique and has been used to study upper-level fronts (Kuo et al., 1998), the tropopause, upper-level water vapor climatology, polar meteorology, stratospheric gravity waves and electron density profiles in the ionosphere (Anthes et al., 2000). Observing system simulation experiments and assimilation of actual GPS/MET data have indicated that the assimilation of RO soundings is likely to have a positive impact on numerical weather prediction (Kuo et al., 2000a).

4. COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate)

The success of the GPS/MET experiment has led to a joint Taiwan-U.S. mission that will launch a constellation of six satellites in 2005. As described by Rocken et al. (2000) and Kramer (2002), each spacecraft will carry three payloads: (1) a GPS RO receiver designed by JPL; (2) a Tiny Ionospheric Photometer (TIP); and (3) a Coherent Electromagnetic Radio Tomography (CERTO) Tri-Band Beacon (TBB) transmitter, both designed by the Naval Research Laboratory (NRL).

### Table 1

| Characteristics of COSMIC Data |
|--------------------------------|
| Limb sounding geometry complementary to ground and space nadir viewing instruments |
| High accuracy |
| High vertical resolution |
| Consistency of horizontal and vertical scales of observations (Lindzen and Fox-Rabinovitz, 1989) |
| All weather – minimally affected by clouds, aerosols, or light precipitation (Solheim et al., 1999) |
| Independent height and pressure |
| Requires no first guess sounding |
| Independent of radiosonde or other calibration |
| No instrument drift |
| No satellite-to-satellite bias |

4.1. Summary of COSMIC and applications of COSMIC data to meteorology and climate

The characteristics of COSMIC data and their relevance to meteorology (including weather prediction) and climate are summarized in Table 1. Their unique characteristics will make COSMIC data highly complementary to other observing systems. ESA (1996), Hoeg et al. (1996), and Melbourne et al. (1994) provide excellent discussions of the potential value of RO data for meteorological and climate research and operations. Anthes et al. (2000) summarize the applications of COSMIC to meteorology and climate.

With a total of 2400-3000 soundings per day distributed over the globe, COSMIC will provide additional independent (from other observations such as from radiosondes or other satellites) data over the entire Earth. The high vertical resolution, accurate, and independent COSMIC data will complement data from geostationary (Menzel et al., 1998) and polar-orbiting satellites, which provide high horizontal but low vertical resolution soundings. The average horizontal spacing of the daily soundings varies with latitude; the spacing is least near the poles (approximately 300-400 km) and greatest at the Equator (approximately 600-700 km).

For climate research and monitoring COSMIC will provide an accurate global thermometer that will monitor Earth’s atmosphere in all weather with unprecedented long-term stability, resolution, coverage, and accuracy. COSMIC will provide an accurate data set for the detection of climate variability and change, the calibration of other satellite observing systems, and the verification and improvement of climate models.
4.2. **COSMIC system overview**

The payload data will be transmitted after each 100-minute orbit in near real time (via two northern Earth stations) to the COSMIC Data Analysis and Archive Center (CDAAC) at UCAR in Boulder, CO. The CDAAC will analyze the GPS RO data and make it available in near real time (within three hours of observation on average) to operational weather centers, universities, and research institutions.

The orbit constellation for the COSMIC mission during the operational phase (the second year) is still undergoing trade studies. The six COSMIC satellites will be launched by a Minotaur rocket into one orbital plane and will then be separated in local time throughout the first year to reach the operational phase configuration. The optimal operational constellation for COSMIC science would consist of six satellites in six orbital planes (with altitudes of 800 km and inclination angles of 72°) separated by 30 degrees in right ascension of ascending node (with a two-hour local time separation). This configuration would provide global coverage every 100-minute orbit. This constellation would adequately sample the diurnal cycle (important especially for climate studies) and would have good coverage in the sun-fixed (local time) frame, which is important for space weather investigations. Between 400 and 500 soundings per day and per satellite are expected to be captured within the high-gain field of view of the proposed fore and aft occultation antennas. Fig. 2 shows the 24-hour distribution of rising and setting COSMIC soundings that would fall within the high-gain field of view during the operational phase of the mission for the constellation distribution discussed above.

To obtain the highest number of good-quality COSMIC RO soundings, especially in the troposphere, several improvements to the BlackJack receiver are currently under development at JPL. While the firmware currently operating in the CHAMP and SAC-C receivers can only track setting occultations, the COSMIC firmware will also track rising occultations. This requires tracking modifications to acquire the signal as the occulted GPS satellite rises above the Earth’s limb. Also, as the comparison statistics in this paper show, many GPS/MET, CHAMP (Wickert et al., 2001), and SAC-C soundings fail to penetrate near the Earth’s surface, especially in the tropics. This is due to sharp gradients in atmospheric water vapor that cause large signal fluctuations that cannot be followed by the current GPS receiver tracking loops. To overcome this problem and to help acquire rising occultations, new, so-called, open-loop tracking techniques are currently under development (Sokolovskiy, 2001). Assuming that open loop tracking will provide data for profiling in the lowest 1 km of the atmosphere, the profile quality in the lowest part is an area of active research.
5. Results from the CHAMP and SAC-C Missions

An initial version of the UCAR CDAAC has been developed and is now processing RO data from the GPS/MET, CHAMP, and SAC-C missions. UCAR has processed a significant amount of RO data from these missions: GPS/MET (1995 days 170-190, 1,300 occultations), CHAMP (2001 day 148 to 2002 day 080, 15,719 occultations), and SAC-C (2001 day 213 to 2002 day 060, 12,616 occultations). Processing data from different missions has helped discover and correct software inconsistencies and has also provided an opportunity to compare each mission’s precision orbit determination (POD) and RO data quality. The data from these missions help UCAR to prepare for COSMIC and to track the progress in receiver firmware development as the JPL team uploads newer versions of tracking software to the CHAMP and SAC-C satellites. The data are also used for: (a) POD of the LEO satellites, and (b) computation of atmospheric profiles. Recent results for both were presented in Schreiner et al. (2002).

5.1. Statistics of CHAMP and SAC-C soundings compared to GPS/MET

Computing profile statistics with independent correlative data is a good approach to validate RO data from a particular mission. The CDAAC database interface web page (http://www.cosmic.ucar.edu/cdaac/DBif/index.html) has been used to generate refractivity statistics for CHAMP, SAC-C, and GPS/MET as shown in Figs. 3-5, respectively (Schreiner et al., 2002). All RO profiles have been computed in the lower troposphere with the Canonical Transform method (Gorbunov, 2001, 2002a,b). The correlative data profiles are interpolated to the time and location of the RO. The GPS/MET profile data are compared to the ECMWF analysis, and the CHAMP and SAC-C data are compared to NCEP’s Aviation weather Model (AVN) operational global analysis. The AVN analyses are available every 12 hours at a horizontal resolution of 1.25° latitude (~140 km) and 11 pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, and 70 hPa). Figs. 3-5 show the global mean and rms deviation of the differences between the ROs and global analysis refractivity profiles, and the number of compared occultations that penetrate below 1 km.
profiles as a function of altitude for each mission. The mean percentage differences in refractivity are less than ~1% from the surface to ~17 km (the maximum altitude for AVN global analysis) for all three missions. The rms deviations of the percent differences for the three missions are ~1% except in the lower troposphere. The number of retrieved ROs that penetrate below 1 km altitude is ~45% of the processed profiles for CHAMP and SAC-C and ~35% for GPS/MET.

To evaluate the performance of the RO data in the tropics, the CDAAC database interface was used to compute statistics for CHAMP in the region defined by 30°S to 30°N. These results exhibit a clear degradation due to tropical moisture (Schreiner et al., 2002). The mean percentage difference in refractivity in the lower troposphere increases to ~1.7%, and the percentage of ROs that penetrate to 1 km altitude is approximately 20%. The mean refractivity difference (RO smaller than NCEP) in the lower troposphere is due to some combination of RO retrieval errors and global analysis errors. At present, it is not yet clear what fraction of the RO retrieval errors in the moist lower troposphere must be attributed to the negative bias that exists in Abel inversions below super-refraction layers and to signal tracking errors, which in fact, may be correlated.

5.2. Some examples of CHAMP and SAC-C soundings

Individual soundings and comparison with radiosondes and analyses from numerical models provide additional insight into the value of RO soundings. This section shows an example of a sounding in a typhoon near Taiwan, three soundings through apparent gravity waves over the Indian Ocean and through a monsoon depression over India.

5.2.1. Sounding through Typhoon Toraji (2001)

A tropical cyclone formed at 0600 UTC 25 July 2001 over the tropical western Pacific to the east of the Philippines at 14°N, 135°E. The storm intensified rapidly, while it moved west northwestward (Fig. 6). This storm was named tropical storm Toraji at 1800 UTC 26 July, and by 1800 UTC 27 July, it had reached typhoon intensity. Typhoon Toraji landed on the east coast of Taiwan, near the city of Hualien, at 1600 UTC 29 July. The peak wind recorded at 1800 UTC 29 July was 100 knots. This storm crossed over Taiwan without significant change in direction and made landfall near Fuzhou, China at 1930 UTC 30 July. This storm produced over 750 mm of rain over the Central Mountain Range of Taiwan. The Taipei Central News Agency reported 72 fatalities, making Toraji the most lethal typhoon to hit Taiwan since 1961. Torrential rain and mudslides caused damage to the island’s agriculture, forestry, fishery, and livestock industries totaling $128 million, while hundreds of thousands of people were left without power and water.

At 2008 UTC 29 July 2001, a CHAMP RO sounding took place southeast of Taiwan in the vicinity of Typhoon Toraji. The sounding extended from 1.3 km to 40 km. The ray perigee point varied from 21.44°N, 122.74°E to 22.63°N, 123.14°E. The GMS IR image at 2000 UTC 29 July (Fig. 7) shows that the CHAMP sounding took place near the edge of the typhoon’s extensive cloud shield. The
center of the storm was located near central north Taiwan at that time.

Fig. 8 (top panel) compares the CHAMP vertical profile of refractivity with those calculated from the NCEP-NCAR reanalysis and ECMWF global analysis (interpolated to the exact location and time of the CHAMP sounding). The results show that the CHAMP refractivity
profile compares very well with the refractivities from both global analyses. The deviation between these three refractivity profiles is generally less than 0.5% throughout the troposphere. The CHAMP radio occultation shows considerably more small-scale variations, as compared with the global analyses, because of the much higher vertical resolution associated with the RO sounding.

Approximately 300 km to the northeast of the CHAMP sounding, the Japanese radiosonde station, Ishigakijima (WMO #47918) was taking measurements at six-hour intervals. Fig. 8 (lower panel) compares the CHAMP refractivity profile with the refractivity profiles derived from the Ishigakijima soundings at 1800 UTC 29 July and 0000 UTC 30 July. The two soundings, in general, also compare very well with the CHAMP refractivity profile. In the layer between 3.5 km and 4.5 km, there are bigger differences in refractivity between the two radiosonde measurements, which are mainly caused by variations in moisture. These comparisons indicate that this CHAMP sounding—through the extensive cloud shield of Typhoon Toraji—maintains very high quality.

As noted earlier, the refractivity in the lower troposphere depends on both temperature and water vapor. We have developed a statistically based retrieval scheme that takes into consideration the respective contributions of moisture and temperature terms to refractivity, which vary with latitude and altitude (Kuo et al., 2000b). This scheme performs well, in general, and is now implemented as part of CDAAC.

Fig. 9 compares the derived CHAMP sounding with the radiosonde measurements at Ishigakijima (47918) at 1800 UTC 29 July and 0000 UTC 30 July. The NCEP-NCAR reanalysis is used as the first guess for computing the water vapor and temperature profiles from the observed CHAMP refractivity profile. The temperature sounding follows closely the moist adiabat of 24°C, representative of a convectively neutral environment, and compares very well with the two radiosonde soundings. The differences between the CHAMP and radiosonde temperature soundings are generally less than 1°C throughout the troposphere. The CHAMP moisture sounding, indicated by the dew point temperatures, also compares well with the dew points from the two radiosonde soundings. Larger differences are found above 500 hPa, where the CHAMP sounding tends to be drier than the two radiosonde soundings. We note that there are considerable small-scale variations in the CHAMP derived moisture sounding. This is attributed to the higher vertical resolution of the RO sounding, which likely is better than 100 meters using the Canonical Transform method in the CHAMP sounding retrieval.

5.2.2. Gravity waves over the Indian Ocean

The high vertical resolution of the GPS RO sounding technique makes it a useful tool for detecting gravity waves in the upper troposphere and stratosphere. Tsuda et al. (2000) analyzed GPS/MET RO data to derive a global distribution of gravity wave activity and found a high level of activity over the Equatorial Indian Ocean. Fig. 10 shows two CHAMP soundings occurring ~100 minutes apart in time and ~700 km apart in distance. Sounding A occurred at 1229 UTC 3 July 2001 at 4.9°S and 78.8°E. Sounding B occurred at 1403 UTC at 11.4°S and 79.1°E.
radiosonde profiles from nearby COCOS Island (96996, 12.1°S, 96.5°E) that exhibit similar perturbations in temperature as seen in Fig. 10 but are ~12 hours away in time and ~2,000 km in distance.

According to Tsuda et al. (2000), a variety of mechanisms may excite gravity waves in the upper troposphere and stratosphere including the interaction of surface wind with topography, jet stream instabilities, synoptic-scale meteorological disturbances, and cumulus convection. Over the Equatorial Indian Ocean, cumulus convection is a likely cause (the INSAT satellite photo for this time, not shown, indicates a long band of clouds with cold tops in the band ~5°S to ~10°S) and temperature perturbations with vertical wavelengths/scales of ~2-10 km could be associated with low frequency inertia-gravity waves with periods of order one day and horizontal wavelengths ~1000 km. In any case, the presence of temperature perturbations with a similar magnitude and vertical scale in the three CHAMP and four radiosonde soundings suggests that these perturbations are real. If they are associated with large-scale, low-frequency inertia-gravity waves, as seems likely, the question arises as to whether these perturbations should be allowed to affect the operational analysis in the tropics and how they might affect the subsequent forecast if they are included and resolved in the initial conditions of a numerical forecast.

5.2.3. SAC-C sounding in a monsoon depression over India

Despite its importance to atmospheric processes over a wide range of spatial and temporal scales, water vapor is one of the least understood and poorly described components of the atmosphere. An important question is whether GPS RO can provide accurate measurements of atmospheric water vapor in the lower troposphere, in particular, over regions of significant precipitation.

On 4 August 2001, a SAC-C occultation took place over eastern India at 0604 UTC. The ray perigee point varied from 22.6°N, 82.6°E to 23.9°N, 83.0°E, and it extended from 1.7 km to 40 km. The 700 hPa analysis at 1200 UTC 4 August (Fig. 12) shows that the radio occultation sounding took place about 400 km to the north of the center of a monsoon depression. The radiosonde station immediately to the east of the SAC-C sounding indicates a temperature of 11°C and a dew point depression of zero. The 700 hPa analysis and the satellite photographs (not shown) indicate that the SAC-C RO occurred over clouds and precipitation associated with the Indian monsoon depression.

Fig. 13(a) compares the SAC-C dry temperature, SAC-C wet temperature (retrieved temperature following the statistical retrieval procedure discussed earlier), the NCEP-NCAR reanalysis interpolated to the exact time and location of the SAC-C sounding, and the temperature profiles obtained from three nearby radiosonde stations. The SAC-C wet temperature sounding derived from the SAC-C RO sounding compares very well with the NCEP-NCAR reanalysis throughout most of the troposphere and stratosphere, with the exception that the SAC-C RO depicts a sharper tropopause. This is attributed to the fact that the analysis has considerably lower vertical resolution compared to the RO sounding. The GPS dry temperature does not deviate from the GPS wet temperature until below approximately 12 km, where the moisture layer begins. Below 8 km, the difference between dry and wet SAC-C RO temperature increases rapidly and reaches more than 60°C at 1.7 km (the lowest level of the SAC-C RO sounding). The radiosonde measurements from nearby stations (which are 300 ~500 km away from SAC-C RO, and six hours apart) show general agreement with the SAC-C sounding. In particular, the 1200 UTC measurements from station 42971 (the station to the
Fig. 12. The 700 hPa analysis at 1200 UTC 4 August 2001. The location of the SAC-C radio occultation sounding at 0604 UTC 4 August 2001 and the nearby radiosonde stations are marked.

Figs. 13(a&b). Comparison of SAC-C sounding, NCEP/NCAR reanalysis, and nearby radiosonde measurements:
(a) temperature and (b) water vapor pressure.
Fig. 14. Comparison of retrieved SAC-C sounding (red curves) with radiosonde measurement taken at 1200 UTC 4 August 2001 at station 42971 (green curves).

Southeast and upstream of SAC-C RO sounding) compares very favorably with the temperature profile of SAC-C sounding throughout the entire troposphere.

The corresponding comparison of water vapor pressure profiles is shown in Fig. 13(b). The moisture profile derived from station 42971 at 1200 UTC is a nearly perfect match with the SAC-C water vapor profile below 6 km, where most of the moisture is located. The moisture profiles from the other two radiosonde stations also compare well with the SAC-C sounding, except that these radiosonde profiles are slightly more moist. It is interesting to note that the NCEP-NCAR reanalysis is significantly drier than the SAC-C sounding below 7 km. Verification against the nearby radiosonde measurements suggests that the SAC-C sounding is likely more accurate than the NCEP/NCAR reanalysis. These comparisons indicate that useful water vapor information can be derived from GPS RO soundings down to the lower part of the troposphere for significant cloud and precipitation systems, such as a monsoon depression over India.

Fig. 14 compares the SAC-C SkewT plot with that of a radiosonde sounding taken at 1200 UTC 4 August 2001 from station 42971. The SAC-C RO sounding compares well with this radiosonde measurement. It is particularly interesting to note that the SAC-C sounding reproduces the drying in the radiosonde sounding between 500 hPa and 300 hPa. Both soundings give a temperature profile that closely follows the moist adiabat of 24°C, and both also show very high moisture content below 500 hPa.

6. Summary and outlook

In this paper we briefly reviewed the GPS RO sounding technique, summarized the key results from the GPS/MET experiment, and presented preliminary analysis of the latest GPS RO datasets from CHAMP.
TABLE 2
Applications of COSMIC data to atmospheric sciences, including weather and climate research and operational weather prediction

| Application                                                                 |
|-----------------------------------------------------------------------------|
| Provide 2400-3000 accurate soundings per day globally and in all weather with high vertical resolution of bending angle, refractivity, and derived products such as temperature and water vapor in the stratosphere and troposphere. |
| Calculate temperature directly where water vapor is negligible (e.g. stratosphere, upper troposphere). |
| Calculate water vapor directly where temperature is fairly well known independently. |
| Estimation of winds through geostrophic or gradient wind relationships in high latitudes or through assimilation of data in models. |
| Direct assimilation of bending angle or refractivity in numerical models to recover temperature, water vapor, and winds. |
| Improve global analyses in real time and research mode (e.g. reanalysis) to obtain improved estimates of temperature, water vapor, and winds, particularly over oceans and polar regions. |
| Improve vertical resolution of upper-level fronts and associated jet streams and tropopause, supporting process studies such as tropospheric-stratospheric exchange. |
| Improve understanding of global water cycle, climatology of water vapor. |
| Investigation of gravity waves in the stratosphere. |
| Investigation of effects of large fires and volcanoes on weather and climate. |
| Resolve the diurnal cycle of temperature globally. |
| Monitor global and regional temperature change with unprecedented accuracy, vertical resolution, and stability in troposphere and stratosphere for climate and global change studies. |
| Resolve discrepancies in temperature records from various sources (e.g. the Microwave Sounder Unit inferred temperature record compared to surface temperature record measured by in-situ instruments). |
| Monitor global distribution of geopotential heights for climate and global change studies. |
| Introduce bending angle and refractivity as new climate change parameters. |
| Observe stratospheric phenomena, including ozone depletion, stratospheric-tropospheric exchange, and volcanic effects. |
| Improve global and regional numerical weather predictions and operational forecasts. |
| Complement existing observing systems and provide independent data for development of improved analysis systems using merged observations. |
| Provide data to calibrate or interpret other satellite-based sounding systems on GOES, POES, and EOS. |
| Provide data to support research field programs (e.g. programs like TOGA-COARE, INDOEX, JASMINE, FASTEX). |

and SAC-C. These results confirm the earlier assessment that GPS RO soundings are of high accuracy and high vertical resolution and offer a number of unique advantages that complement existing observing systems. Through a collaboration between the U.S. and Taiwan, the COSMIC mission will be launched in 2005 and will provide approximately 2400–3000 RO soundings per day with uniform global coverage. In contrast to other missions (GPS/MET, CHAMP and SAC-C), COSMIC will provide RO data in near real time to demonstrate their utility in operational weather prediction. When used with other independent observing systems, COSMIC data will improve our understanding of global and regional atmospheric processes as well as weather forecasts and climate projections into the future. Table 2 summarizes the most important scientific contributions to meteorology and climate that COSMIC will provide.

Acknowledgements

We acknowledge the support of the National Science Foundation, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the U.S. Air Force, and the U.S. Navy in
the United States and the National Science Council and National Space Program Office in Taiwan for their leadership and support of COSMIC. We thank GFZ for the release of CHAMP data and JPL for the release of SAC-C data. We especially acknowledge Jay Fein at the National Science Foundation for his support of GPS/MET, COSMIC, and the UCAR CDAAC. We thank Doug Hunt, Tae-Kwon Wee, and Ying Zhang at the UCAR COSMIC Office and Bill Randel in NCAR for their assistance in the preparation of this paper.

References

Anthes, R. A., Rocken, C. and Kuo, Y. H., 2000, “Applications of COSMIC to meteorology and climate”, TAO, 11, 115-156.

ESA, 1996, “Atmospheric profiling mission. ESA SP-1196(7). The nine candidate Earth explorer missions”, European Space Agency, ESA Publications Division, Noordwijk, The Netherlands, p58.

Fjeldbo, G., Kliore, A. J. and Eshleman, V. R., 1971, “The neutral atmosphere of Venus as studied with the Mariner V radio occultation experiment”, Radio Sci., 4, 879-897.

Gorbunov, M. E., 2001, “Radiophysical methods for processing radio occultation data in multipath regions”, DMI Report 01-02, Copenhagen, p32.

Gorbunov, M. E., 2002a, “Canonical transform method for processing radio occultation data in the lower troposphere”, Radio Sci. (in press).

Gorbunov, M. E., 2002b, “Radio-holographic analysis of MircoLab-1 radio occultation data in the lower troposphere”, J. Geophys. Res. (in press).

Hajj, G. A., Kursinski, E. R., Romans, L. J., Bertiger, W. I. and Leroy, S. S., 2002, “A technical description of atmospheric sounding by radio occultation”, JASTP, 64, 451-469.

Hocke, K., 1997, “Inversion of GPS meteorology data”, Ann. Geophys., 15, 443-450.

Hoeg, P., Hauchecorne, A., Kirchengast, G., Syndergaard, S., Belloul, B., Leitinger, R. and Rothleitner, W., 1996, “Derivation of atmospheric properties using a radio occultation technique”, Sci. Rep., 95-4, Danish Met. Inst.

Kramer, H. J., 2002, “Observations of the Earth and its environment: Survey of missions and sensors, 4th Ed.”, Springer, New York, p1510.

Kuo, Y. H., Zou, X., Chen, S. J., Gao, Y. R., Huang, W., Anthes, R., Hunt, D., Exner, M., Rocken, C. and Sokolovskiy, S., 1998, “A GPS/MET sounding through an intense upper-level front”, Bull. Amer. Met. Soc., 79, 617-626.

Kuo, Y. H., Sokolovskiy, S. V., Anthes, R. A. and Vandenberghe, F., 2000a, “Assimilation of GPS radio occultation data for numerical weather prediction”, TAO, 11, 157-186.

Kuo, Y. H., Wee, T. K., and Ha, S. Y., 2000b, “Applications of GPS radio occultation data for weather analysis and prediction over the Antarctic”, Proceedings, COSMIC International Workshop, 27-29 September 2000, Taipei, Taiwan, 18-26. [Available from Prof. Ching-Yuan Huang, National Central University, Chungli, Taiwan].

Kursinski, E. R., Hajj, G. A., Bertiger, W. I., Leroy, S. S., Meehan, T. K., Romans, L. J., Schofield, J. T., McCleese, D. J., Melbourne, W. G., Thornton, C. L., Yunck, T. P., Eyre, J. R. and Nagatani, R. N., 1996, “Initial results of radio occultation observations of Earth's atmosphere using the Global Positioning System”, Science, 271, 1107-1110.

Kursinski, E. R., Hajj, G. A., Schofield, J. T., Linfield, R. P. and Hardy, K. R., 1997, “Observing the Earth's atmosphere with radio occultation measurements using the Global Positioning System”, J. Geophys. Res., 102, D19, 23429-23465.

Lindzen, R. S. and Fox-Rabinovitz, M., 1989, “Consistent vertical and horizontal resolution”, Mon. Wea. Rev., 117, 2575-2583.

Melbourne, W., Davis, E., Duncan, C., Hajj, G., Hardy, K., Kursinski, E., Meehan, T., Young, L. and Yunck, T., 1994, “The application of space borne GPS to atmospheric limb sounding and global change monitoring”, JPL Publ., 94-18, p147.

Menzel, W. P., Holt, F. C., Schmit, T. J., Aune, R. M., Schreiner, A. J., Wade, G.S. and Gray, D.G., 1998, “Application of GOES-8/9 soundings to weather forecasting and nowcasting”, Bull. Amer. Met. Soc., 79, 2059-2077.

Reigber, C., Schwintzer, P., Koenig, R., Neumayer, K. H., Bode, A., Barthelmes, F., Foerste, Ch. (GFZ Potsdam), Balmino, G., Biancale, R., Lemoine, J.-M., Loyer, S. and Perosanz, F., 2001, “Earth gravity field solutions from several months of CHAMP satellite data”, Eos Trans AGU, 82 (47), Fall Meeting Suppl G41C.

Rocken, C., Anthes, R., Exner, M., Hunt, D., Sokolovskiy, S., Ware, R., Gorbunov, M., Schreiner, W., Feng, D., Herman, B., Kuo, Y. and Zou, X., 1997, “Analysis and validation of GPS/MET data in the neutral atmosphere”, J. Geophys. Res., 102, 29849-29866.

Rocken, C., Kuo, Y. H., Schreiner, W., Hunt, D., Sokolovskiy, S.V. and McCormick, C., 2000, “COSMIC system description”, TAO, 11, 1, 21-52.

Schreiner, W., Hunt, D., Rocken, C. and Sokolovskiy, S. V., 2002, “Radio occultation data processing at the COSMIC Data Analysis and Archival Center (CDAAC)”, 1st CHAMP Science Meeting, Springer-Verlag, (in press).

Sokolovskiy, S. V., 2001, “Modeling and inverting radio occultation signals in the moist troposphere”, Radio Sci., 36, 3, 441-458.

Solheim, F. S., Vivekanandan, J., Ware, R. and Rocken, C., 1999, “Propagation delays induced by dry air, water vapor, hydrometeors and other particulates”, JGR-Atmospheres, 104, D8, 9663-9670.

TAO, 2000, Special issue for “Applications of the Constellation Observing System for Meteorology, Ionosphere and Climate”, Terrestrial, Atmospheric and Ocean Sciences, 11, Taipei, p380.

Tsuda, T., Nishida, M., Rocken C. and Ware, R. H., 2000, “A global morphology of gravity wave activity in the stratosphere revealed by the GPS occultation data (GPS/MET)”, J. Geophys. Res., 105, 7257-7273.
Ware, R., Exner, M., Feng, D., Gorbunov, M., Hardy, K., Herman, B., Kuo, Y., Meehan, T., Melbourne, W., Rocken, C., Schreiner, W., Sokolovskiy, S., Solheim, F., Zou, X., Anthes, R., Businger, S. and Trenberth, K., 1996, “GPS sounding of the atmosphere from low Earth orbit: Preliminary results”, Bull. Amer. Met. Soc., 77, 19-40.

Wickert, J., Reigber, C., Beyerle, G., Konig, R., Marquardt, C., Schmidt, T., Grunwaldt, L., Galas, R., Meehan, T. K., Melbourne, W. G. and Hocke, K., 2001, “Atmosphere sounding by GPS radio occultation: First results from CHAMP”, Geophys. Res. Lett., 28, 3263.