Radio Occultation Data Processing at the COSMIC Data Analysis and Archival Center (CDAAC)

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Abstract

The UCAR CDAAC has analyzed radio occultation data from the GPS/MET, CHAMP, and SAC-C missions. Approximately 45 % of all CHAMP and SAC-C 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 nearly 1 % compared to NWP models. When constrained to the tropics, the CHAMP data show a negative refractivity bias of approximately 1.7 %, and only 20 % of occultation profiles reach 1 km. Current CDAAC LEO orbit determination for CHAMP agrees with JPL orbits at the 30 cm 3D root mean square level, which can result in temperature errors of about 0.3 degrees K at 30 km altitude.

Introduction

In 1995, the University Corporation for Atmospheric Research (UCAR) in collaboration with the Jet Propulsion Laboratory (JPL), the University of Arizona, and Orbital Sciences Corporation demonstrated the concept of GPS active limb sounding with the launch and successful two-year operation of the GPS/MET receiver payload. This success has led to a joint

U.S.-Taiwan six spacecraft follow-on mission called the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC), which is funded and due to launch near the end of 2005. A diagram illustrating the data flow of the ground and space segments of the COSMIC system is shown in Figure 1. Each spacecraft will carry three payloads: 1) a GPS Radio Occultation (RO) receiver designed by JPL 2) a Tiny Ionospheric Photometer (TIP) and 3) a Tri-Band Beacon (TBB). 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 Archival Center (CDAAC) at UCAR in Boulder, CO. The CDAAC will analyze the GPS RO data and make it available to operational weather centers, universities and research institutions. In prepartion

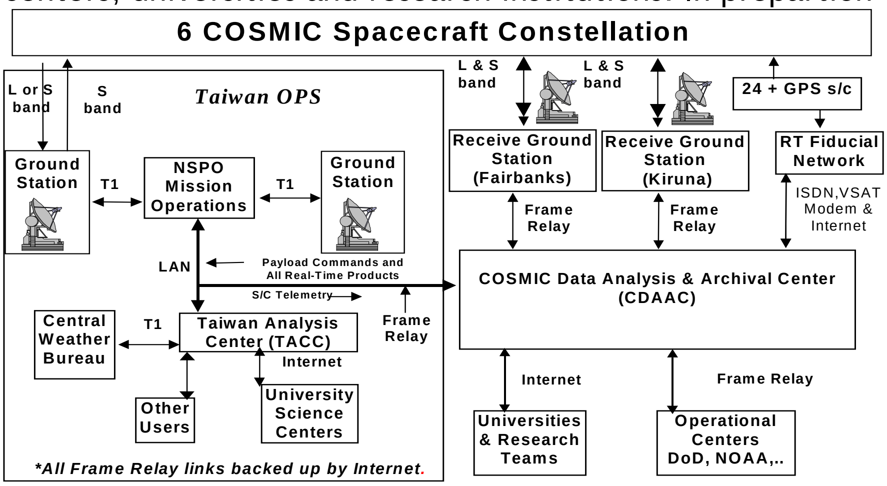

Fig. 1. The CDAAC within the COSMIC System

for the upcoming COSMIC mission, UCAR has been developing the CDAAC. A CDAAC prototype (version 1.0) has been finished and is now processing RO data from available missions such as GPS/MET, CHAMP and SAC-C in a post processing mode. This paper describes the CDAAC, gives an overview of its architecture, data processing software, and initial results that were obtained from neutral atmospheric RO data processing with emphasis on CHAMP and SAC-C.

The CDAAC System

The main responsibilities of the CDAAC are: payload monitoring, incoming data quality checking, RO data processing, validation, and data archiving and distribution. The CDAAC RO data processing will be performed in two modes: 1) a quasi-operational near real time mode where data are continuously analyzed and fed to operational weather centers within 3 hours of observation and 2) a more accurate and better validated post processed mode to be used for climate and other research applications. Initially, Level 0 data consisting of a raw dump of LEO data, IGS GPS orbits (predicted or final), and GPS ground fiducial data flow into the CDAAC and are quality checked and reformatted into a mission independent set of level1a data files. The level1a to level1b processing consists of LEO precise orbit determination (POD), generation of an occultation table, and the calibration of excess atmospheric phase delay for each RO. The level1b excess phase and amplitude files are lastly inverted into level2 profiles of refractivity with the Abel inversion software. The CDAAC system is controlled by an event driven task scheduler, where tasks are automatically put on a processing queue when their corresponding dependencies (usually files) arrive on disk. This task scheduler is well suited for real time processing. A separate post-processing subsystem can also be run when all dependency files are present. All RO geometry as well as analysis information from each process are stored in a database. A web-based interface to this database is used to analyze and validate all CDAAC data products. The CDAAC software runs in a UNIX operating system, is written predominantly in Perl and Fortran, and is version controlled using CVS software. The current CDAAC development hardware consists of 2 dual Pentium-III 700 MHz machines connected to a RAID. More details regarding the CDAAC can be found at http://www.cosmic.ucar.edu/cdaac/index.html. Some details regarding level1a-to-level2 processing will now be discussed.

Level 1a to Level 1b Processing: Calibration of Excess Phase Delay

The most critical step in calibrating the atmospheric excess phase delay for a RO event is the POD of the LEO spacecraft. The goal for CDAAC POD is to determine the relative LEO GPS velocity to about 0.1 mm/sec. This corresponds to a requirement to estimate the LEO position to 10 cm 3-D root mean square (rms). The CDAAC is using a beta version of the Bernese software to perform the LEO POD. This software uses a combination of kinematic point positioning and subsequent dynamic smoothing over a defined arc length to provide precise LEO orbits (Bock et al. 2000). The kinematic point positioning requires precise high rate GPS clocks that are estimated from ground GPS data while holding the GPS orbits, zenith troposphere delay and ground station coordinates fixed (Bock et al. 2001). The dynamic model that is used to smooth the kinematic LEO positions includes the EGM96 gravity field, a cannon ball drag model with MSISE90 air density, and constant and 1 cycle per orbit revolution empirical accelerations.

Once the GPS and LEO orbits are available, the CDAAC computes an occultation table that defines the date, time and location of all possible RO events. The excess phase delay is then computed for each event by removing the GPS and LEO orbital motion (known) and clock errors (via double differencing with 1 Hz ground data) from the raw RO observations. The excess phase delay can also be computed with single differencing (i.e. no ground data), which eliminates potential error sources from the ground GPS data (Rocken et al. 2000, Wickert et al. 2002). This method of processing has been coded, but not tested.

Level 1b to Level 2 Processing: Abel Inversion

The CDAAC Abel inversion software computes the level2 profile data from the level1b excess phase files. The inversion software first filters the excess phase and computes a Doppler profile, and then computes a bending angle versus impact parameter profile that is inverted to refractivity versus altitude with the classical Abel integral transform (Eshleman 1973). Because there is little signal at high altitudes, the bending angle near the top of a RO is combined with a climate-derived (CIRA+Q, (Kirchengast et al. 1999)) bending angle in a statistical optimization procedure (Sokolovskiy and Hunt 1996). In the lower troposphere, the bending angle profile derived from Doppler is frequently multi-valued because of multipath created by sharp moisture-induced refractivity gradients. The CDAAC has tested three radio holographic methods (Back Propagation (Gorbunov et al. 1996), Sliding Spectral (Sokolovskiy 2001), and Canonical Transform (Gorbunov 2001,2002)) that use both phase and amplitude data in an effort to create single-valued bending angle profiles that are required by the Abel transform. These tests were performed by forward modeling and inverting of RO signals using high resolution radiosonde data, and it was found that the Canonical Transform performed the best. Another necessary task that is performed by the software is to find and remove erroneous tracking data near the bottom of the RO, which is needed when the receiver tracks in either the closed loop or so-called "fly wheeling" mode. This objective data screening is done by comparing the observational Doppler with Doppler predicted from orbital motion and climatology, and discarding data with large deviation. This is based on magnitude of the weather-induced spread of Doppler in LEO estimated for open loop tracking (Sokolovskiy 2001a). Finally, all level2 data files are passed through a quality control procedure to remove corrupted profiles.

Early CDAAC Results

UCAR has now post processed a significant amount of RO data from the GPS/MET (1995.170-190), CHAMP (2001.148-309) and SAC-C (2001.213-299) missions with version 1.0 of the CDAAC software system. Processing data from different missions has helped discover and correct many software inconsistencies and has also provided an opportunity to compare each missions' POD and RO data quality. The remainder of the section presents CDAAC POD quality, RO data issues, and validation statistics with the use of independent data from atmospheric dynamic models.

POD Quality

The POD quality results for each mission are shown in Table 1. Internal orbit overlaps are computed as the rms difference (over 1 orbit) between two adjacent CDAAC orbit solutions and are a good indicator of orbit quality, but they can be optimistic if the orbit errors in adjacent solutions are correlated. A better indicator

Table 1. CDAAC LEO POD Quality Results

Mission	Altitude [km]	Date Range	Internal Orbit Overlaps 3D rms [m]	External Orbit Overlaps with JPL (IGSLEO) 3D rms [m]	Resulting Temperature Error at 30 km [K]
GPS/MET	735	1995.170-192	0.5	-	0.4
CHAMP	430	2001.140-150	1.0	1.5	0.8
SAC-C	700	2001.213-226	0.3	-	0.3

of orbit quality is to compute the rms difference between orbits from different
processing centers, called an external orbit overlap. The average CHAMP external overlap of 1.5 m 3D rms with the JPL IGSLEO orbits is large due to gravity and drag forces that are difficult to model precisely at an altitude of 430 km. The JPL orbits are believed to be accurate at ~15 cm 3d rms. The last column in Table 1 gives an estimate of the retrieval temperature error at 30 km altitude due to the orbit error. As

stated above the CDAAC goal for post processed orbit position quality is 10 cm 3D rms (~0.1 mm/sec in velocity).

Radio Occultation Data Issues/Problems

We have noticed several repeatable issues/problems with the CHAMP and SAC-C RO data, which were not present in the GPS/MET data. These issues generally do not cause serious problems for the inversion process. Figure 2 shows a plot of observed Doppler minus predicted Doppler (based on CIRA+Q) for a typical CHAMP RO from 2001.148. One can see from Figure 2 that the CHAMP data have large tracking errors for the initial 1-2 seconds of a RO, L1 and L2 Doppler spikes every 5 seconds, and large L2 Doppler noise in the lower troposphere. Other data problems we have noticed include: the CHAMP receiver often start tracking below 80 km altitude, SAC-C has small one-second L1 Doppler spikes,

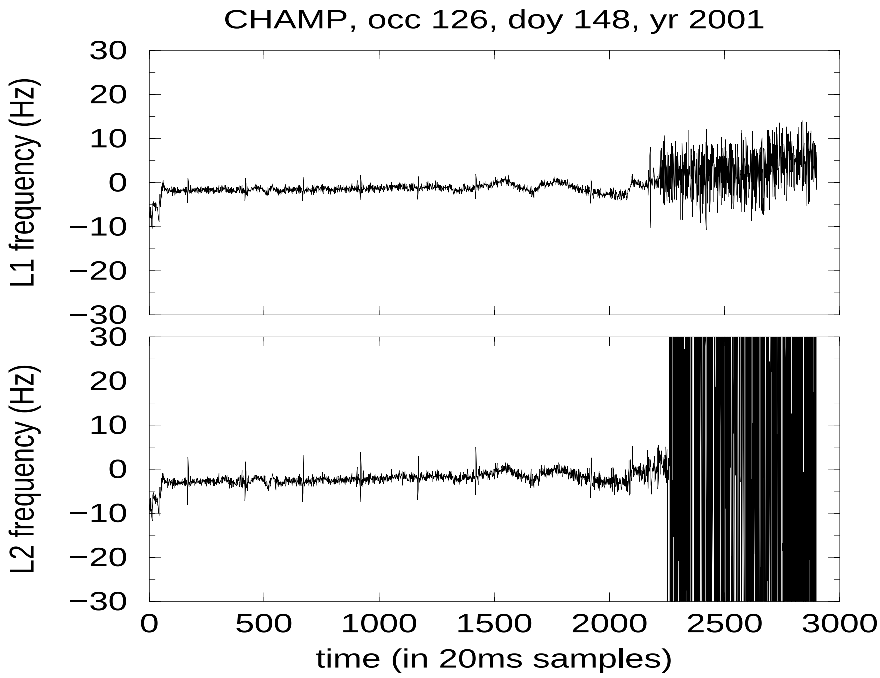

Fig. 2. Residual Doppler plot showing some CHAMP receiver tracking issues

and SAC-C has larger L2 Doppler noise than CHAMP. It should be noted that these observations regarding the CHAMP and SAC-C RO data were noticed in data collected early on in the missions and they may have already been corrected by the JPL receiver group.

Validation Statistics

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 has been used to generate refractivity statistics for CHAMP, SAC-C, and GPS/MET as shown in Figures 3-6, respectively. All RO profiles have been computed in the lower troposphere with the Canonical Transform method. The correlative data profiles are interpolated to the time and location of the RO. The GPS/MET profile data are compared to ECMWF, and the CHAMP and SAC-C data are compared to NCEP's low resolution Aviation Weather Model (AVN) because the ECMWF or high resolution NCEP data were not yet available. Figures 3-5 show the global mean and rms deviation of the differences between the RO's and model refractivity profiles, and the number of matches as a function of altitude for each mission. One can see from the figures that the mean percent difference in refractivity is less than ~1 % from the surface to ~17 km (the maximum altitude for AVN) 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 RO's that penetrate below 1 km altitude is ~45% 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 deg < latitude < 30 deg. These results are shown in Figure 6 and exhibit a clear degradation due to tropical moisture. The mean percent difference in refractivity in the lower troposphere increases to ~1.7% and the percentage of RO's that penetrate to 1 km altitude is approximately 20%.

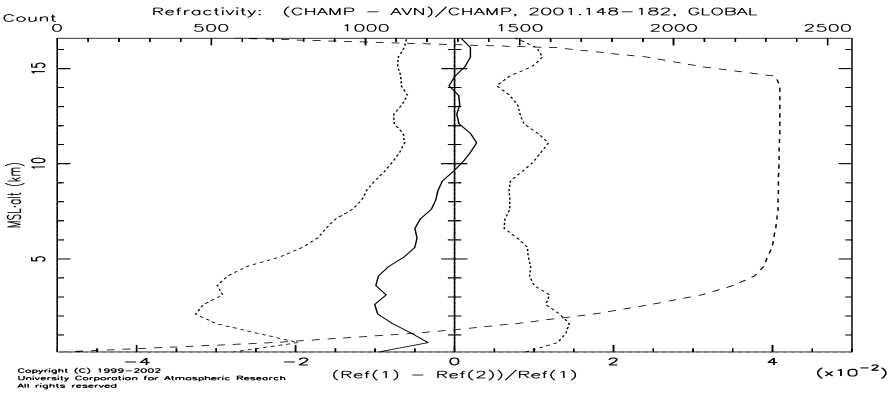

Fig. 3. Mean (solid), rms (short dash), and count (long dash) global comparison statistics between CHAMP occultations and AVN model. Approximately 45% of occultations penetrate to below 1 km

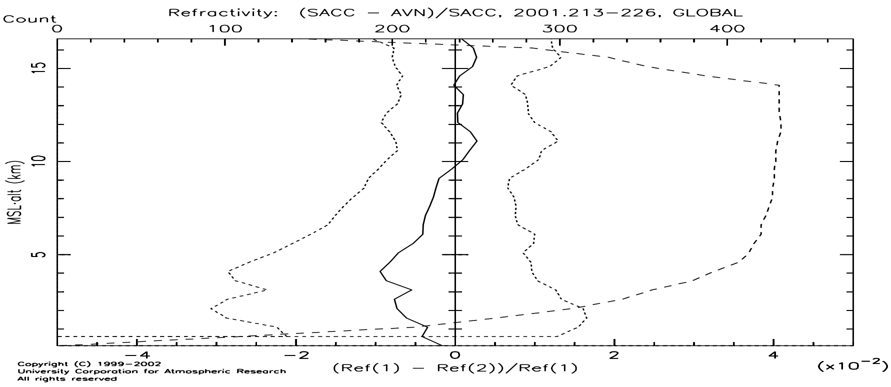

Fig. 4. Global comparison statistics between SAC-C occultations and AVN model. Approximately 45% of occultations penetrate to below 1 km

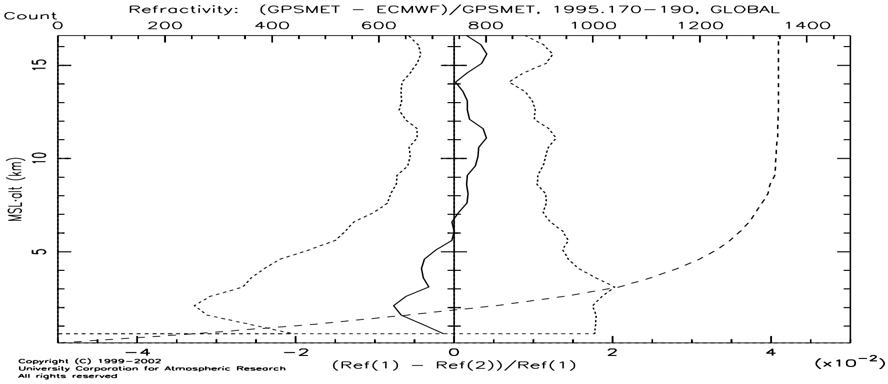

Fig. 5. Global comparison statistics between GPS/MET occultations and ECMWF model. Approximately 35% of occultations penetrate to below 1 km

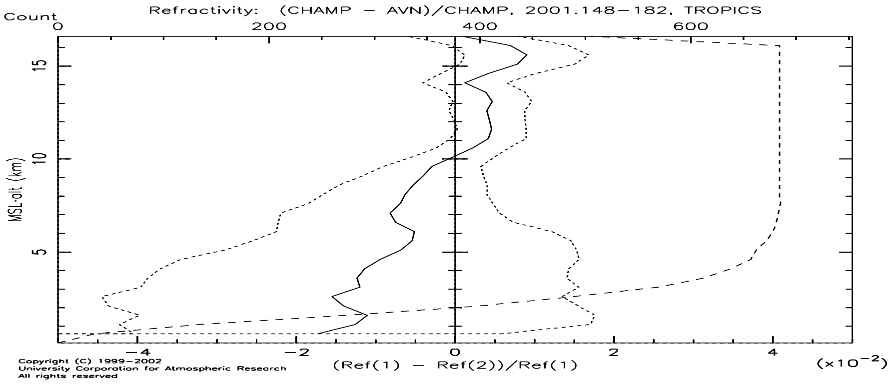

Fig. 6. Tropical comparison statistics between CHAMP occultations and AVN model. Approximately 20% of occultations penetrate to below 1 km

Conclusions and Future Work

UCAR has successfully inverted and catalogued over 15,000 RO's from the CHAMP (9,500), SAC-C (5,400), and GPS/MET (1,300) missions with version 1.0 of the CDAAC software. This analysis has enabled UCAR to identify problems and issues that should be studied and hopefully resolved before the COSMIC launch in 2005. The validation statistics presented above show a lack of penetration in the lower troposphere, especially in the tropics where only ~20% of the RO profiles penetrate to 1 km altitude. In addition, the tropical refractivity statistics for CHAMP show a significant bias below 10 km altitude with respect to the AVN model (and to radiosondes, not shown) that approaches 1.7% near the Earth's surface. It is not yet clear to what extent these lower troposphere problems are caused by receiver tracking errors, insufficient antenna gain, and atmospheric super-refraction. Open loop tracking data will be acquired in the near future by the SAC-C receiver and may provide some insight into this problem. Another area of concern is related to CHAMP and SAC-C tracking errors, such as Doppler spikes, but these issues are not catastrophic to the inversion procedure and are expected to be resolved for COSMIC. A final issue that must be addressed before the COSMIC launch is the CDAAC POD quality. The post-processed results presented above using a preliminary version of the Bernese LEO POD software (i.e. 1.5 m 3D rms difference with respect to JPL CHAMP orbits), have already been improved. Recent CDAAC CHAMP POD results obtained with the new gravity model EIGEN (Reigber et al. 2001) show agreement with the JPL orbits at the 30 cm 3D rms level for the period 2001.140-150. The approach to be used for the near real time orbit determination mode is still being studied, but is not expected to significantly degrade the higher level data products. GeoForschungsZentrum (GFZ), JPL, and UCAR have just initiated a study effort called ROSE (Radio Occultation Sensor Evaluation) to compare RO results between agencies. This effort should lead to a better understanding of RO issues and will provide the best possible GPS receiver payload for the COSMIC mission.

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