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# Analysis and validation of Challenging Minisatellite Payload (CHAMP) radio occultation data

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[1] We performed statistical comparisons of data from Challenging Minisatellite Payload (CHAMP) with European Centre for Medium-Range Weather Forecasting (ECMWF) analyses. Our data processing technique includes: (1) radio holographic (radio optics) and canonical transform analysis of wave fields, (2) visualization of the local spatial spectra of wave fields for interactive data quality control, (3) ionospheric correction and noise reduction based on statistical optimization, (4) Abel inversion, and (5) comparison of CHAMP and ECMWF data based on forward modeling and inversion of artificial radio occultation data. In the tropics and midlatitudes at heights below 10 km, the CHAMP-ECMWF differences are significantly greater than the GPS Meteorology (GPS/MET)-ECMWF differences. Because big systematic negative differences between observed and simulated refraction angles are also observed in this region, we can explain that by poor quality of the CHAMP data in multipath regions due to signal tracking errors. Elsewhere, systematic CHAMP-ECMWF differences do not exceed 1 K in the tropics and polar latitudes, and 0.5 K in midlatitudes, and deviations of CHAMP data from ECMWF analyses are smaller than those of GPS/MET data. This can be explained by enhancement in the latest ECMWF analyses. *INDEX TERMS:* 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 6969 Radio Science: Remote sensing; *KEYWORDS:* radio occultation, CHAMP, validation

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## 1. Introduction

[2] In this paper we describe analysis and statistical validation of radio occultation data provided by Challenging Minisatellite Payload (CHAMP) [*Wickert et al.*, 2001]. The first GPS radio occultation soundings of Earth's atmosphere were performed by the Microlab-1 satellite, during the proof-of-concept GPS Meteorology (GPS/MET) experiment [*Ware et al.*, 1996; *Kursinski et al.*, 1996]. During the period 1995 to 1997 this satellite provided a big archive of measurement data, which played a very important role in assessing the capabilities of the radio occultation technique. The CHAMP satellite was launched on 15 July 2000. The mission objectives include determination of Earth's gravity and magnetic field, and limb sounding of Earth's neutral atmosphere and ionosphere by means of the GPS radio occultation technique. The satellite carries a "Blackjack" GPS flight receiver developed and built at the Jet Propulsion Laboratory. The receiver utilizes advanced signal tracking techniques. A high gain antenna allows for improved signal quality. CHAMP provides about 200 globally distributed soundings per day.

[3] The radio occultation technique has the following advantages: (1) it provides global coverage, (2) it is weather-independent, (3) the instrument does not require calibration, which provides long-term stability [*Kursinski et al.*, 1997; *Rocken et al.*, 1997], (4) a high vertical resolution of 50–100 m can be achieved [*Gorbunov et al.*, 1996b, 1996a; *Karayel and Hinson*, 1997; *Gorbunov and Gurvich*, 1998b; *Mortensen et al.*, 1999; *Gorbunov*, 2002b].

[4] The difficulties in processing radio occultation data can be classified as follows:

[5] 1. Radio occultation data are sensitive to atmospheric refractivity, which depends on temperature, pressure, and humidity. Using the hydrostatic equation it is possible to retrieve temperature and pressure from refractivity profiles above 7–12 km [*Gorbunov and Sokolovskiy*, 1993; *Rocken et al.*, 1997], where the atmosphere is dry. In the lower troposphere the humidity term in refractivity is significant, and some a priori information is necessary. It is only possible to retrieve humidity using a background temperature profile, or, vice versa, to retrieve temperature using a background humidity profile. Another solution is 1/3/4D

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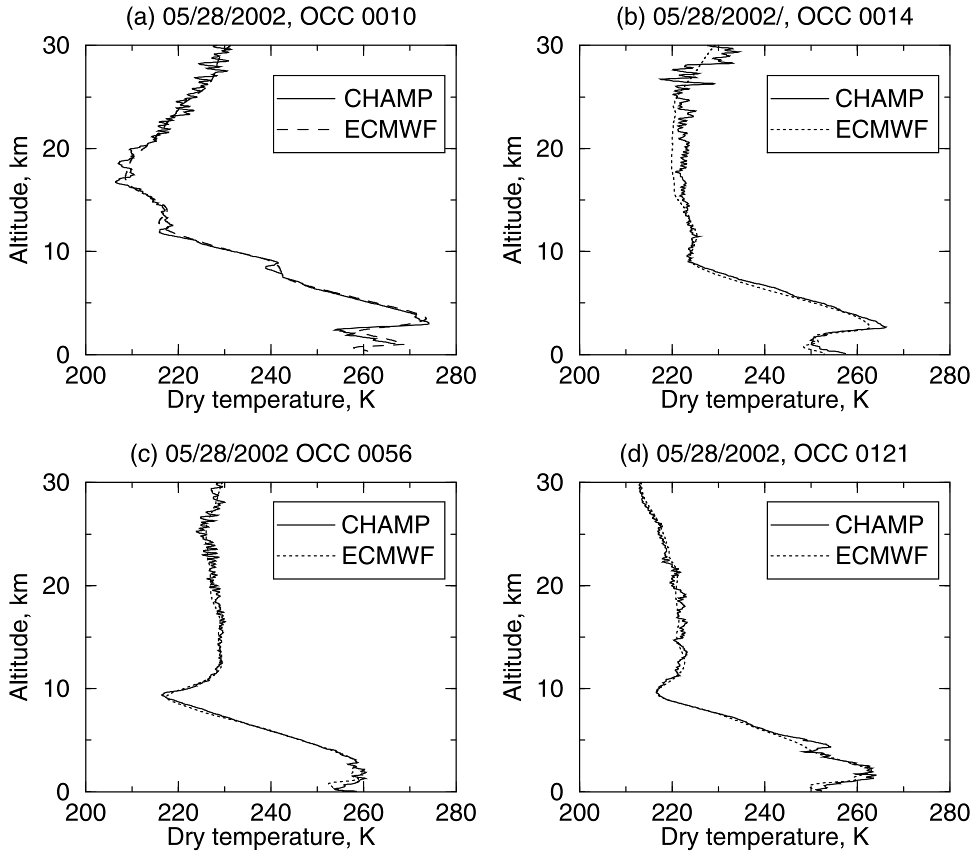


**Figure 1.** Examples of retrievals of dry temperatures for 4 occultations events observed on 28 May 2002: (a) event 0010, UTC 00:49, 36.3°N 127.9°E; (b) event 0014, UTC 01:15, 42.2°N 44.2°W; (c) event 0056, UTC 05:45, 78.8°N 105.9°W; and (d) event 0121, UTC 12:33, 54.9°S 136.1°E.

variational assimilation (1/3/4DVar) [*Eyre*, 1994; *Zou et al.*, 1995, 1999, 2000; *Kursinski and Hajj*, 2001].

[6] 2. Radio occultations, as all limb sounding techniques, provide integral information about the refractivity field along the line of sight. The characteristic scale of horizontal averaging is about 500 km [*Gorbunov and Sokolovskiy*, 1993]. Reconstruction of vertical profiles of refractivity is performed assuming local spherical symmetry, and thus horizontal gradients result in retrieval errors [*Ahmad and Tyler*, 1999; *Healy*, 2001]. This difficulty can also be overcome in the 3/4DVar approach. In the framework of 3/4DVar the use of such integral information of atmospheric fields can be preferable compared to local measurements performed by radio sondes.

[7] 3. Refractivity field in the lower troposphere, especially in the tropics, can have a complicated structure due to humidity. This results in multipath propagation of the radio waves that are received at the Low-Earth orbiter [*Gorbunov et al.*, 1996a; *Gorbunov and Gurvich*, 1998b]. The mathematical problem of inversion of measurements of the wave field diffracted by Earth's atmosphere has been recently solved to a significant extent [*Gorbunov*, 2001, 2002a, 2002b]. However, accurate measurement of wave fields in multipath zones remains the main technical problem [*Sokolovskiy*, 2001b; *Gorbunov*, 2002b; *Beyerle et al.*, 2003]. Strong scintillations of amplitude and phase and significant attenuation of the signal due to regular refraction often result in loss of track of the signal by the phase-lock loop.

[8] Our data analysis techniques include radioholographic (radio-optical) analysis [*Lindal et al.*, 1987; *Pavelyev*, 1998; *Hocke et al.*, 1999; *Igarashi et al.*, 2000; *Beyerle and Hocke*, 2001; *Gorbunov*, 2001; *Sokolovskiy*, 2001a] and the canonical transform (CT) method [*Gorbunov*, 2001, 2002a, 2002b]. Radio-optical analysis is a simple and efficient technique for data visualization. It is convenient for interactive data analysis, and it allows detection of some technical problems in the measurement data [*Gorbunov*, 2002b]. The CT method allows accurate derivation of refraction angle profiles from measurements of amplitude and phase at a high sub-Fresnel resolution [*Gorbunov*, 2001, 2002a, 2002b].

[9] For statistical validation we utilize the approach which was also applied for GPS/MET data [*Gorbunov and Kornblueh*, 2001]. We use reanalyses of the ECMWF. By means of wave-optics modeling of radio occultations signals we produce artificial radio occultation data with the same observation geometry as in real radio occultations. Then both real and simulated radio occultation data are processed by the same inversion algorithm. The derived refractivities, temperatures, and humidities are then compared. The inversion algorithm is based on Abel inversion in the approximation of local spherical symmetry [*Phinney and Anderson*, 1968; *Fjeldbo et al.*, 1971; *Ware et al.*, 1996]. So-called dry temperature is derived by neglecting

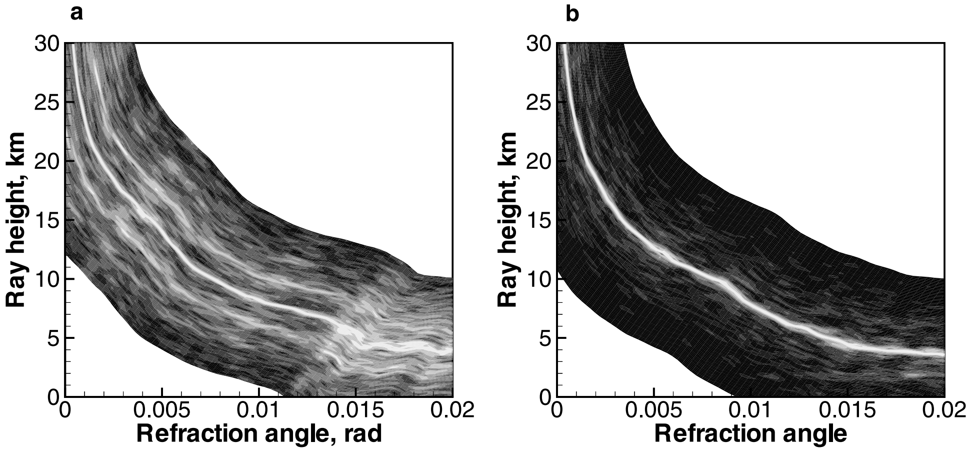


**Figure 2.** Examples of local spatial spectra of wave fields for two occultation events: (a) occultation event 0015 observed on 28 May 2002, UTC 01:17, 27.7°N 68.9°W, the spectra with parasitic modulation; and (b) occultation event 0024 observed on 28 May 2002, UTC 02:01, 44.1°S 105.9°E, the spectra of good quality data.

the humidity term in the refractivity [*Ware et al.*, 1996; *Gorbunov et al.*, 1996b; *Kursinski et al.*, 1997]. This method of comparison excludes inversion errors due to horizontal gradients and humidity. All the discrepancies between profiles derived from real and artificial data only result from measurement errors and the deviation of the reanalysis from the real state of the atmosphere. It must be noticed that forward modeling can also introduce additional

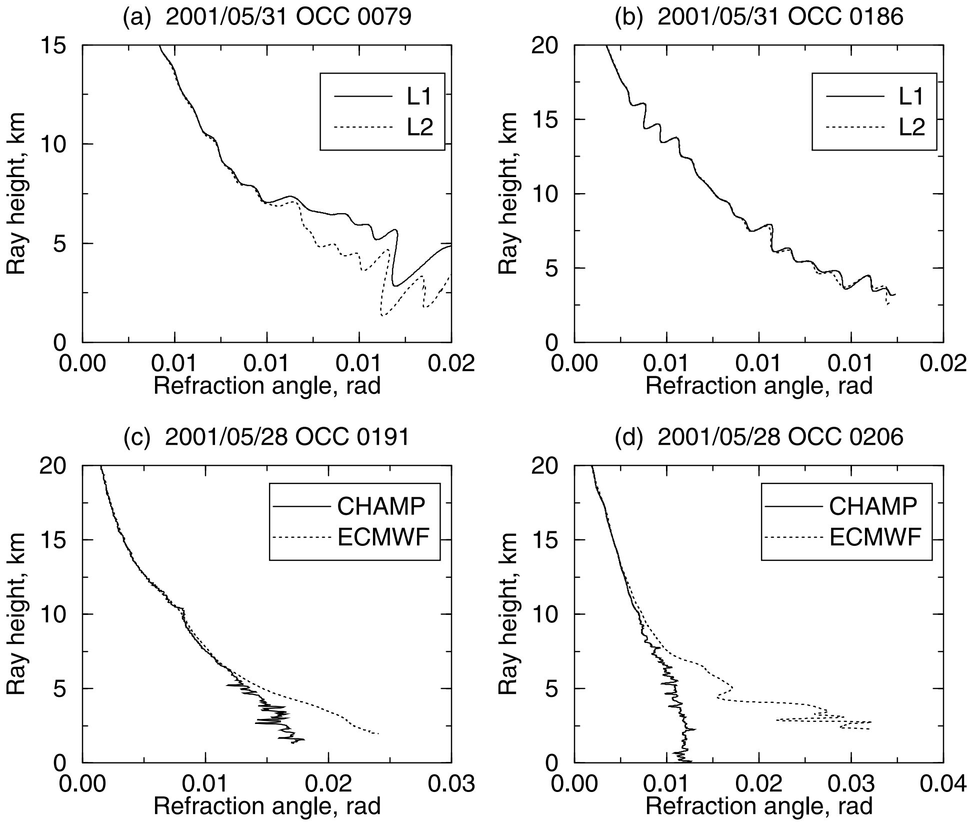


**Figure 3.** Examples of occultation events with different problems: (a) occultation event 0079 observed on 31 May 2001, UTC 08:38, 12.2°N 155.9°W, too big L1-L2 difference below 7.5 km; (b) occultation event 0186 observed on 31 May 2001, UTC 20:55, 47.7°N 12.2°W, strong perturbations in L1 and L2 channels at heights about 15 km and below 7.5 km; (c) occultation event 0191 observed on 28 May 2001, UTC 20:36, 60.9°S 157.7°W, very big errors in the lower troposphere; and (d) occultation event 0206 observed on 28 May 2001, UTC 22:29, 15.9°N 178.7°W, very big errors in the lower troposphere.

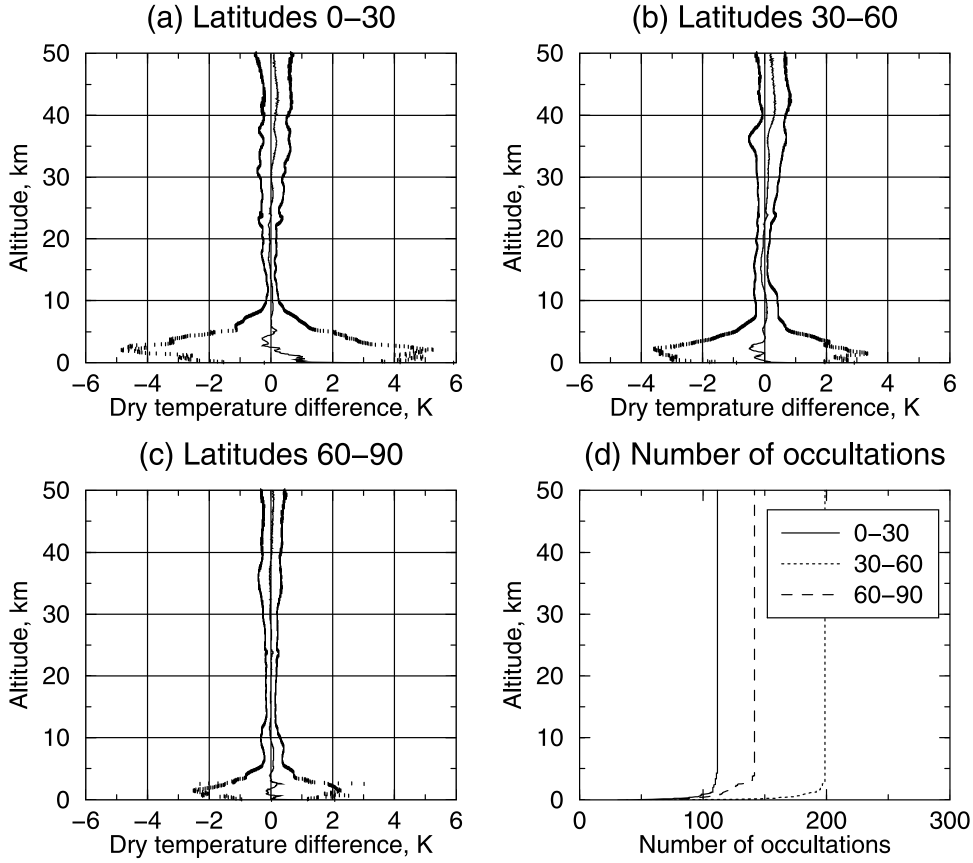


**Figure 4.** Abel inversion errors computed for radio occultations simulated using ECMWF reanalyses for three latitude zones: (a) 0–30°, (b) 30–60°, (c) 60–90°, and (d) numbers of occultations for each latitude zone.

errors. However, numerical simulations show that these errors are small enough (do not exceed 0.1–0.2 K).

## 2. Data Analysis

[10] Our data analysis technique includes the following important parts:

[11] 1. Ad hoc preprocessing algorithms which allow reduction of the amount of occultation that need to be sorted out. The final fragment of each occultation contains unusable data measured in shadow zone. These fragments need to be cut off because they create numerous problems for processing: (1) they may affect algorithms of monotonization of impact parameters, which are used to obtain single-valued profiles of refraction angles, and (2) they can impair CT processing. Using a very strong smoothing of L1 phase excess we computed an estimate of refraction angle profile and discarded data after the estimated refraction angle reaching some threshold, which was chosen to equal 0.03 rad. We also used a simple click-removal algorithm applied to L2 channel.

[12] 2. Radioholographic and canonical transform analysis of wave fields, which allow for accurate retrieval of bending angles. A combination of the back propagation [*Marouf et al.*, 1986; *Gorbunov et al.*, 1996a; *Karayel and Hinson*, 1997; *Gorbunov and Gurvich*, 1998a, 1998b] and canonical transform techniques [*Gorbunov*, 2001, 2002a, 2002b] is used. This technique of extracting the geometric optical ray structure of wave fields has the following advantages: (1) It allows for the simple formulation of the inverse problem in the geometric optical approximation, (2) it allows for achieving high resolution, which is defined by the size of the synthetic aperture and diffraction inside the atmosphere.

[13] 3. Plotting local spatial spectra of wave fields [*Gorbunov*, 2001]. This technique is a fast, simple, and efficient means for visualization of radio occultation data, which allows for data quality control.

[14] 4. Use of an ionospheric correction and noise reduction scheme based on statistical optimization [*Gorbunov*, 2002c]. The background estimation of refraction angles is computed using ECMWF reanalyses. Because below 3–7 km L2 data are unusable, they cannot be used in the ionospheric correction algorithm. We used an ad hoc procedure for cut-off unusable L2 data where L2-L1 difference significantly exceeds some estimate of the ionospheric effect [*Gorbunov*, 2002c].

[15] 5. Use of Abel inversion in order to retrieve refractivity profiles. Hybrid temperature profiles (also referred to as wet temperatures) are computed from refractivities using the hydrostatic equation and the background estimation of humidity [*Gorbunov and Sokolovskiy*, 1993; *Ware et al.*, 1996]. Dry temperatures are computed assuming a dry atmosphere. Using background profiles of temperature from the ECMWF reanalysis, the hybrid humidities are computed.

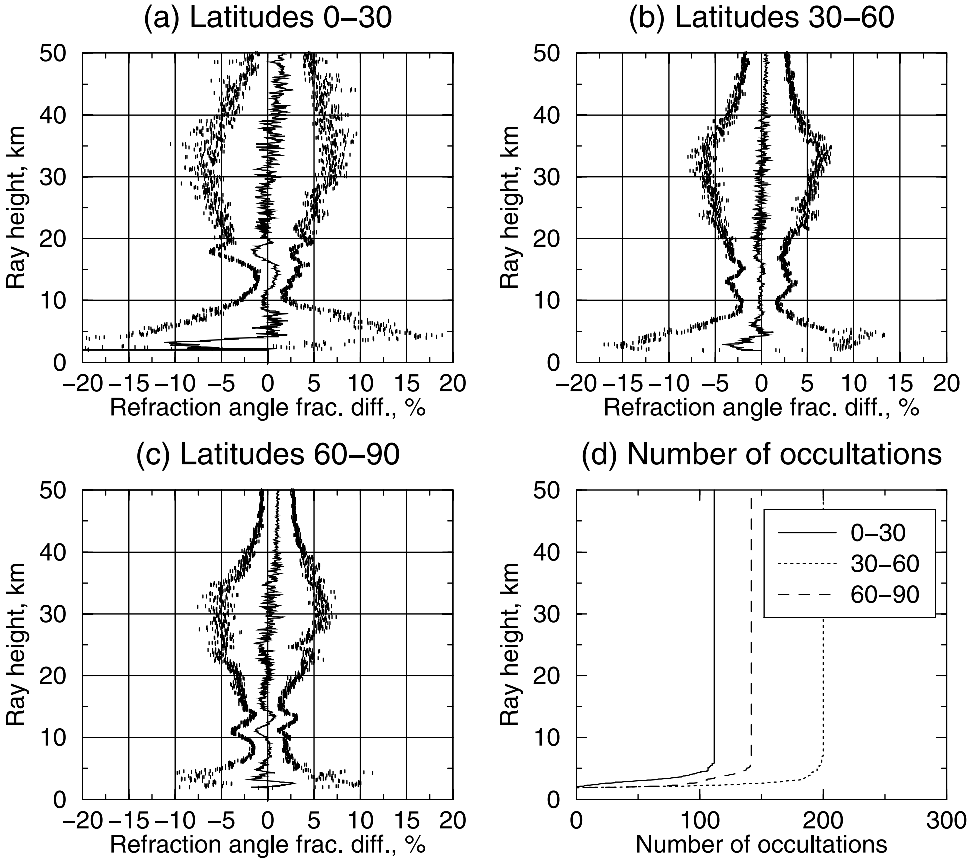


**Figure 5.** Differences of CHAMP and ECMWF refraction angles computed for three latitude zones: (a) 0–30°, (b) 30–60°, and (c) 60–90°, and (d) numbers of occultations for each latitude zone.

[16] 6. Comparison of CHAMP and ECMWF data using forward modeling. The reanalyses have a horizontal resolution of 0.5° × 0.5° and a height range up to about 60 km with 60 height levels. The vertical resolution is 25–250 m below 1 km and 300–600 m between 1 and 10 km. The time step is 6 hours. For each occultation we take the reanalysis nearest in time and compute artificial occultation data using the wave optics propagation model [*Gorbunov and Kornblueh*, 2001]. We do not interpolate the reanalyses in time, because the time difference between an occulation and the nearest reanalysis never exceeds 3 hours, and the RMS time difference is $\sqrt{3} \approx 1.7$ hours. We assume that the variability of the atmosphere within 1.7 hours can be neglected compared to the observed CHAMP-ECMWF differences. The artificial occultation data are then processed using the same algorithm as that used for processing real measurement data. This excludes the errors of Abel inversion due to horizontal gradients, because Abel inversion is applied both for real and artificial data. This comparison technique is superior to comparison of model local temperatures and retrieved temperatures, especially in the lower troposphere, because retrieved temperatures are complicated functionals of 3-D fields of atmospheric parameters rather than local temperatures. Statistics for the error due to the traditional way of comparing local model temperature with retrieved temperatures will be shown in section 3.

[17] Like in the processing of GPS/MET data, interactive data quality control is used. For this purpose the refraction angles, local spatial spectra, and inversion results are plotted for each occultation. Some examples of dry temperatures retrieved from CHAMP data and artificial occultations generated for the ECMWF reanalyses are shown in Figure 1.

[18] Some occultations were sorted out manually for different problems. Note, L2 data for ray heights below 3–7 km were always unusable, and at these heights only L1 refraction angles were used. We processed 4 days (28–31 May 2001) of data. From 608 occultations, 523 were found usable for further processing, and 85 were sorted out. The reasons for excluding data are as follows.

[19] 1. Thirteen occultations indicate parasitic modulation, which is visualized in the local spatial spectra of the wave fields. In the spectra plotted in ray coordinates (refraction angle, impact parameter) using pseudo-color, the refraction angle profile is visualized as a white line. Parasitic modulation results in additional parallel lines as shown in of Figure 2a. Figure 2b shows an example of good spectra without parasitic modulation.

[20] 2. In 11 occultations the measurements begin at too low a height (15–20 km). Our inversion algorithm requires measurements up to a height of 70 km or more.

[21] 3. Some of the occultations indicate a very low quality of L1 and/or L2 signal at heights below 20 km, some examples are shown in Figures 3a and 3b. The detailed analysis showed the following: (1) 12 occultations indicate localized perturbations in L1 and/or L2 channel that result in strong wave-like perturbations of the retrieved profiles; (2) 16 occultations indicate low quality in L1 and

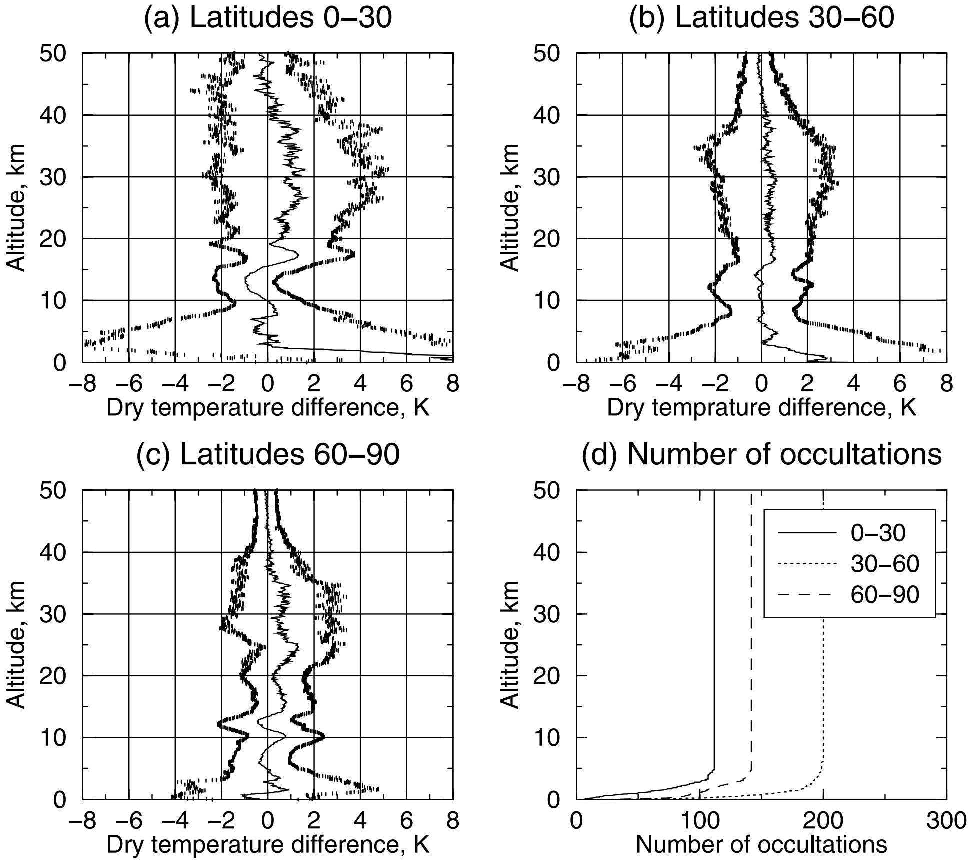


**Figure 6.** Differences of CHAMP and ECMWF dry temperatures computed for three latitude zones: (a) 0–30°, (b) 30–60°, (c) 60–90°, and (d) numbers of occultations for each latitude zone.

L2 lower tropospheric data, where unusable final part was still not cutoff and significantly impaired CT processing.

[22] 4. Twenty-three occultations indicate very high level of noise.

[23] (5) In 11 occultations, retrieved refraction angles deviate very strongly from their background estimates. Examples are shown in Figures 3c and 3d.

[24] (6) In 10 "weird" occultations the perturbations of phase path in the final fragment were so strong that they affected the retrieval of refraction angles even at heights of 20–25 km.

## 3. Results

[25] For each occultation artificial data were generated using ECMWF reanalyses. Then we used the same algorithm for processing real and artificial data, and compared the refraction angles, the retrieved refractivities, dry temperatures, and hybrid humidities.

[26] For each artificial occultation we compared retrieved dry temperatures and dry temperatures computed from the local refractivity profile. The local profile is taken above the location of the lowest ray perigee, which can be estimated from the satellite coordinates and refraction angle. This gives an estimate of the errors of Abel inversion due to horizontal gradients. The results of this comparison are shown in Figure 4. Comparisons are performed for 3 latitude zones 0–30 (30°S–30°N), 30–60 (30°S–60°S and 30°N–60°N), and 60–90 (60°S–90°S and 60°N–90°N).

[27] Figure 5 shows the results of statistical comparison of refraction angles computed from CHAMP and artificial data. The central line, which shows the average difference of refraction angles, indicates very small systematic bias. The biggest systematic deviations are at tropopause height, because tropopause is not well resolved by the ECMWF reanalyses. The refraction angles are functions of ray height defined as $p - r_E$, where $p$ is ray impact parameter, and $r_E$ is Earth's local curvature radius. Note that the ray height for the lowest ray touching Earth's surface is about 2 km. The standard deviation lines indicate that the best agreement is in the 10–15 km height interval. This height interval is most favorable, because the quality of measurement data is optimal here, due to the following reasons: (1) neutral atmospheric refraction angles are big enough, in comparison to ionospheric refraction angles, that errors due to imperfect ionospheric correction are reduced; (2) multipath propagation effects do not play a significant role, and so the quality of measurements is good.

[28] Below 10 km, the difference between CHAMP and ECMWF data increases abruptly, especially in the tropics. A big systematic negative difference is evident here. This is explained by the fact that below 10 km, effects of multipath propagation are significant, resulting in difficulties tracking the signal and hence reducing data quality [*Beyerle et al.*, 2003] (see also the discussion below).

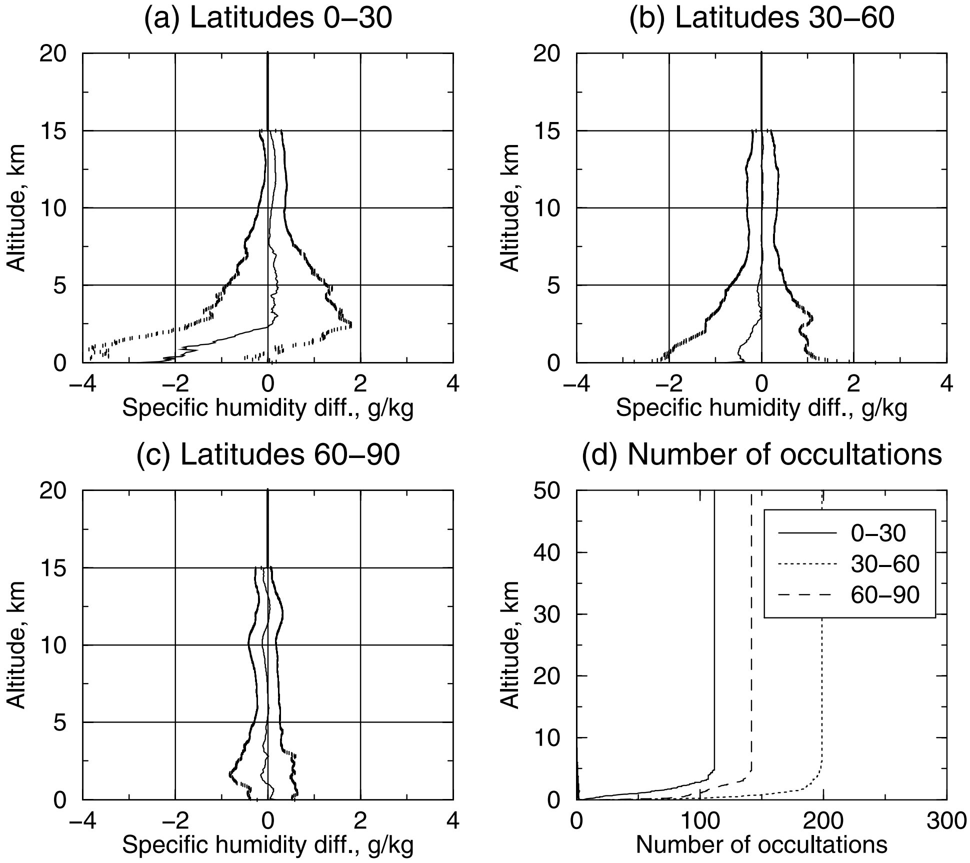


**Figure 7.** Differences of CHAMP and ECMWF hybrid humidities computed for three latitude zones: (a) 0–30°, (b) 30–60°, (c) 60–90°, and (d) numbers of occultations for each latitude zone.

[29] Above 15 km, the CHAMP-ECMWF difference increases and reaches its maximum at a height of 30–35 km. This is explained by the fact that neutral atmospheric refraction angles decrease approximately exponentially with height, while the magnitude of ionospheric refraction angles is approximately constant. Thus relative errors increase due to the imperfect ionospheric correction. Above 35 km, where ionospheric errors begin to dominate, the statistical optimization decreases the deviation of the estimated refraction angles from their background estimate, computed from ECMWF data.

[30] Figures 6 and 7 show statistical comparisons of retrieved dry temperatures and hybrid humidities. The CHAMP-ECMWF difference increases below 10 km. Above 3 km, the systematic difference does not exceed 1 K for tropical and polar latitudes, and it is below 0.5 K for midlatitudes. The biggest systematic retrieval error is observed in the tropics below 3 km. We can consider the following explanations for that: (1) effect of small-scale inhomogeneities, (2) Effect of super-refraction, and (3) signal tracking errors. Simulations with 2D models of lower-tropospheric inhomogeneities performed by *Sokolovskiy* [2003] showed that they do not result in big systematic retrieval errors. Super-refraction can be a source of significant systematic errors. However, refraction angle profiles can be accurately retrieved by the CT method also in presence of super-refraction layers [*Sokolovskiy*, 2003]. Figure 5 shows that big negative systematic CHAMP-ECMWF lower-tropospheric differences are also revealed in the comparison of observed and simulated bending angles. Simulation of tracking lower-tropospheric radio occultation signals was performed by *Sokolovskiy* [2001b], who showed that phase-locked loop (PLL) introduces significant tracking errors in the lower troposphere. Recent simulations [*Beyerle et al.*, 2003; C. O. Ao et al., Lower-troposphere refractivity bias in GPS occultation retrievals, submitted to *Journal of Geophysical Research*, 2003, hereinafter referred to as Ao et al., submitted manuscript, 2003] also show that the use of two-quadrant phase detector is a very significant error source even in open-loop tracking. The simulated retrieval errors in the work of *Beyerle et al.* [2003] and Ao et al. (submitted manuscript, 2003) are very similar to the observed CHAMP-ECMWF differences. This indicates that tracking errors must be looked at as the most probable explanation.

[31] The analysis of CHAMP data was also compared with a similar analysis of GPS/MET data acquired by the Microlab-1 satellite [*Gorbunov and Kornblueh*, 2001] during the Prime Time 4 period (2–16 February 1997). For this purpose, we reprocessed GPS/MET data using the latest versions of the processing software. Figure 8 shows statistical GPS/MET-ECMWF differences. In the tropics and midlatitudes, at heights below 10 km, rms difference CHAMP-ECMWF is much greater then RMS difference GPS/MET-ECMWF.

[32] This can be explained by the fly wheeling mode which the Blackjack receiver goes into in the lower troposphere. This allows the receiver to track lower in the

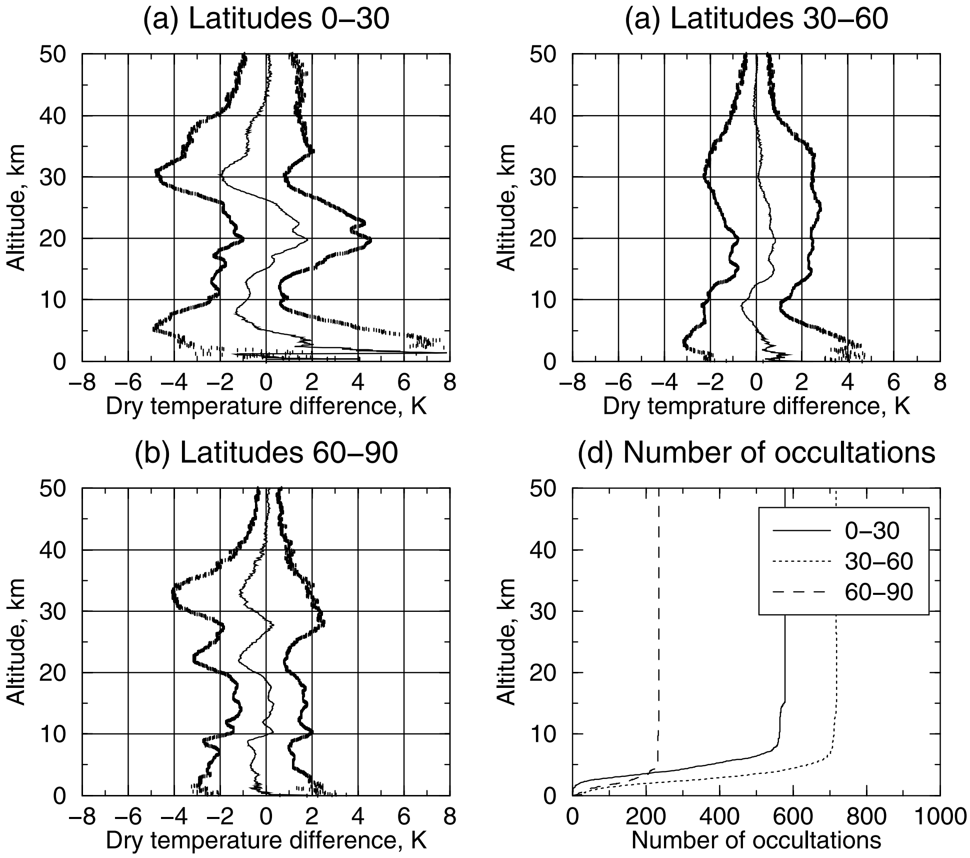


**Figure 8.** Differences of GPS/MET and ECMWF dry temperatures computed for three latitude zones: (a) 0–30°, (b) 30–60°, (c) 60–90°, and (d) numbers of occultations for each latitude zone.

atmosphere with the potential of creating large biases because of tracking errors. GPS/MET did not have fly wheeling during Prime Time 4 and therefore the signal was lost much higher in the atmosphere on average. This indicates that, potentially, CHAMP may provide more information about the lower troposphere. However, in order to release this potential, one must devise a quality control method which should filter out bad data. While big enough tracking errors can be detected by comparing RO signals to the signals modeled from orbit data and refractivity climatology, as outlined by *Sokolovskiy* [2001a, 2001b], complete automated sorting-out of corrupted data in the operational mode is a difficult problem (S. V. Sokolovskiy, personal communication, 2003).

[33] The results for midlatitudes above 10 km, for CHAMP and GPS/MET data are very similar. In polar latitudes CHAMP data indicate smaller RMS deviations, and in the tropics above 10 km, CHAMP data indicate smaller systematic deviations. This can be explained by the improved quality of the latest ECMWF reanalyses as discussed below.

[34] Figure 9 shows regional comparison of CHAMP and GPS/MET data with ECMWF reanalyses. Statistics were calculated between 30–60° North and 30–60° South. For the latest ECMWF reanalyses, which were used for the validation of CHAMP data, the statistics for Northern and Southern Hemispheres are very similar. For the earlier ECMWF data, used for the validation of the GPS/MET data, the statistics for the Southern Hemisphere indicates bigger systematic differences, but for the Northern Hemisphere it is better than CHAMP. We also notice that the CHAMP plots are more jagged than those for GPS/MET, although the GPS/MET data we present were computed using exactly the same processing software with exactly the same parameters. This indicates that CHAMP data are more noisy at big heights, which can be accounted for by active ionospheric state.

[35] These results can be compared with the anomaly correlations of the ECMWF fields, which are defined as the correlation coefficient between observed and predicted deviations from climatology of the 500 mb height field. Anomaly correlations are easy and inexpensive to compute, they provide a reliable indication of overall forecast skill, and they can be regionalized. An anomaly correlation score of 1.0 implies a perfect forecast. On the basis of experience, a score near 0.6 suggests that the forecast errors are sufficiently large to indicate a minimal skill. A score below 0.6 signifies that the forecast is not useful.

[36] Figure 10 shows the anomaly correlations for Southern and Northern Hemispheres for February 1997 and May 2002. The anomaly correlations for Northern Hemisphere are very similar for February 1997 and May 2002. For Southern Hemisphere, however, we notice a visible improvement of the forecast skill in May 2002 compared to February 1997. This is in agreement with the fact that the biggest systematic differences are observed between

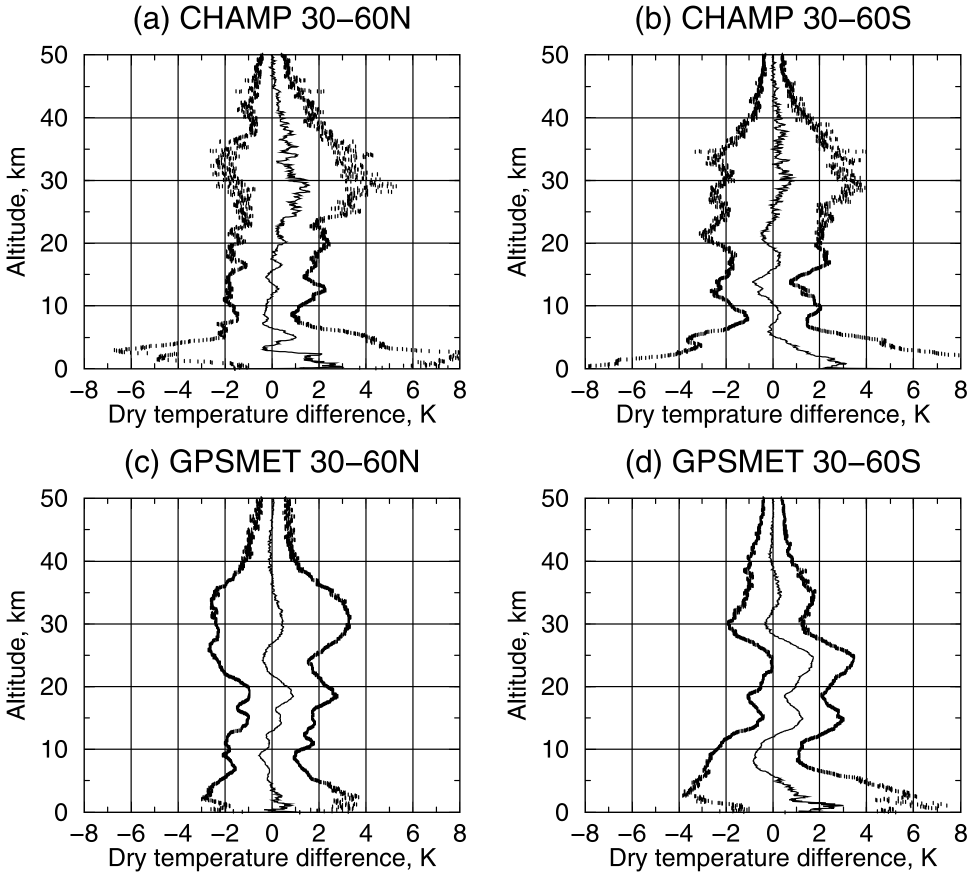


**Figure 9.** Comparisons of CHAMP and GPS/MET dry temperatures with ECMWF analyses: (a) CHAMP for latitudes 30–60°N, (b) CHAMP for latitudes 30–60°S, (c) GPS/MET for latitudes 30–60°N, and (d) GPS/MET for latitudes 30–60°S.

GPS/MET and ECMWF data in Southern Hemisphere for February 1997.

## 4. Conclusions

[37] Statistical comparisons of CHAMP data with ECMWF reanalyses were performed. In the tropics and midlatitudes at heights below 10 km, CHAMP data indicate big RMS deviations from ECMWF reanalyses. In the tropics CHAMP data also indicate very strong systematic deviations from ECMWF reanalyses. This can be explained by poor quality of radio occultation data in the lower troposphere, where multipath propagation results in significant signal tracking errors. Elsewhere, the systematic

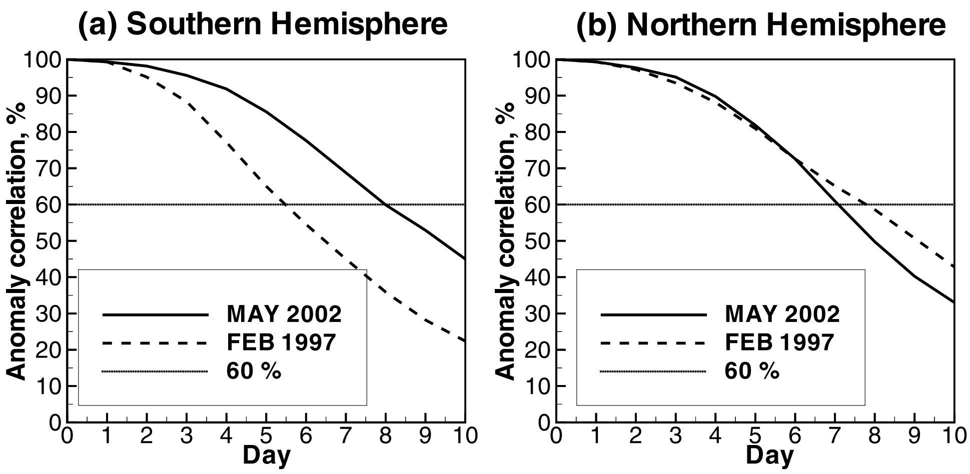


**Figure 10.** Anomaly correlation for the ECMWF model for February 1997 (dashed lines) and May 2002 (solid lines): (a) Southern Hemisphere and (b) Northern Hemisphere.

difference does not exceed 1 K for tropical and polar latitudes, and it is below 0.5 K for midlatitudes.

[38] In the tropics and midlatitudes at heights below 10 km, CHAMP-ECMWF difference is much greater than GPS/MET-ECMWF difference. Elsewhere, the deviations of CHAMP data from ECMWF reanalyses are smaller than the deviations of GPS/MET data from ECMWF reanalyses. This can be explained by the enhancement of the latest ECMWF reanalyses, which can also be corroborated through the anomaly correlations of ECMWF reanalyses.

[39] It must be noticed that GPS/MET data were acquired under anti-spoofing (A/S) off, while CHAMP data are collected under A/S on conditions. A/S only affects L2 and it may serve as an explanation of degraded L2 quality. This does not explain the increased problems with L1 in CHAMP data set, which has larger antenna gain than GPS/MET. The biggest differences between CHAMP and GPS/MET data can be related to multipath propagation conditions. The Blackjack receiver provides more lower-tropospheric data, however, they indicate significant systematic differences with respect to ECMWF reanalyses. Receiver simulations with realistic models of radio occultation signals suggest that these differences can be explained by signal tracking errors. The simulations also show that this can be amended by the use of an improved phase detector and open-loop signal-tracking technique. We emphasize that these problems are not a fundamental limitation of the radio occultation technique (because many of them were not observed in GPS/MET results) but are technical, related to the current version of the BlackJack receiver, which can and must be improved.

[40] **Acknowledgments.** This work was performed with the financial support of the Max-Plank Institute for Meteorology and the Russian Foundation for Fundamental research (grants 01-05-64269 and 03-05-64366). The authors are grateful to Erik Anderson (ECMWF) for providing anomaly correlations of ECMWF reanalyses. The authors are also grateful to S. V. Sokolovskiy (UCAR) for useful scientific discussions.

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