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THE RADIO OCCULTATION EXPERIMENT ABOARD THE GERMAN SATELLITE CHAMP

This paper provides a review of the radio occultation experiment flown on the German satellite CHAMP. This experiment has produced up to now the longest and most comprehensive occultation data set. Wit the limb sounding by occultation from the GRACE twin satellites more than 500 globally distributed temperature and water vapour profiles are to be expected per day.

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The paper responds to Action 30.20:
EUMETSAT to invite scientists participating in CHAMP to submit a report on sounding experiences at the next CGMS.

THE RADIO OCCULTATION EXPERIMENT ABOARD THE GERMAN SATELLITE CHAMP

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1. Introduction

The past decade has witnessed the development of revolutionary applications of the Global Positioning System (GPS) in space geodesy and also in the atmospheric and ionospheric sciences. Besides various regional dense GPS ground station networks having been established in Japan, Europe and the USA since 1993 which allow to derive in quick succession the distribution of the vertically integrated water vapour over a specific region (e.g. Reigber et al., 2002), the GPS radio limb sounding or radio occultation technique started its success way in 1995 with the pioneering GPS/MET flight experiment aboard the Microlab 1 spacecraft (e.g. Ware et al., 1996). During its life GPS/MET recovered over 40,000 occultations and demonstrated by comparison with correlative data sets from operational weather analyses and radiosondes for the first time the remarkable capabilities of this new remote sensing technique. In the sequel improved GPS flight receivers and limb sounding antennas were embarked and launched on five different low Earth orbiting satellite missions: SUNSAT (1997), Ørstedt (1999), CHAMP (2000), SAC-C (2000) and GRACE (2002). The first two missions failed to produce good quality occultation data and for the GRACE twin satellites, the generation of limb sounding observations has not yet been commanded. From the remaining two missions, the CHAMP radio occultation experiment has produced up to now the longest and largest occultation data set in a routine and short latency operational procedure. SAC-C is the first satellite doing forward- and aft-looking soundings. We will report here about our experience with the radio occultation (RO) experiment aboard the German satellite CHAMP.

2. Space & Ground Segment Components for the RO Experiment

The geoscientific mission CHAMP (Reigber et al., 2001, 2002) is a joint project of the GeoForschungsZentrum Potsdam (GFZ) and the German Aerospace Center (DLR). As shown on Figure 2.3 the mission consists as usual of a space segment and a ground segment. The space segment was placed on July 15, 2000 into an almost polar ($i = 87°$), low altitude ($h = 450$ km) and near circular ($e = 0.003$) orbit. In the meantime, after having been exposed to natural drag for more than 3 years and after 2 orbit lift manoeuvres, the satellite is orbiting the Earth at altitudes below 400 km. The trapezoidal CHAMP satellite (see Fig. 2.1) carries 7 different instruments, partly provided by NASA, CNES and the USAF, to generate a continuous science data stream for dealing with the scientific tasks of the mission: global Earth gravity and magnetic field recovery and neutral atmosphere and ionosphere sounding. All of the instruments have been in a good state and function since the beginning of the mission. The main instrument for sounding the atmosphere and ionosphere aboard CHAMP is the GPS flight receiver with its zenith- and aft-looking antennas. Detailed thermospheric density structures can be sensed with the three-axes precision accelerometer in the centre of the spacecraft (Grunwaldt et al., 2003).

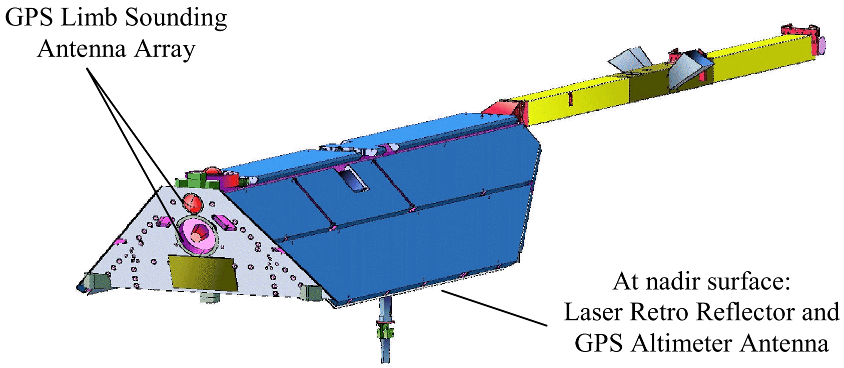

Fig. 2.1: Rear side view of CHAMP with location of instruments

The CHAMP GPS receiver (NASA/JPL's "BlackJack" instrument) performs dual frequency phase and range measurements and serves 4 antennas: one zenith-viewing POD, two limb-viewing and one on the nadir side of the spacecraft. The arrangement of POD and limb-viewing antennas is shown in Fig. 2.2. The receiver architecture employs redundant digital electronics and relies on commercial grade, non-radiation-hardened components. The receiver firmware is re-programmable in orbit and displays a high level of flexibility. It allows for tracking of up to 12 GPS satellites in parallel for POD.

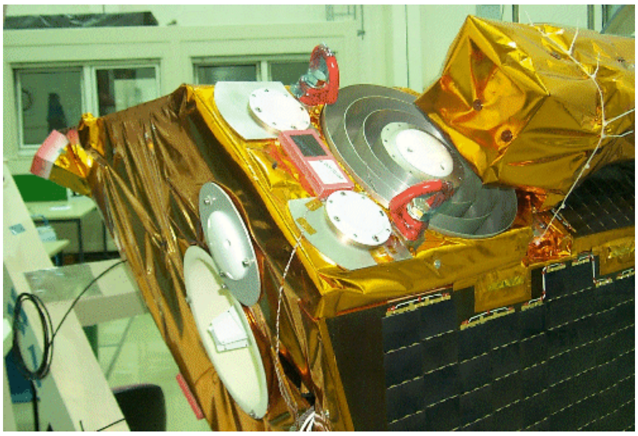

Fig. 2.2: CHAMP GPS antenna array of limb-viewing elements (left) and the zenith-looking POD antenna on a choke ring.

Besides the above-mentioned role within the satellite bus operations, the "BlackJack" GPS receiver serves for precise radiometric observations of phase and range for post-processed orbit determination in the order of few centimetres. Simultaneously with POD observations, the medium gain, limb-viewing RHCP helix antenna allows high-frequency occultation measurements of the ionosphere and the neutral atmosphere. The nadir-viewing LHCP helix antenna will serve for a GPS altimetry experiment. A short list of the main specifications for the receiver can be found in Table 2.1.

CHAMP's ground segment comprises all ground-based components which perform the operational control of the spacecraft and instruments, the data flow from the on-board memory and supporting ground networks to the processors and users and standard science product generation. Figure 2.3 shows the general scheme.

Table 2.1: Specifications of the “BlackJack” GPS receiver on CHAMP

Accuracy of the real-time navigation solution	< 10 m (SA off)
Time calibration accuracy	< 1 µs
Dual-frequency range and integrated carrier for POD	
Phase (ionosphere-free)	< 0.2 cm
Range (ionosphere-free)	< 30 cm
Limb-sounding observables	
L1 carrier phase	< 0.0005 (1s)
L2 carrier phase	< 0.03 cm (1s)

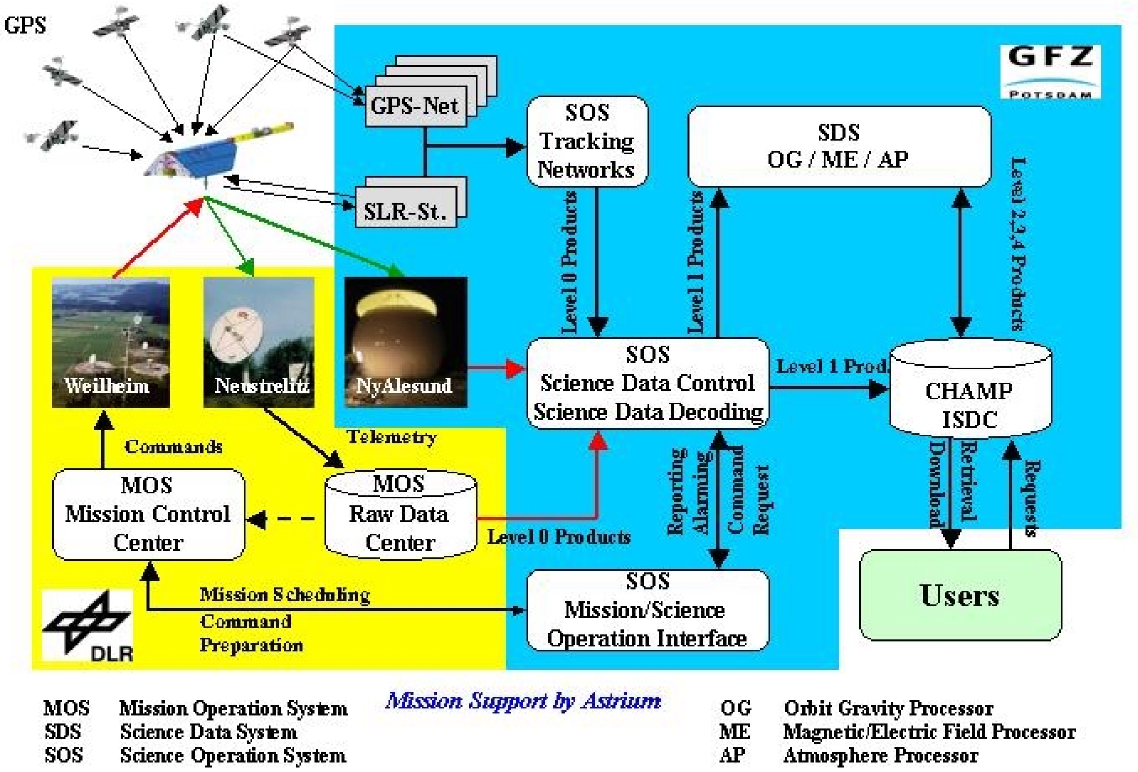

Figure 2.3: CHAMP ground segment

The main infrastructure elements for the generation of radio occultation products in the frame of the overall tasks of the CHAMP mission are: two downlink stations for receiving CHAMP data (Neustrelitz, Germany and Ny Ålesund, Spitsbergen) operated by DLR and GFZ, an orbit processing facility for determination of (ultra) rapid precise orbits for the GPS satellites and CHAMP, a fiducial low latency GPS ground network, the CHAMP Atmospheric Processor (CAP) for generating CHAMP radio occultation products (atmospheric excess phase, bending angle, refractivity, temperature, and humidity profiles) and the CHAMP Information System and Data Centre (ISDC) for archiving and distribution of CHAMP data (Reigber et al., 2001). All these components have been set up in the course of the GPS Atmosphere Sounding Project GASP (Reigber et al., 2003), a strategic project of the Helmholtz Association which was carried out in the 1999-2002 time frame.

3. Operational Data Processing and Product Delivery

Figure 3.1 visualizes the data and information flow in GFZ's radio occultation processing system. The Black-Jack GPS receiver onboard CHAMP records phase and amplitude variations with high temporal resolution (50 Hz) during an occultation event. By using the high precision orbit information provided by GFZ's orbit group for CHAMP and the occulting GPS satellites (König et al., 2003) the atmospheric excess path delay can be extracted which is related to a bending angle profile. A double differencing method is applied to remove clock errors (Wickert et al., 2001a). For this reason and for the ultrarapid orbit generation the aforementioned high-rate/low latency GPS ground station network is used. With CHAMP occultation data for the first time the feasibility of the application of a space-based single differencing technique for precise GPS occultation processing was demonstrated by Wickert et al. (2002). The results suggest that after the termination of SA (Selective Availability) the space-based single difference technique provides nearly identical refractivity and temperature profiles compared to profiles processed using double differencing. This would not only significantly simplify the occultation processing system (no more direct use of ground station data), but also avoid measurement error contributions from ground-to-satellite links (e.g. phase path noise, uncorrected ionosphere/troposphere or multipath at the ground station sites).

Ionospheric effects are corrected by a linear combination of the bending angles derived from the two GPS frequencies.
Refractivity profiles are calculated by inverting the bending angle profiles using an Abel inversion. Finally, with the assumption of dry air the hydrostatic equation is used to calculate pressure and temperature profiles by downward integration of the refractivity profile. By using additional temperature information from operational analyses (ECMWF) water vapour can be calculated in the troposphere (Gorbunov and Sokolovskiy, 1993).
The CHAMP Atmospheric Processor (CAP) is a modular structured and dynamically configurable software package consisting of a science and control module. The scientific software calculates the atmospheric excess phase for each occultation event and vertical atmospheric profiles. CAP ensures the continuous data flow of all input data through the scientific analysis modules and provides the interface for transferring the radio occultation products into the ISDC.
CAP is designed to be easily extendable by additional scientific modules or input data. Thus, it also allows for an extension to other single- or multi-satellite radio occultation missions as, e.g., SAC-C, GRACE, TerraSAR-X and others.
The use of analysis results obtained from radio occultation data as, e.g., atmospheric excess phases, by weather prediction centres requires an operational data processing system generating and delivering data products automatically and with high reliability within a certain time limit. The crucial factor here is the reliability and the timeliness for providing the input data. These are: CHAMP's occultation data, the fiducial network data and the precise orbit data of CHAMP and the GPS satellites.

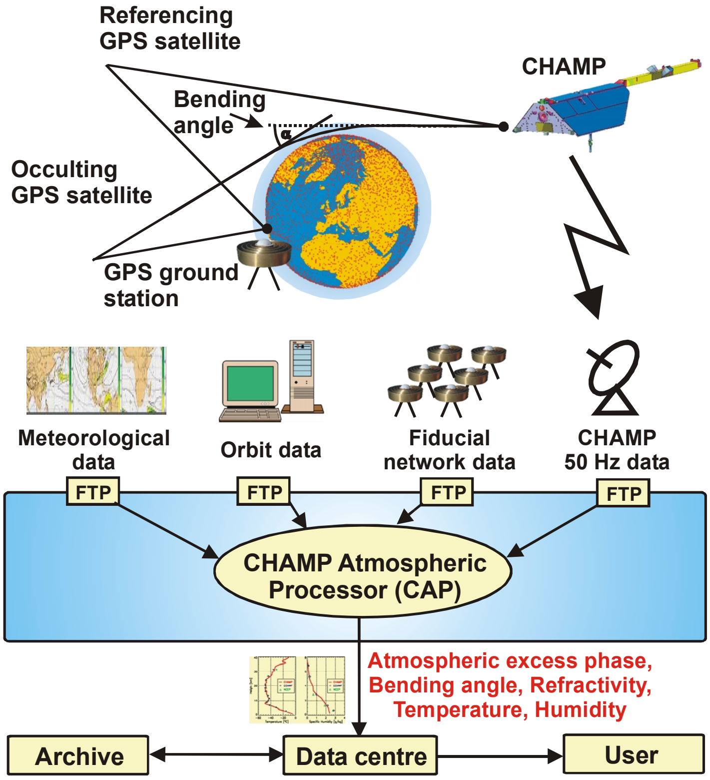

Fig. 3.1: Measuring principle and infrastructure for the radio occultation experiment onboard CHAMP.

The first requirement is the rapid availability of the GPS/CHAMP satellite-to-satellite tracking data for the CHAMP orbit determination (1/10 Hz phases and pseudoranges) and the occultation processing (50 Hz phases). This is realized by using the GFZ/DLR near-polar receiving station at Ny Ålesund, Spitsbergen. A ground contact occurs about every 90 minutes within the station coverage zone. The time delay for transferring the data to the processing centre at GFZ is negligible.

The time delay for providing the global GPS ground data via the ISDC is currently between 30 to 70 minutes.

Since April 2002 the GPS and CHAMP satellite orbit ephemerides are available about every 3 hours after the last data take (Ultra rapid Science Orbit, USO). The USO spans a 14 hours (CHAMP) and 24 hours (GPS) time window, respectively, up to ~3 hours before delivery. The accuracy of the USO product is comparable to the CHAMP standard orbit product, the Rapid Science Orbit (RSO), which is delivered on a daily basis with ~24 hours latency (König et al., 2002).

Because of the availability of ultra rapid science orbits the demonstration of Near-Real-Time provision of precise GPS occultation data products became feasible and is demonstrated at GFZ Potsdam since April 2002. The daily averaged time delay between occultation measurements and availability of calibrated atmospheric excess phases is presently about 5 hours (Fig. 3.2).

The standard CHAMP radio occultation products are generated within ~16 hours after data taking. We note that the real delay between measurement and the provision of vertical temperature and humidity profiles is enlarged by the need to get independent meteorological data (global weather analyses from ECMWF) for the quality control. This results presently in a total delay of ~1-2 days between measurement and provision of the profiles at the ISDC.

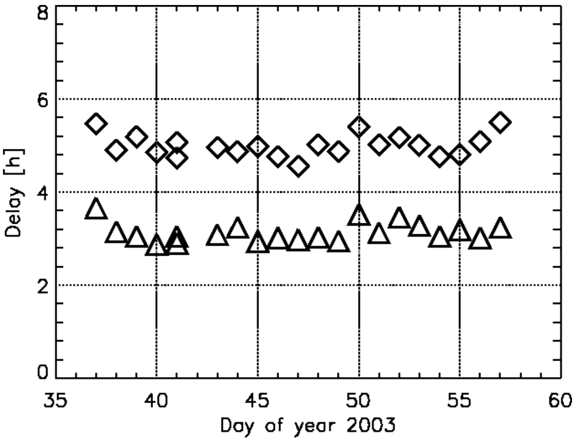

Fig 3.2: Time delay between CHAMP occultation measurements and availability of analysis results at GFZ since February 2003. Diamonds indicate the daily mean of the time delay between measurement and availability of calibrated atmospheric excess phases for all occultation events. For the entire period an average of ~5 hours is reached. The minimum time delays are marked by triangles.

Until mid-September 2003 about 116,000 radio occultation products, as e.g. atmospheric excess phases, profiles of refractivity, temperature and water vapour were fed into the Information System and Data Centre (ISDC) at GFZ Potsdam (Fig. 3.3). After a flight-receiver software update on March 10, 2002 continuously about 170 occultation products were delivered daily.

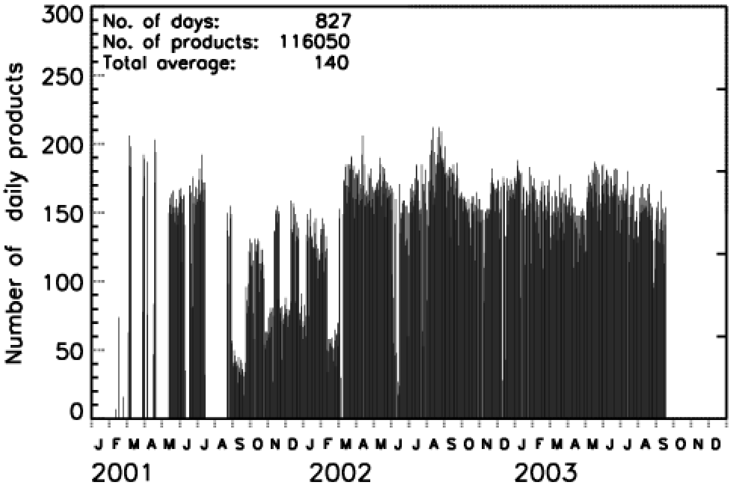

Fig 3.3: Number of daily CHAMP radio occultation products delivered to the Information System and Data Centre (ISDC).

4. Advanced retrieval methods

First validation studies based on CHAMP observations indicate that the observed temperature bias with respect to European Centre for Medium-Range Weather Forecasts (ECMWF) global analyses is less than 1 K above the tropopause and less than 0.5 K between 12 to 20 km at mid and high latitudes (Wickert et al., 2001, Hajj et al., 2002). In the lower troposphere, however, at mid and low latitudes a negative refractivity bias of more than 1% is observed. The same phenomenon was found for the GPS/MET occultation experiment (see e.g., Rocken et al., 1997, Marquardt et al., 2001). The negative bias is commonly attributed to complexities involved in tracking signals and retrieving bending angles from phase and amplitude data affected by multipath propagation (see e.g., Gorbunov, 2002). Multipath is caused by the variability of the tropospheric refractivity field generated by spatial variations of the water vapor distribution.

The analysis of radio occultation data affected by multipath is extensively discussed in the literature. Marouf et al. (1986), Gorbunov and Gurvich (1998) and Mortensen et al. (1999) employed the back propagation method. The Fresnel inversion was studied by Melbourne (1994) and Mortensen and Hoeg (1998). Radio optic or sliding spectral methods were used by Lindal et al. (1987), Pavelyev (1998) and Sokolovskiy (2001). Because all of these approaches are subject to restrictions they are not regarded as suitable methods for operational data processing.

The problem of bending angle retrieval in multipath zones was solved by the Gorbunov (2001, 2002a) with the formulation of the so-called canonical transform (CT) method. A graphical illustration of the CT is shown in Fig. 4.1. Within the framework of the CT method the bending angle as a function of ray impact parameter is calculated by transforming the observed signal from geometrical space (plane on right-hand side in Fig. 4.1) to an abstract impact parameter space (bottom plane). Under the assumption that each ray is uniquely characterized by its impact parameter the transformed solution does not exhibit multipath. More recently, Jensen et al. (2003) introduced the full spectrum inversion (FSI) method, an alternative bending angle retrieval technique that is equivalent to CT method and allows for an efficient and fast numerical implementation.

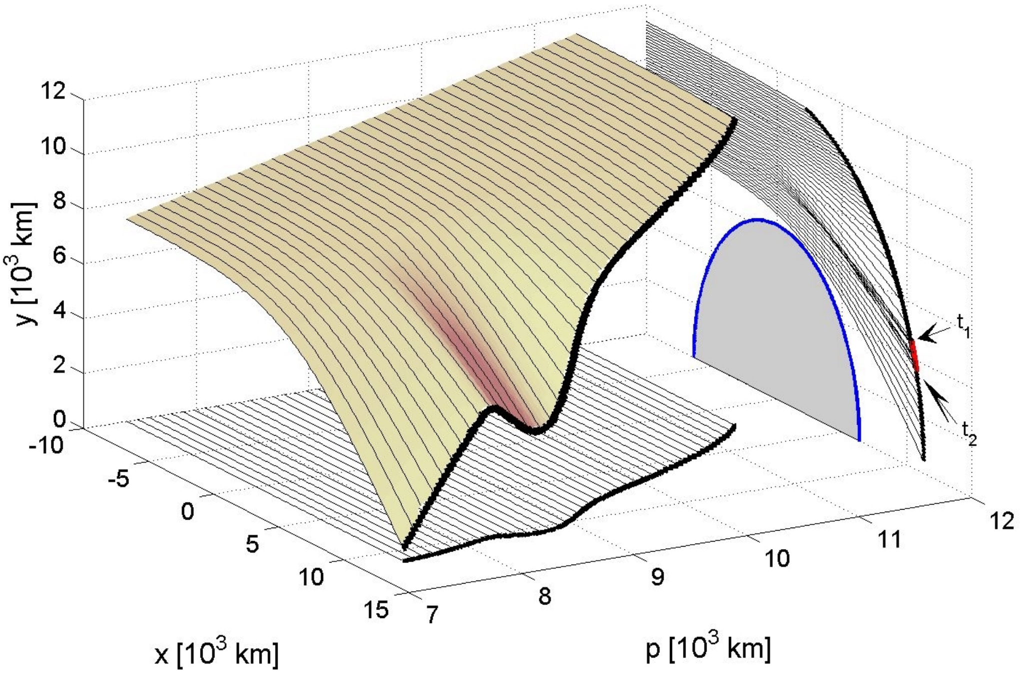

Fig. 4.1: Ray manifold in three dimensional (x,y,p) space. x and y span the occultation plane in geometrical space, impact parameter p and x form the impact parameter space. In this example, the receiver encounters a multipath region between t1 and t2 (red-colored section): within this region rays probing the atmosphere on different paths superimpose and interfere with each other. The individual contributions are separated by canonically transforming the measured signal from geometrical to impact parameter space.

CT and FSI processing of a large number of CHAMP observations showed, however, that these advanced retrieval methods did not completely remove the refractivity bias suggesting that the quality of the lower tropospheric data is degraded (cf. section „Validation of products“). End-to-end simulation studies including the GPS receiver's signal tracking process confirmed that receiver tracking errors can lead to an underestimation of refractivity in the lower troposphere (Ao et al., 2003, Beyerle et al., 2003a). In addition, further simulation runs could reproduce the true refractivity profiles with high accuracy if the receiver model was excluded from the simulation. Modifications to the receiver tracking algorithm significantly improved the retrieval results. In particular, replacing the carrier loop's two-quadrant phase extractor with a four-quadrant discriminator resulted in an five-fold decrease of the refractivity bias (Beyerle et al., 2003a).

The simulation studies revealed the sensitivity of the CT method with respect to receiver-induced phase errors. Since signal amplitudes seem less affected by receiver tracking errors a heuristic retrieval method, based on the CT method and the sliding spectral technique, was developed to derive reliable bending angle profiles from the amplitude of the transformed signal (Beyerle et al., 2003b). Fig. 4.2 shows bending angle profiles obtained from a simulation study including the receiver tracking process. Receiver-induced phase errors cause the CT solution (green line) to deviate significantly from the true bending angle profile (blue) at ray heights between 4 and 5.5 km. The heuristic CTss bending angle (red) on the other hand which is calculated from the "CTss amplitude" (coded in gray) seems to be more robust with respect to tracking errors at the expense of a reduced vertical resolution.

We note that simulation runs with by-passed receiver signal tracking the CT bending angle profiles reproduce the true profiles with excellent accuracy (Beyerle et al., 2003b).

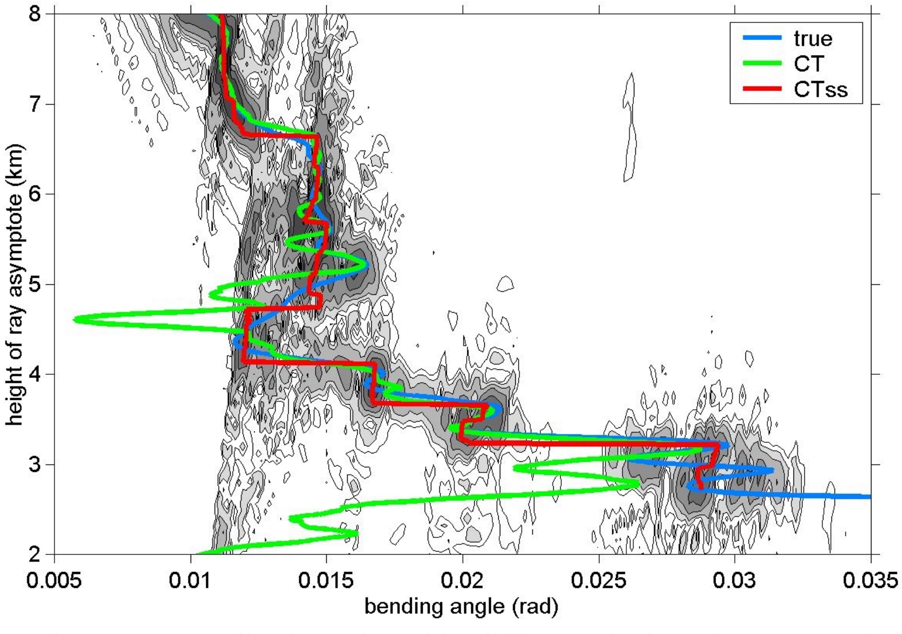

Fig. 4.2: The "CTss amplitude" (plotted in different shades of gray) as a function of bending angle and ray height derived from a this simulation including the receiver tracking process. Profiles of the true bending angle (blue), the CT result (dashed green) and the CTss processing result (red) are superimposed. Receiver-induced phase tracking errors cause the CT solution to deviate strongly between 4 and 6 km ray height. The heuristic CTss solution (red) exhibits smaller retrieval errors; the vertical resolution is significantly smaller, though.

5. Validation of products

CHAMP data products are validated against meteorological analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) and radio sonde observations. The sonde data are provided by the Stratospheric Research Group, Free University of Berlin.
Fig. 5.1 shows the zonal mean (bias) between observed dry temperatures and ECMWF temperatures in the upper troposphere and stratosphere. The comparison is based on about 60,000 CHAMP observations covering the measurement period between March 2002 and March 2003. Refractivity profiles deviating from ECMWF by more than 10% are removed from the data set. The statistics are obtained by interpolating 6 hourly ECMWF analysis fields at the occultation's location on the 60 ECMWF model levels and by sorting the data in 5O latitude bins.

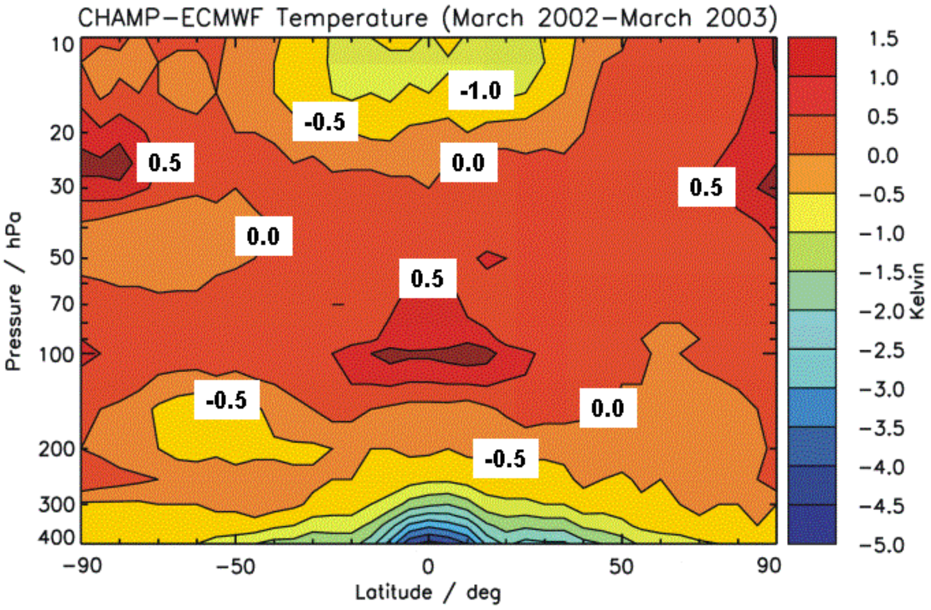

Fig. 5.1: Zonal mean difference between observed CHAMP dry temperatures and ECMWF temperatures. The analysis is based on about 60,000 observations recorded between March 2002 and March 2003.

The cold bias in the troposphere below 300 hPa is partly caused by ignoring humidity contributions which are significant at these altitudes. Above 300 hPa up to altitudes of about 30–50 hPa the temperature bias is less than +/–0.5 K except at the tropics where ΔT exceeds 1 K. The tropical bias enhancement correlates with a corresponding rise of root-mean-square (rms) deviation (not shown). This rms increase is related to gravity wave activity that is resolved by CHAMP but not by ECMWF (see Marquardt et al., 2003). Similarly, between 300 hPa and 30–50 hPa the rms error is below 2 K. Above 20 hPa altitude CHAMP observations exhibit a significant bias of several K in combination with an increase in rms deviation. The sign and magnitude of this bias depends on the bending angle smoothing and initialization procedure. Here, bending angle smoothing is performed using the MSISE-90 climatology (Hedin, 1991); by using ECMWF profiles as a-priori data the bias can be removed almost completely (Marquardt et al., 2003).

Statistical comparisons with radio sonde data confirm these good agreements in the upper troposphere and stratosphere (Marquardt et al., 2003; Schmidt et al., 2003). Fig 5.2 shows the difference between CHAMP dry temperatures and sonde temperatures based on more than 6,000 soundings during March 2002 – March 2003. The data set is composed of sonde observations performed within 300 km of the occultation's tangent point and within a time window of +/-3 hours. With respect to the sonde data the CHAMP bias and rms deviation is below 1 K and less than 2–3 K, respectively, at altitudes between 200 and 10 hPa. Again, the cold bias below 200 hPa humidity is caused by neglecting humidity contributions.

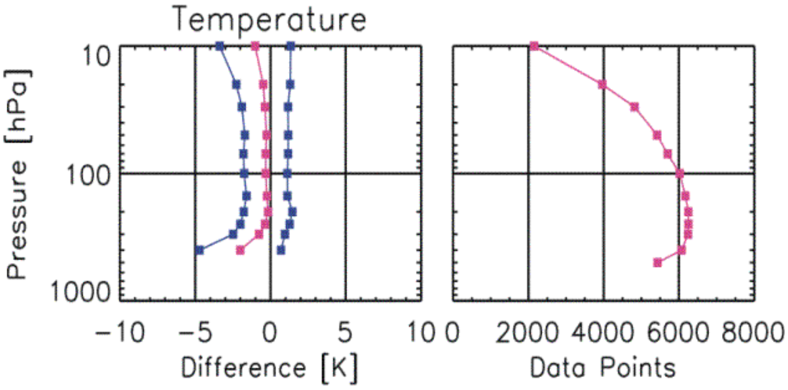

Fig. 5.2: Comparison of CHAMP dry temperatures with radio sonde observations (left panel). With respect to the sonde temperatures the CHAMP bias (red points, left panel) and rms deviations (blue points, left) are below 1 K and less than 2–3 K, respectively, at altitudes between 200 and 10 hPa. The analysis is based on more than 6000 profiles (right panel). (Data provided by Stratospheric Research Group, Free University of Berlin.)

In the lower troposphere at altitudes below 500 hPa, however, the zonal mean relative deviation between CHAMP and ECMWF refractivities exhibits a significant negative bias (Fig. 5.3). It reaches 5% at mid latitudes and exceeds 10% in the tropics (Marquardt et al., 2003). Fig. 5.3 shows the mean fractional refractivity error (N-N0)/N0 as a function of altitude based on more than 4000 CHAMP observations. Here, N denotes the observed, N0 the corresponding ECMWF refractivity. The CT solution is plotted in blue, the corresponding CTss result is plotted in red. Below about 8 km altitude the CTss method performs significantly better than the CT algorithm with the bias compared to ECMWF reduced by more than a factor of 2. The right panel in Fig. 5.3 shows the relative number of data points used in this intercomparison. I.e., 50% of the profiles reach an altitude of 1.1 km, only 10% pass below 300 m. The corresponding rms deviation of the fractional refractivity is plotted in the middle panel of Fig. 5.3. Again, below about 10 km altitude the CTss rms deviations are significantly less than the CT values. A negative bias persists, though, that is most likely due to occurrences of critical refraction (Sokolovskiy, 2003).

The quality of the provided water vapor profiles (derived according to Gorbunov and Sokolovskiy, 1993) suffers from the negative refractivity bias, characterized above. It corresponds to mean meridional dry biases of the specific humidity up to ~30% for the GO retrievals. The use of the CTss refractivity profiles (Beyerle et al., 2003b) for the water vapor retrieval results in significantly improved specific humidity (Wickert et al., 2003b). In Fig. 5.4 we show the meridional distribution (10° bins in latitude, 0.2 km in altitude) of the mean specific humidity difference to ECMWF (in %) for a set of 3,457 CHAMP measurements (GO and CTss profiles), recorded between May 14 and June 10, 2001. The CTss profiles show significantly less deviation in relation to the analyses. The dry bias of the water vapor retrievals is reduced by about a factor of 3. Biases larger than 15% are observed only in the tropics below ~1 km. This can be related to a fundamental limitation of the GPS occultation method, the ducting problems associated with strong refractivity gradients at the top of the planetary boundary layer at 1-2 km altitude (e.g. Ao et al., 2003). Large deviations are also visible in the upper troposphere, however here very small absolute values of the specific humidity of ~0.02-0.05 g/kg are observed.

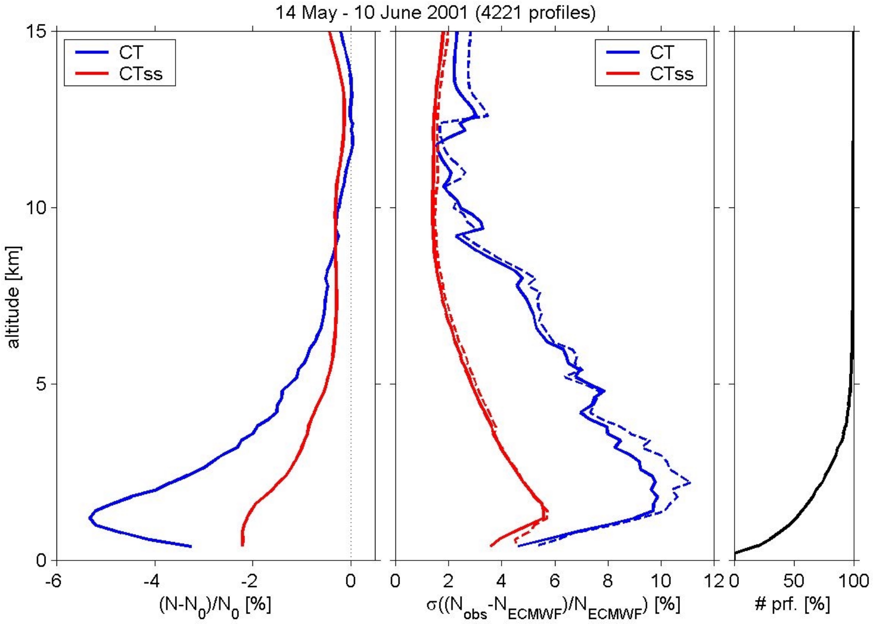

Fig. 5.3: Mean fractional refractivity deviation of CT (blue) and the heuristic CTss (red) analyses (left panel). The corresponding rms deviation is plotted in the middle panel. The right panel shows the relative number of data points used in the analysis.

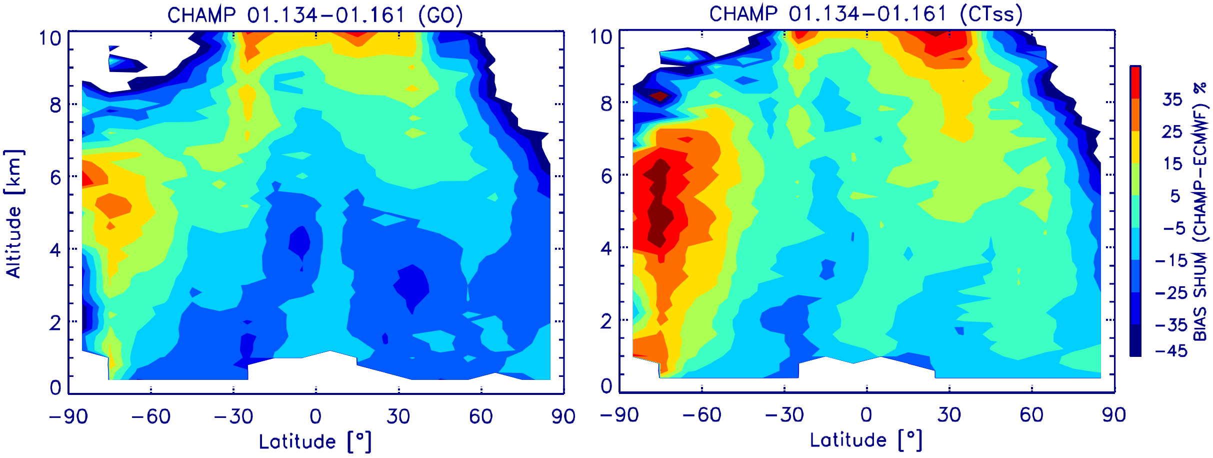

Fig. 5.4: Meridional distribution of the mean specific humidity difference (in %) between 3,457 CHAMP retrievals and ECMWF. The profiles are derived using (left) the geometrical optics approximation and (right) the CTss method for the refractivity retrieval. Both sets of humidity profiles are derived using the iterative method from Gorbunov and Sokolovskiy (1993).

6. Outlook

The CHAMP mission has generated an unprecedented large number of GPS radio occultation observations since switch-on of the RO experiment in 2001. The established RO data acquisition, processing and dissemination infrastructure at GFZ is demonstrating its ability to provide RO products with good quality and a 3-5 hours latency. With the CHAMP mission's life being predicted to last until mid 2008 after the recent two orbit lift manoeuvres and the switch-on of the limb sounding experiment of the two GRACE satellites within the next few months, more than 500 globally distributed temperature and water vapour profiles per day can by expected in the very next future for supporting the development of improved retrieval techniques and short-term weather prediction and multi-year climate studies over the next few years.

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