# Evaluation of refractivity profiles from CHAMP and SAC-C GPS radio occultation

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**Summary.** Since their launch, CHAMP and SAC-C have collected thousands of GPS radio occultations. In order to evaluate the refractivity derived from these radio occultation measurements by the Jet Propulsion Laboratory (JPL) using geometrical optics, we compare CHAMP and SAC-C refractivity with refractivity calculated from the Data Assimilation Office (DAO) 6-hour forecast global fields of temperature and humidity. We show that the differences between DAO and CHAMP refractivity present biases and standard deviation very similar to those of the differences between DAO and SAC-C refractivity. We also demonstrate a seasonal cycle in the standard deviation of the differences for altitudes below 12 km. Furthermore, the histograms of the differences for CHAMP and SAC-C are very similar, which is important for future assimilation and climate studies using GPS radio occultation from various missions. The skewed distributions usually translate into an apparent refractivity bias.

**Key words:** Radio-occultation - Refractivity - Skewness - Seasonal cycle - Data assimilation

## 1 Introduction

The CHAMP [WBS03] and SAC-C missions have each collected more than 30,000 GPS radio occultations since May 2001 (July 2001, respectively). Both missions carry a second-generation Blackjack receiver, capable of sounding the lower troposphere closer to the surface than the proof-of-concept GPS Meteorology experiment (GPS/MET). Theoretical studies [HE00] as well as studies based on data from the GPS/MET [PJK02] have suggested that GPS

radio occultation data could have a potential impact on data assimilation applied to Numerical Weather Prediction (NWP) and/or climate studies. With the wealth of GPS radio occultation data now available, the NWP community is now given an amount of observations which compete in number with other observing systems (e.g. radiosondes) with, for example, the advantage that radio occultation observations collected by a high-inclination Low-Earth Orbiter are distributed more evenly on our planet.

In the present paper, we compare DAO 6-hour forecasts with CHAMP and SAC-C refractivity derived by JPL using geometrical optics, for a total of about 54,000 occultations. Advanced processing methods such as back-propagation and canonical transform have been developed by radio occultation processing centers, but they were not considered in the present study because we needed an extensive dataset, and also because geometrical optics is widely in use. We also investigate the distribution of the differences in terms of histograms to potentially verify the usual assumptions used in variational retrievals and data assimilation (Gaussian unbiased errors).

## 2 Methodology

In order to evaluate the refractivity derived from CHAMP and SAC-C, we investigate time, latitude and altitude dependence of the differences between DAO 6-hour forecasts and refractivity derived from radio occultation. We focus here on 6-hour forecasts because our interest is future assimilation of refractivity into latest available 6-hour forecasts. All the refractivity differences are DAO forecasts minus occultation retrievals (or "observed" refractivity), expressed in percent of observed refractivity, in order to account for the fact that refractivity decays exponentially with altitude and spans about two orders of magnitude between the surface and 30km altitude.

### 2.1 Refractivity Derived from DAO Forecasts

We ran the DAO Finite Volume Data Assimilation System between April 2001 and April 2002 with a horizontal resolution of 2×2.5degrees (lat/lon) and 55 levels between the surface and 0.01hPa. Conventional observations (including radiosondes) as well as (A)TOVS brightness temperature and SSM/I precipitable water were assimilated. No GPS radio occultation observations were assimilated in this run. We derived local refractivity at the tangent point latitude/longitude/altitude reported in each occultation by applying the formula derived by Smith and Weintraub [SW53]. We did not perform any horizontal averaging to account for the effects of horizontal refractivity gradients.

### 2.2 Refractivity Derived from CHAMP and SAC-C

We used the refractivity data obtained by JPL, available through an anonymous FTP website (http://genesis.jpl.nasa.gov). Details of the geometrical

optics processing employed to process the raw radio occultation measurements can be found in the literature [HA02]. The data producers rejected all occultations presenting for any point between the surface and 30 km altitude a difference with respect to NCEP analyses more than 10% in refractivity or or more than 10K in retrieved temperature. We did not apply any further quality control to the dataset. Table 1 shows the number of occultations used in our study.

**Table 1.** Number of radio occultations used in the present study.

| | May 2001 | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan 2002 | Feb | Mar | Apr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CHAMP | 2295 | 3284 | 2352 | 1157 | 1715 | 2717 | 2666 | 1995 | 3245 | 2698 | 3785 | 2175 |
| SAC-C | - | - | 824 | 3249 | 3994 | 2835 | 2666 | 2339 | 3183 | - | 3467 | 1769 |

### 2.3 Origins of the Refractivity Differences

The refractivity differences we are looking at in the present paper arise from three error types: representativeness, observation, and forecast errors. The first errors include limitations in our observation operator (assumes local refractivity and does not account for horizontal gradients). The term 'observation errors' covers "GPS radio occultation"-related issues, many of which are discussed by other authors in the present volume (e.g. limitations of the geometrical optics processing, hardware and software tracking of the occultations etc.). Eventually, forecast errors represent a motivation for assimilating GPS radio occultation data in NWP.

## 3 Mean and Standard Deviation of the Differences: Large-Scale Space and Time Variations

It is of prime importance for the purposes of data assimilation to use adequate errors in order to ensure adequate weighting of the observations versus other sources of information (i.e. numerical forecast, other observations). These errors are usually modeled as Gaussian errors in data assimilation systems, thus requiring *a priori* knowledge of the mean departure (bias) as well as the standard deviation.

We investigate first the spatial variations of the differences at a given time (January 2002, entire month). Figure 1a shows the bias for the DAO minus CHAMP refractivity. This bias has already been reported by several authors [e.g. [RAE97]]. Its origins have been investigated recently with end-to-end simulations and are shown to be related to the geometrical optics processing method as well as measurement errors caused by the closed-loop GPS signal

tracking algorithm as implemented in the current receivers [AMH03]. The magnitude of the bias decreases with altitude and is more important in the lower atmosphere, where water vapor is more abundant. We found that the regions of higher bias move with latitude and seasons. Figure 1b is the same plot but for SAC-C refractivity. It is reassuring to notice very similar patterns, except for a small -0.5% bias in the Tropics between 7 and 20 km altitude.

Figure 1c shows zonal averages for the standard deviation of the differences. Those are larger in the lower layers where horizontal gradients play a larger role. The numbers agree with the SAC-C results shown in Figure 1d.

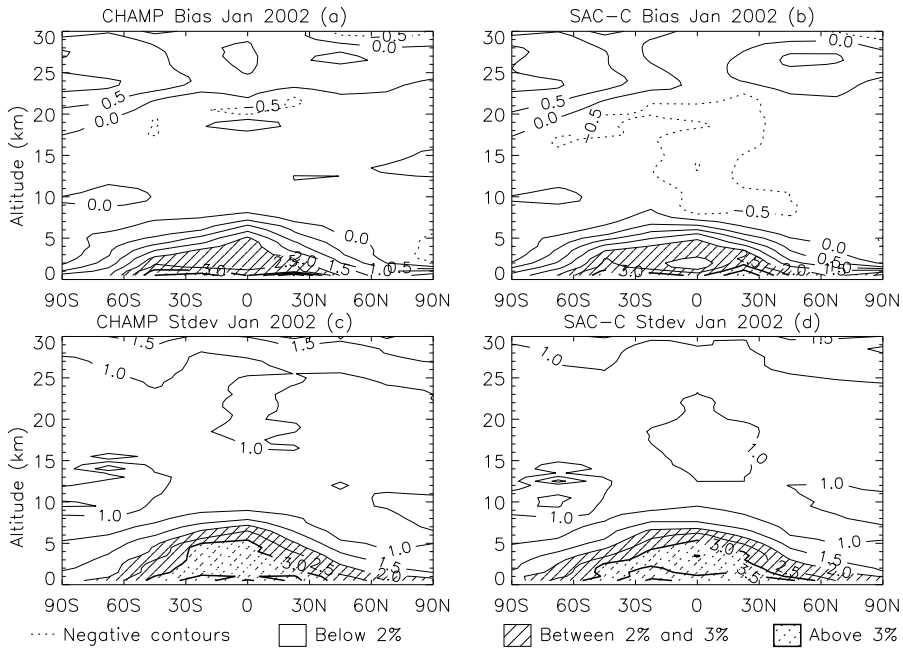


**Fig. 1.** Zonal averages of bias and standard deviation of the differences between DAO 6-hour forecasts refractivity and CHAMP (SAC-C). Contour every 0.5%.

Figure 2a shows the variations in the standard deviations throughout one year (from May 2001 until April 2002) for CHAMP, at 5.5km altitude. For a fixed latitude in the Northern hemisphere (45°N for example), a seasonal cycle can be seen: larger standard deviations occur in July. This cycle appears smaller in the Southern hemisphere but the idea is similar. Larger standard deviations are observed in the summer hemisphere. Figure 2b shows similar results for SAC-C. Figure 2c is for a lower altitude (3.5km), where more humidity is present. Humidity may play a role in the refractivity differences through the three sources of errors. Consequently, it is not possible to sort out the origin of the seasonal cycle shown here. The seasonal cycle appears definitely

stronger in the Northern hemisphere than in the South. These conclusions are reinforced by looking at Figure 2d (for SAC-C), as well as Figures 2e and 2f (2.5 km altitude).

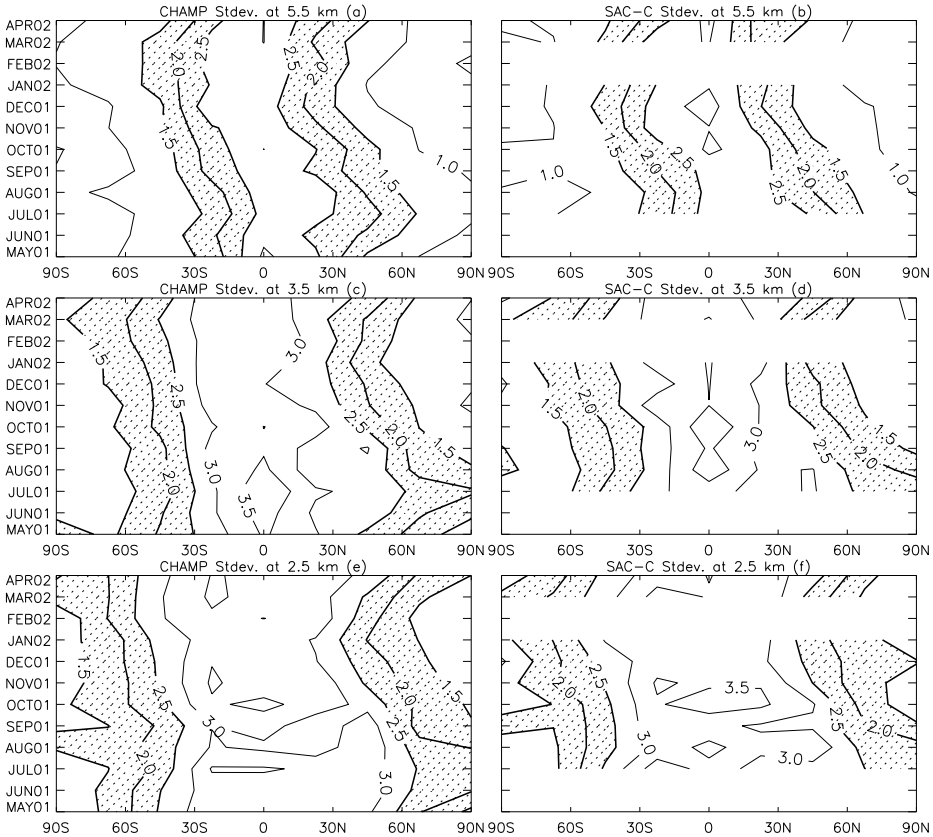


**Fig. 2.** Time evolution of the quantities shown in Figure 1 for several altitudes (2.5km, 3.5km, and 5.5km, standard deviations only). Shaded area: standard deviation between 1.5% and 2.5%. Note for SAC-C: no data for May and June 2001, and missing data for February 2002.

## 4 Histograms of the Refractivity Differences

As stated earlier, assimilation methods usually assume Gaussian errors. We attempt to verify this assumption by inspection of histograms of the refractivity differences. Figure 3 shows histograms of refractivity differences DAO minus CHAMP and DAO minus SAC-C (for all 54,000+ occultations). We use

the same x-axis for all figures (between -5% and +5%), and within each figure the distributions are normalized (i.e. each distribution was divided by its respective maximum). The excellent agreement of the refractivity differences between both satellites gives an indication of the robustness of these results. It also testifies that two similar GPS receivers onboard different satellites describe the same atmosphere, which is very important for climate monitoring and data assimilation. It ensures for now that the radio occultation data to be assimilated are consistent from one mission to the other.

For example, the histogram corresponding to 5 km altitude and 10S-10N latitude exhibits a skewed shape. The mode of the distribution is at zero, which indicates that the maximum likelihood is encountered for differences of zero. However, events with a positive differences are more common than events with a negative difference, thus leading to a skewness, and then a bias (2.3%) in the distribution. A Gaussian fit (not plotted here for clarity purposes) would show the positive bias that results from the skewed distribution. Also, we found that the Gaussian fits always underestimate the number of events that occur for zero differences. This results stands for all altitudes and all latitudes.

Figure 4 shows the dependence of the skewness of the refractivity differences mentioned before as a function of altitude and latitude. This skewness is similar for CHAMP and SAC-C and appears to be negative at altitudes 8-10 km in the Tropics, but positive at high latitudes and below 6 km altitude.

## 5 Conclusions and Future Directions

This study compares about 30,000 CHAMP and 24,000 SAC-C geometrical optics refractivity profiles with DAO 6-hour forecasts. The results obtained in this study will be used to refine error characteristics in order to perform one-dimensional variational analyses of the refractivity profiles derived by radio occultation. It seems that the refractivity differences do not vary with much intensity over time, although a seasonal cycle in the differences is observed for mid-latitudes in both hemispheres (apparently stronger in the Northern hemisphere than in the South). The refractivity differences show fairly constant means and standard deviations between 12 and 28 km altitude.

The histograms of refractivity differences are very similar for CHAMP and SAC-C, which is important for future use of these data for data assimilation and climate monitoring. The histograms present skewed distributions, whose skewness varies as a function of latitude and altitude. Since Ao et al. [AMH03] showed that the refractivity bias can be reduced by processing with an advanced processing method such as the canonical transform and with implementation of open-loop tracking onboard the GPS receiver, it is anticipated that the present study will have to be repeated when an improved extensive dataset becomes available. Already, preliminary comparisons made with data

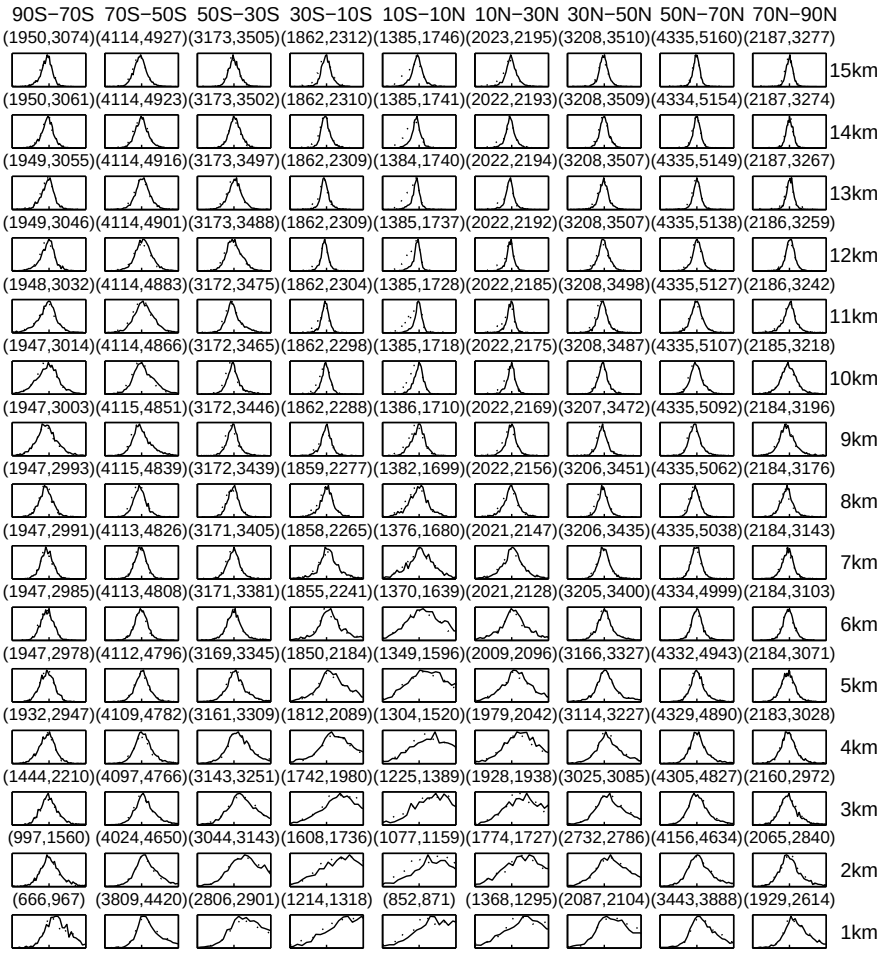


**Fig. 3.** Histograms of the refractivity differences for CHAMP (solid) and SAC-C (dotted). Each row corresponds to a different altitude and each column corresponds to a different latitude band (in parentheses: number of occultations for SAC-C and CHAMP, respectively). All plots use an x-axis [-5%,+5%]

produced with advanced methods suggest that the refractivity biases are reduced as compared to geometrical optics refractivity, and that the standard deviations of the differences DAO minus CHAMP remain similar [PAT03].

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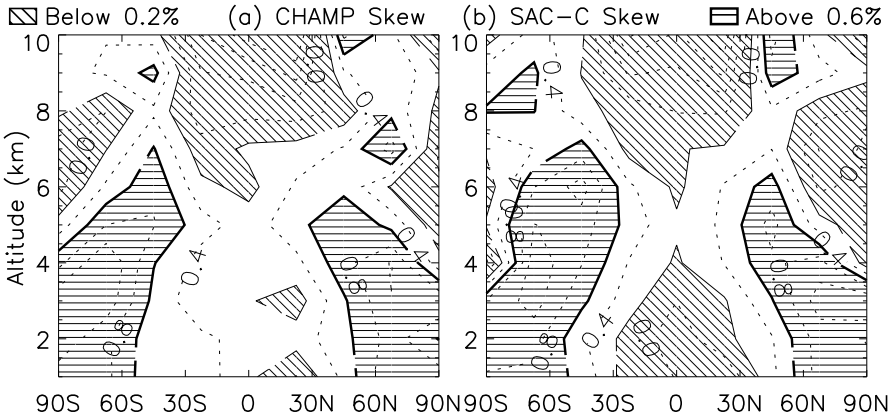


**Fig. 4.** Skewness coefficients for the refractivity differences DAO 6-hour forecast minus CHAMP (SAC-C) refractivity. Contour every 0.2%.

Res., **Accepted,** doi:10.1029/2002JD003216 (2003)

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