

## Atmospheric sounding using GPS radio occultation

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**सार** – इस शोध-पत्र में पृथ्वी की कक्षा के निचले स्तर में घूमने वाले (एल.ई.ओ.) उपग्रहों में भूमंडलीय अवस्थिति प्रणाली (जी.पी.एस.) वाले उपग्रहों वाले जी.पी.एस. अभिग्राहियों का उपयोग करके पृथ्वी के वायुमंडल की सुदूर ध्वनि के लिए रेडियो ऑक्यूलेशन (आर.ओ.) तकनीक के बारे में संक्षेप में बताया गया है। जी.पी.एस. उपग्रहों के आगे और पीछे घूमने वाले एल.ई.ओ. उपग्रहों के कारण जी.पी.एस. उपग्रहों से निकलने वाली रेडियो तरंगें पृथ्वी के वायुमंडल से अपवर्तित होती हैं। वायुमंडलीय अपवर्तन के उर्ध्वाधर प्रोफाइलों को प्राप्त करने के लिए रेडियो तरंगों के बेडिंग कोण के संक्षिप्त मापनों का उपयोग किया गया है। जो आयनमंडल में इलैक्ट्रान घनत्व तथा समतापमंडल और क्षोभमंडल में तापमान और जलवाष्प का कार्य है।

जी.पी.एस./एम.ई.टी., सी.एच.ए.एम.पी. और एस.ए.सी.-सी. आर.ओ. मिशनों के परिणामों का सार प्रस्तुत किया गया है और जाँच के उदाहरण प्रस्तुत किए गए हैं। सी.एच.ए.एम.पी. और एस.ए.सी.-सी. ऑकड़ों के विश्लेषण से पता चलता है कि जी.पी.एस./एम.ई.टी. के लिए केवल 35 प्रतिशत की तुलना में लगभग 45 प्रतिशत सी.एच.ए.एम.पी. और एस.ए.सी.-सी. से प्राप्त रेडियो ऑक्यूलेशन प्रोफाइल्स 1 कि.मी. ऊँचाई से कम पहुँचते हैं। सभी मिशन एन.डब्ल्यू.पी. मॉडलो की तुलना निम्न क्षोभमंडल 1 प्रतिशत से 2 प्रतिशत के बीच नकारात्मक अपवर्तन बायस दर्शाते हैं। उष्णकटिबंध तक नियंत्रित होने की स्थिति में केवल लगभग 20 प्रतिशत सी.एच.ए.एम.पी. ऑक्यूलेशन प्रोफाइल्स सतह से 1 कि.मी. तक पहुँचती है।

ताइवान नेशनल स्पेस प्रोग्राम ऑफिस (एन.एस.पी.ओ.) यूनिवर्सिटी कारपोरेशन फॉर एटमोस्फेरिक रिसर्च (यू.सी.ए.आर.), जेट प्रॉपलेशन लेबोरेटरी (जे.पी.एल.), नेवल रिसर्च लेबोरेटरी (एन.आर.एल.), और विश्वविद्यालय समुदाय के अन्य सहभागी सी.ओ.एस.एम.आई.सी. (मौसम विज्ञान, आयनमंडल और जलवायु के लिए तारामंडल प्रेक्षण तंत्र) का विकास कर रहे हैं जो मौसम और जलवायु, अंतरिक्ष मौसम और भूगणितीय विज्ञान के लिए परियोजना है। सी.ओ.एस.एम.आई.सी. की 2005 में छह उपग्रहों के प्रेक्षण की योजना है। प्रत्येक उपग्रह ट्रैकड जी.पी.एस. रेडियो संकेतों से मुख्य आयनमंडलीय और वायुमंडलीय लक्षणों की 400–500 तक दैनिक प्रोफाइल्स पुनः प्राप्त करेगा क्योंकि उन्हें पृथ्वी से बाहर ऑक्यूलेट किया गया है। सी.ओ.एस.एम.आई.सी. से प्राप्त किए गए रेडियो ऑक्यूलेशन साउंडिंग ऑकड़ों से वायुमंडलीय अनुसंधान, मौसम पूर्वानुमान और जलवायु माडलन में महत्वपूर्ण योगदान मिलेगा।

**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 refractivity. 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:

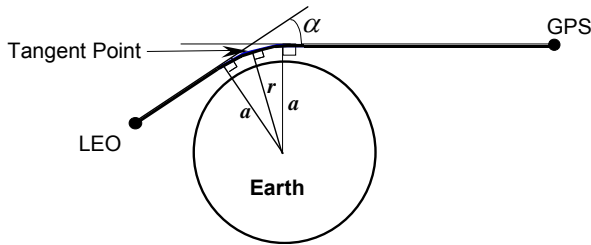
$$\ln[n(a)] = \frac{1}{\pi} \int_a^{\infty} \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} da' \quad (1)$$

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

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{P_w}{T^2} - 40.3 \frac{n_e}{f^2} \quad (2)$$

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  $T < 240\text{K}$ , 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.



**Fig. 1.** Instantaneous occultation geometry for the GPS and LEO satellites. The bending angle  $\alpha$  and impact parameter  $a$  are determined from the Doppler frequency shift, spacecraft position, and spacecraft velocity measurements

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**

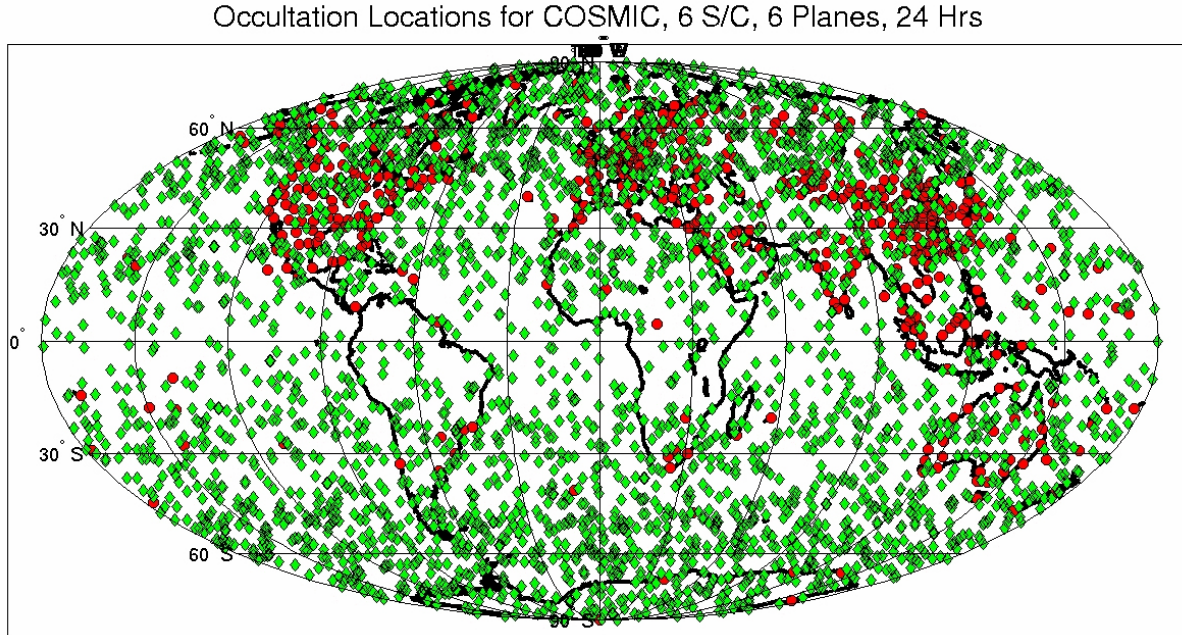
Limb sounding geometry complementary to ground and space nadir viewing instruments
High accuracy
High vertical resolution
Consistency of horizontal and vertical scales of observations (Lindzen and Fox-Rabinovitz, 1989)
All weather – minimally affected by clouds, aerosols, or light precipitation (Solheim <i>et al.</i> , 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.



**Fig. 2.** COSMIC RO sounding distribution for 24-hour period with current 28 GPS satellite constellation. The assumed antenna field of view was 45 degrees in azimuth. Occultation locations (3115 soundings) are shown in green and radiosonde locations (536 sites) are shown in red

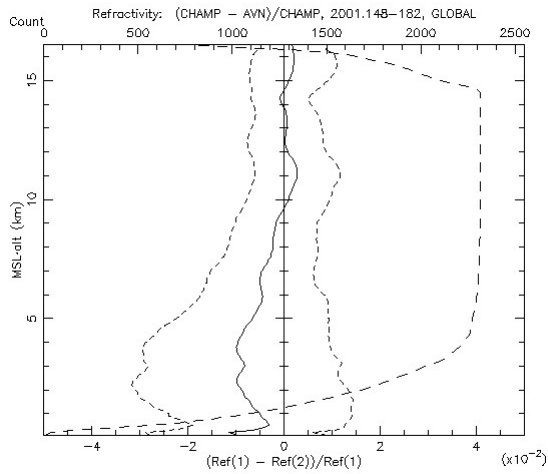
#### 4.2. *COSMIC* system overview

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.

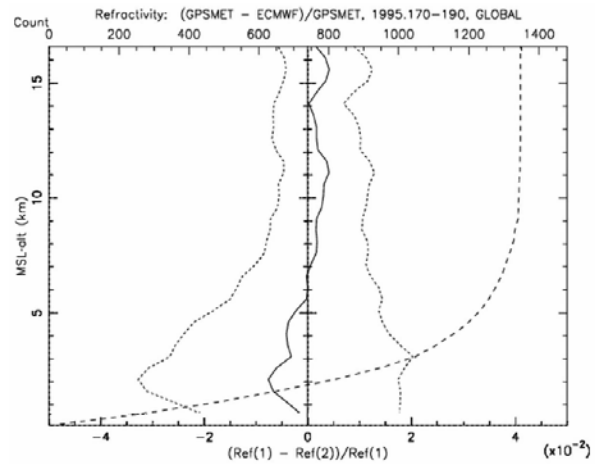
The orbit constellation for the COSMIC mission during the operational phase (the second year) is still undergoing trade studies. The six COSMIC satellites will be launched by a Minotaur rocket into one orbital plane and will then be separated in local time throughout the first year to reach the operational 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.

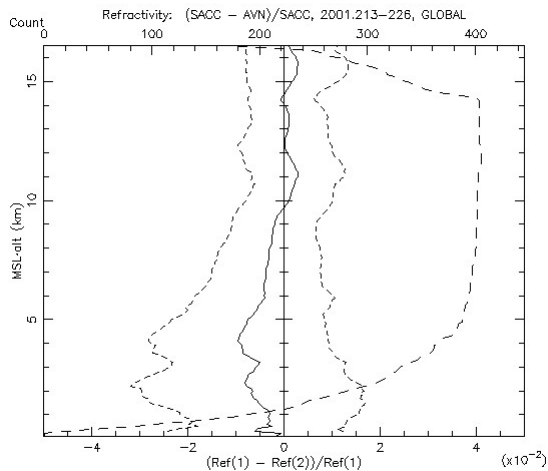
To obtain the highest number of good-quality COSMIC RO soundings, especially in the troposphere, several improvements to the BlackJack receiver are currently under development at JPL. While the firmware currently operating in the CHAMP and SAC-C receivers can only track setting occultations, the COSMIC 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.



**Fig. 3.** Mean (solid), rms (short dash), and count (long dash) global comparison statistics between CHAMP occultations and AVN model. Approximately 45% of occultations penetrate to below 1 km



**Fig. 5.** Global comparison statistics between GPS/MET occultations and ECMWF model. Approximately 35% of occultations penetrate below 1 km



**Fig. 4.** Global comparison statistics between SAC-C occultations and AVN model. Approximately 45% of occultations penetrate to below 1 km

## 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



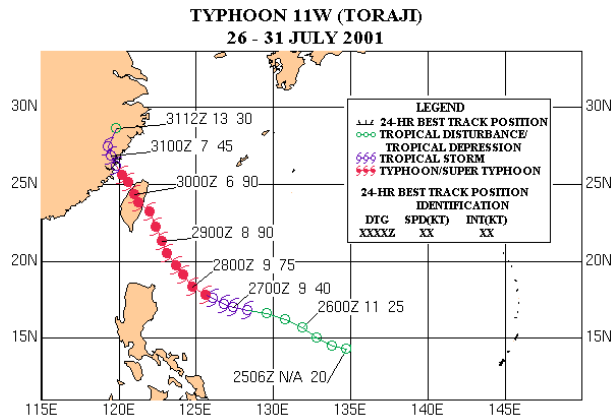


Fig. 6. Track of Typhoon Toraji (obtained from the Joint Typhoon Warning Center)

profiles as a function of altitude for each mission. The mean percentage differences in refractivity are less than  $\sim 1\%$  from the surface to  $\sim 17$  km (the maximum altitude for AVN global analysis) for all three missions. The rms deviations of the percent differences for the three missions are  $\sim 1\%$  except in the lower troposphere. The number of retrieved ROs that penetrate below 1 km altitude is  $\sim 45\%$  of the processed profiles for CHAMP and SAC-C and  $\sim 35\%$  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  $30^\circ$  S to  $30^\circ$  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  $\sim 1.7\%$ , 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.

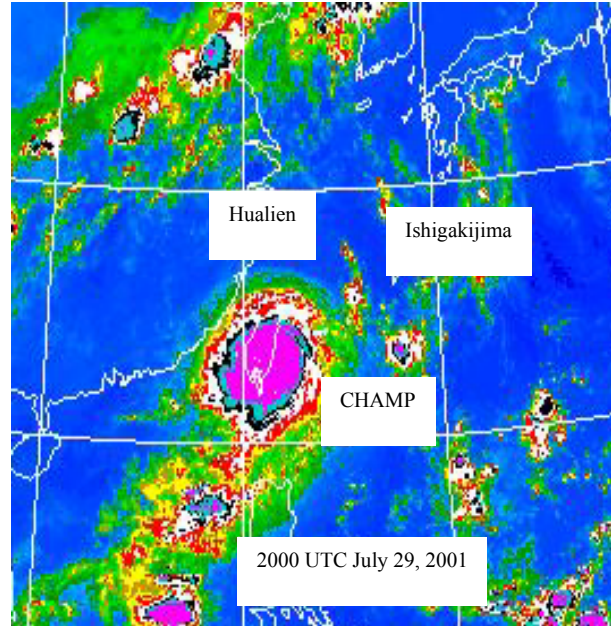
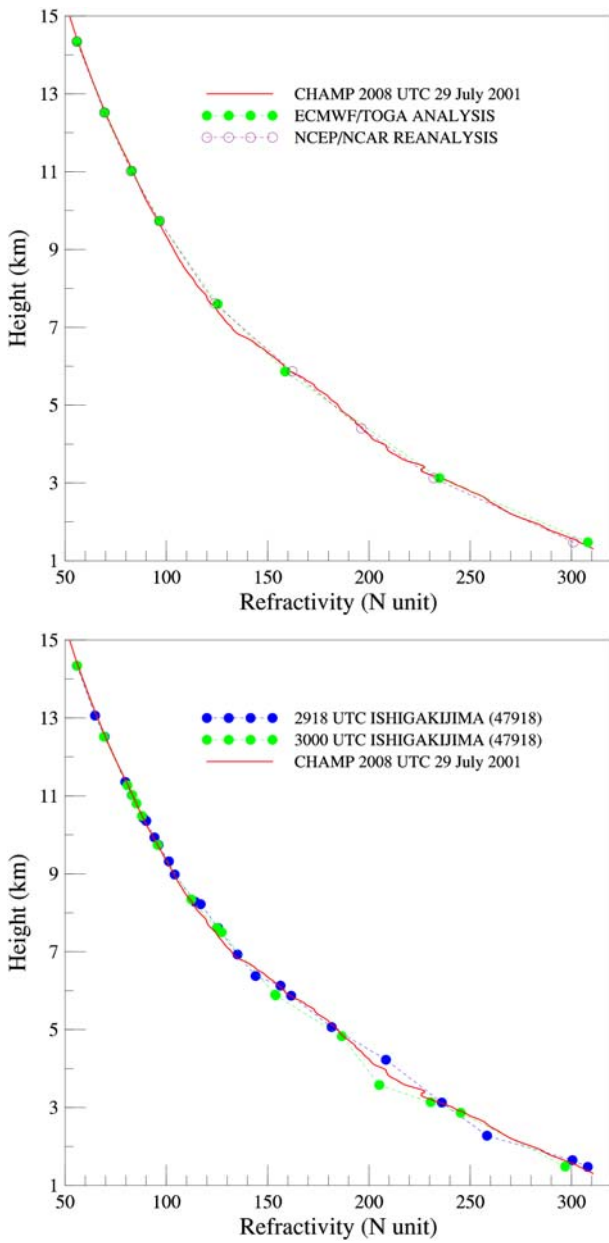


Fig. 7. GMS Infrared image at 2000 UTC 29 July 2001 (04:00 Local Taiwan time). The location of the CHAMP RO sounding and the radiosonde stations of Ishigakijima (47918) and Hualien (red dot) on the east coast of Taiwan are marked

### 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  $14^\circ$ N,  $135^\circ$ 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.

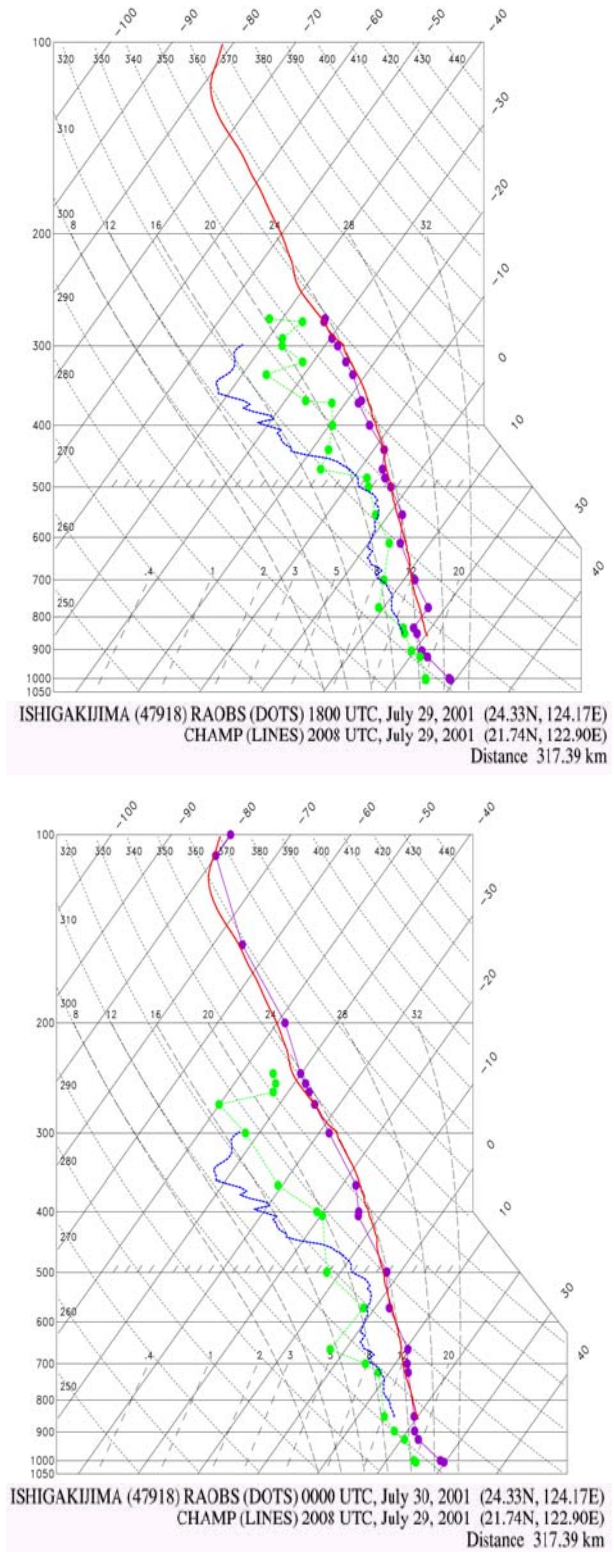
At 2008 UTC 29 July 2001, a CHAMP RO sounding took place southeast of Taiwan in the vicinity of Typhoon Toraji. The sounding extended from 1.3 km to 40 km. The ray perigee point varied from  $21.44^\circ$ N,  $122.74^\circ$ E to  $22.63^\circ$ N,  $123.14^\circ$ E. The GMS IR image at 2000 UTC 29 July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



**Fig. 8.** Vertical profiles of refractivity from CHAMP at 2008 UTC 29 July 2001 and (top) ECMWF/TOGA reanalysis and NCEP/NCAR reanalysis and (bottom) radiosonde soundings from Ishigakijima at 1800 UTC 29 July and 0000 UTC 30 July 2001

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



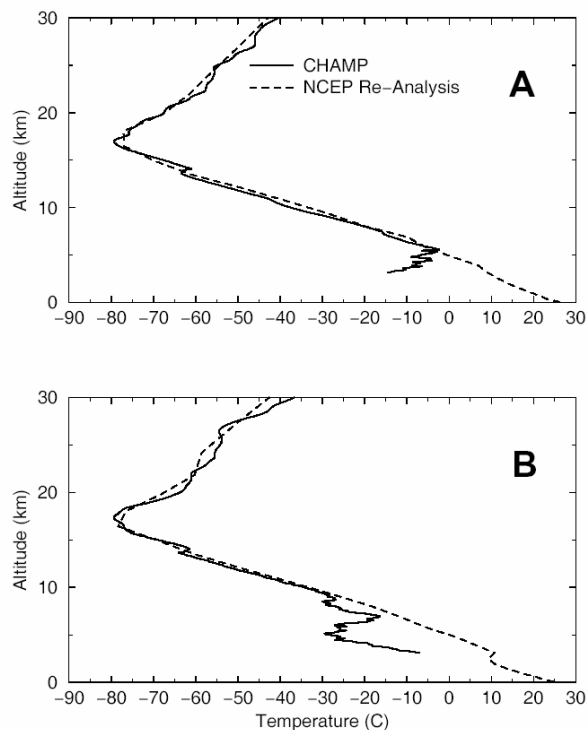
**Fig. 9.** Comparison of CHAMP RO sounding (solid lines) at 2008 UTC 29 July 2001 with radiosonde soundings (solid lines connecting the dots) from Ishigakijima at 1800 UTC 29 July (top) and 0000 UTC 30 July 2001 (bottom)

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 radiosondes 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.

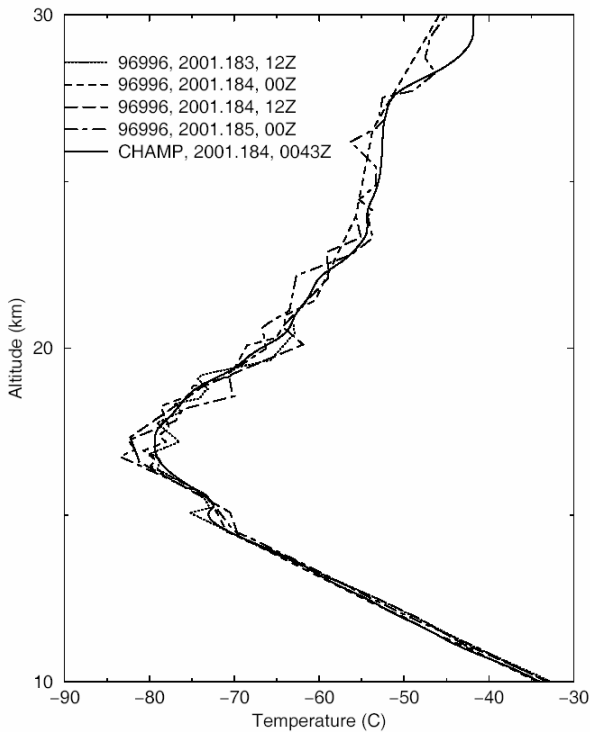


**Fig. 10.** Shown are CHAMP dry temperature and NCEP analysis temperature profiles for two occultation soundings (A and B) over the Indian Ocean. The two CHAMP soundings occurred ~100 minutes apart in time and ~700 km apart in distance. Sounding A occurred at 1229 UTC 3 July 2001 at 4.9°S and 78.8°E. Sounding B occurred at 1403 UTC at 11.4°S and 79.1°E.

### 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 (A: 1229 UTC, 4.9°S, 78.8°E; B: 1403 UTC, 11.4°S, 79.1°E) that occurred within 95 minutes and ~700 km of each other on 3 July, 2001 (2001.184). The CHAMP dry temperature, computed assuming a dry atmosphere (Ware *et al.*, 1996), is shown along with the temperature from the NCEP analysis. These soundings both show a temperature fluctuation of about 3° C at ~14 km, in addition to wave activity in the stratosphere. These manifestations of gravity waves are not present in the analysis. Fig. 11 shows another CHAMP sounding (0043 UTC, 11.0°S, 98.3°E) from 3 July 2001 along with four consecutive





**Fig. 11.** Shown are a CHAMP dry temperature sounding and four radiosonde temperature profiles from COCOS Island (96996). The CHAMP sounding (11.0°S, 98.3°E) occurred approximately 165 km away from the COCOS Island radiosonde site (12.1°S, 96.5°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

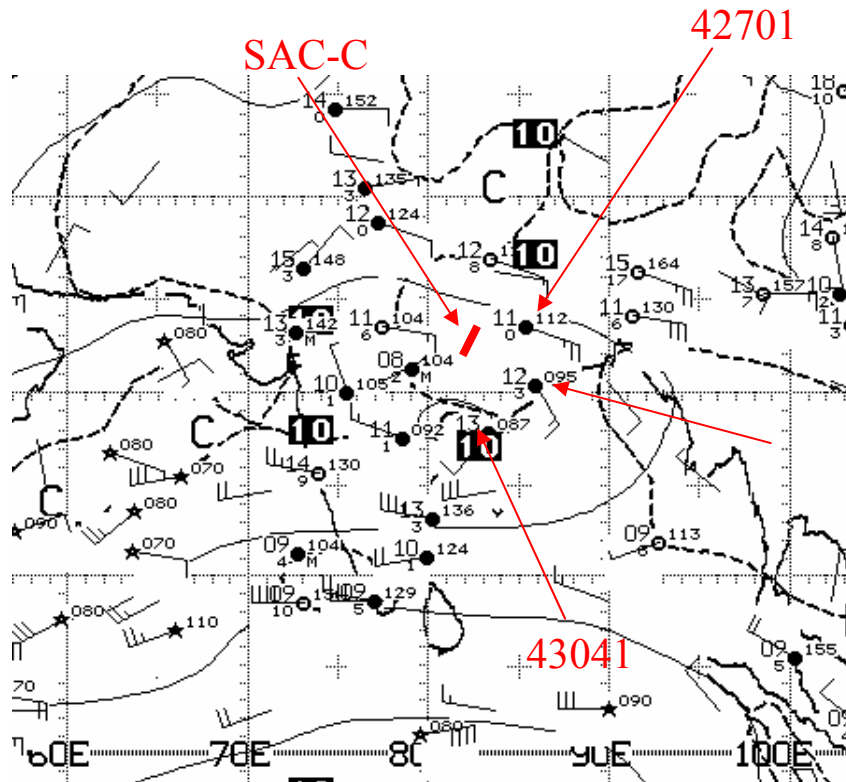
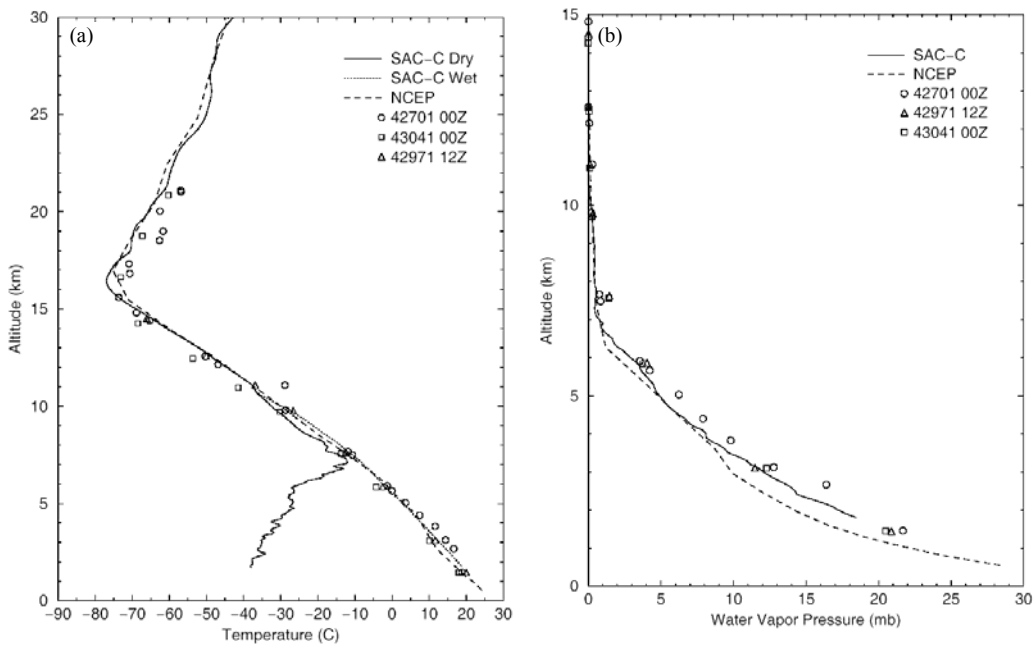
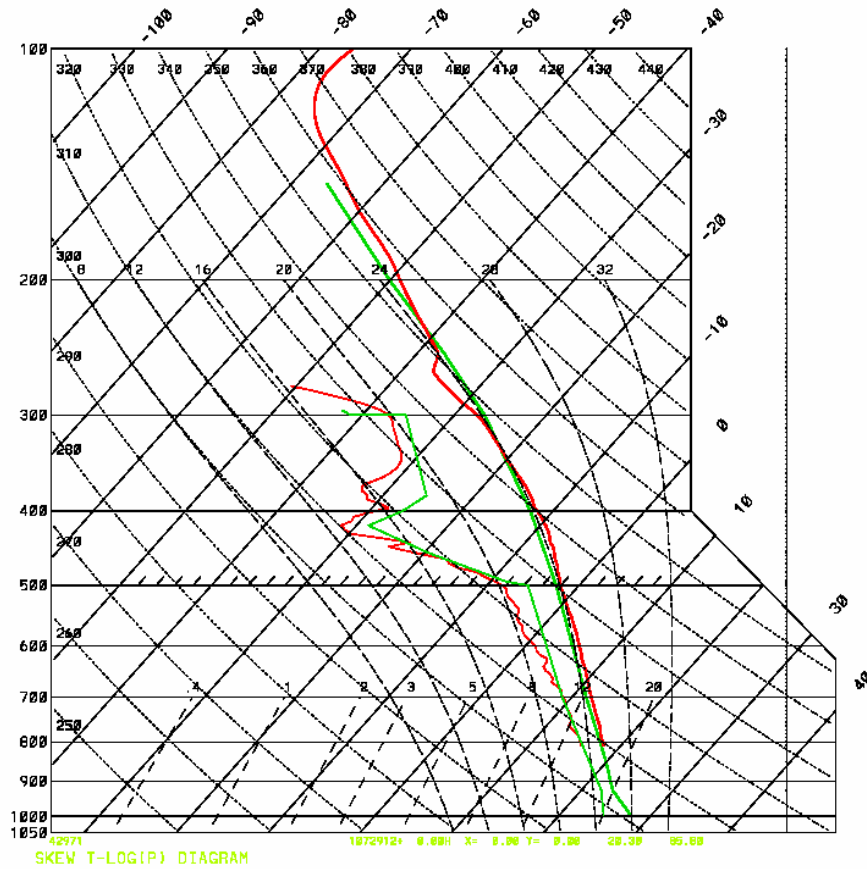


Fig. 12. The 700 hPa analysis at 1200 UTC 4 August 2001. The location of the SAC-C radio occultation sounding at 0604 UTC 4 August 2001 and the nearby radiosonde stations are marked



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**


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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).

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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.

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