Atmospheric sounding with CHAMP: GPS ground station data for occultation processing

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Atmospheric sounding with CHAMP: GPS ground station data for occultation processing

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Abstract. The double difference technique is the standard processing method of CHAMP's (CHAllenging Minisatellite Payload) GPS (Global Positioning System) occultation data to correct for satellite clock errors. In order to apply this technique, the implementation of a global fiducial GPS ground network is required. This network ("High Rate and Low Latency network") was installed jointly by GeoForschungsZentrum Potsdam (GFZ) and Jet Propulsion Laboratory (JPL) in preparation of the CHAMP occultation experiment and is operated jointly by both institutes. Presently (May/June 2001) it consists of 28 stations (18 funded and operated by JPL, 10 by GFZ). Aspects of utilizing the ground station data for the GPS occultation processing are discussed. The network configuration allows for occultation data processing with about ~3.5 ground stations per occultation event. The global distribution of that redundancy is found to be irregular. The network fulfills low latency requirements imposed by Numerical Weather Prediction (NWP) systems. For the first time reduced acquisition rates of 1/5, 1/10 and 1/30 Hz compared to the current standard 1 Hz were applied to GPS occultation data processing. For the three resulting sets of 1,400 vertical dry temperature profiles (using 1/5, 1/10 and 1/30 Hz, respectively) it was shown that the mean and standard deviation of the dry temperatures in relation to corresponding meteorological analyses are almost identical in relation to those of a referencing 1 Hz data set.

1 Introduction

The German geoscience CHAMP satellite was launched on July 15, 2000 from Russian COSMODROME Plesetzk. CHAMP's measurements are used to determine Earth's gravity and magnetic field and to derive precise information about vertical temperature, humidity and electron density distribution on a global scale using the innovative GPS radio occultation technique (Reigber et al., 2002).

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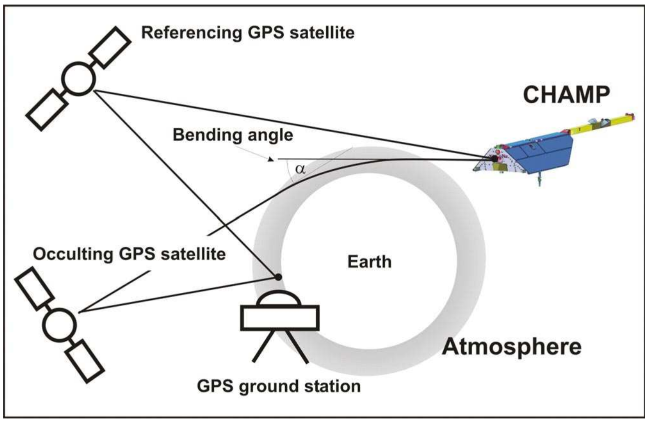

Fig. 1. Geometry for double difference processing of CHAMP's GPS radio occultation data. Involved are two satellite to satellite links (occulting and referencing GPS satellite to CHAMP) and two satellite to ground links (GPS satellites to the ground station). The atmospheric influence on the propagation of the GPS signal is characterized by the bending angle α.

The calibration-free GPS based limb sounding allows for global and all weather atmospheric/ionospheric monitoring with high accuracy and high vertical resolution. These properties offer great potential for atmospheric research, improvement of the numerical weather forecasts and climate change detection (Anthes et al., 2000; Kuo et al., 2000; Kursinski et al., 1997). Future multi-satellite occultation missions such as ACE+ (Atmosphere and Climate Explorer; Hoeg and Kirchengast, 2002), COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate; Rocken et al., 2000) or METOP (METeorology OPerational; Edwards and Pawlak, 2000) with the GRAS sensor (Global navigation satellite system Radio occultation receiver for Atmosphere Sounding; Loiselet et al., 2000) will operationally provide up to ~5.000 (for ACE+) precise and globally distributed vertical atmospheric profiles daily.

CHAMP's atmosphere profiling experiment was activated on February 11, 2001 (Wickert et al., 2001b), first vertical profiles of electron density were recorded on April 11, 2001 (Jakowski et al., 2002). Due to improved instrument

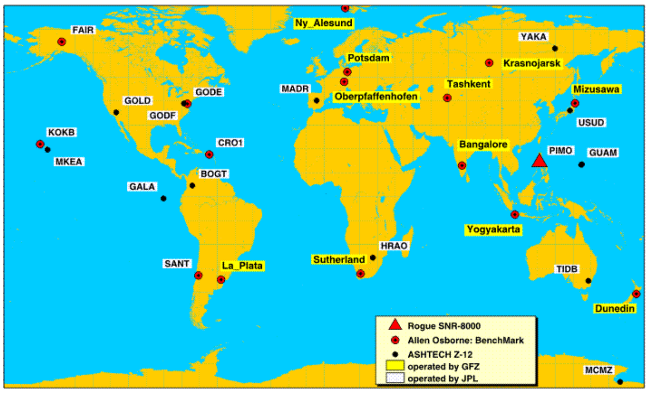

Fig. 2. Configuration of the "H/R Low Latency GPS Ground Tracking network" for CHAMP (Status June 2001, 28 Stations, from Galas et al., 2001).

characteristics (state-of-the-art GPS flight receiver "BlackJack", provided by JPL, and optimized occultation antenna characteristics) compared to the proof-of-concept mission GPS/MET (GPS/METeorology) the CHAMP data are available continuously. Since March 8, 2002 CHAMP provides continuously up to 270 neutral atmosphere and in parallel up to 200 ionosphere occultation measurements per day. Information about the current status of the CHAMP radio occultation experiment can be obtained via:
http://www.gfz-potsdam.de/pb1/GASP/GASP2/index_GASP2.html.
Since the mission is expected to last until 2006, a unique long-term set of GPS occultation data will be available. These measurements will stimulate the development of new processing strategies and algorithms as well as the improvement of currently existing and the installation of new occultation processing systems.

The GPS radio occultation technique is based on precise dual-frequency phase measurements (L-band) of a GPS receiver on a Low-Earth-Orbiting satellite (LEO) tracking a setting or rising GPS satellite. Combining these measurements with the satellites' position and velocity information, the phase path increase due to the atmosphere during the occultation event can be derived. To correct for satellite clock errors a double difference technique is applied (Fig. 1 with CHAMP as LEO): The 50 Hz LEO precise phase data are synchronized with the 1 Hz (current standard) phase data of an appropriate GPS ground station (Wickert et al., 2001a; Schreiner et al., 1998). These types of differencing techniques utilizing additional ground based data were already introduced in the early 1990s in order to correct for clock variations in satellite based GPS measurements (e.g., Wu et al., 1990).

The data of a global ground network are necessary to get a complete global coverage of the occultation measurements. For a pre-operational delivery of the atmospheric data products within the framework of the German GPS Atmosphere Sounding Project (GASP; see Reigber, 1998) with maximum time delay of not more than 3 hours between measurement and provision at GFZ's data center the network has to deliver the data with low latency. The network, fulfilling these requirements ("High Rate Low Latency GPS Ground Tracking network", Galas et al., 2001), was installed in preparation of the CHAMP mission and is operated jointly by JPL and GFZ with cooperating partners. The network data are used also for the Precise Orbit Determination of CHAMP and the GPS satellites.

After the calibration of the atmospheric excess phase atmospheric bending angles are derived. Assuming spherical symmetry of the atmosphere, vertical profiles of the refractive index can be determined and converted to atmospheric parameters as pressure, temperature and, using independent knowledge of temperature (e.g. from meteorological analyses), to water vapor within the lower troposphere. Details of the retrieval are given e.g. by Hajj et al. (2002), Wickert (2002), Steiner et al. (1999), Hocke (1997) or Kursinski et al. (1997).

Here we focus on various aspects of utilizing the ground station data to derive the atmospheric excess phase with the double difference technique.

2 Network topology

The application of the double difference technique requires appropriate geometry between the LEO (here CHAMP), the ground station and the GPS satellites involved (Fig. 1). A correlation exists between the location of the ground based receiver and the area, for which occultations can be analysed using the measurements of this receiver. This relation and the resulting redundancies, which can be obtained using various proposed network configurations (due to logistical conditions) were investigated in preparation of the network installation (Wickert et al., 2001a). For this purpose the ROST (Radio Occultation Simulation and Tracking) software tool was used, which is part of the GFZ occultation processing software. ROST predicts the number, the time intervals and the location of occultation events for GNSS (Global Navigation Satellite System) radio occultation experiments taking into account the geometrical constraints due to the use of ground station data for double differencing.

Based on these simulation studies a network, consisting of 28 stations (May/July 2001, see Fig. 2) was installed, which is operated jointly by JPL and GFZ with cooperating partners (Galas et al., 2001). The ROST simulations, performed already before the launch of CHAMP using this configuration of 28 stations (Fig. 2), have shown that on global average a redundancy of about 4 ground stations for the occultation processing is reached (Wickert et al., 2001a).

3 Data flow

An overview of the GPS ground data flow is depicted in Fig. 3. Pseudoranges and carrier phases on both GPS frequencies are recorded with an acquisition rate of 1 Hz. Then, the measurements are transmitted as data files covering 15 min via FTP (File Transfer Protocol) with a latency of not more than 15 min to the Level-1-Data processing center at GFZ. The data format is compressed Turbo Binary (Galas and Koehler, 2001), for all ground stations a total data amount of ~540 MByte daily is

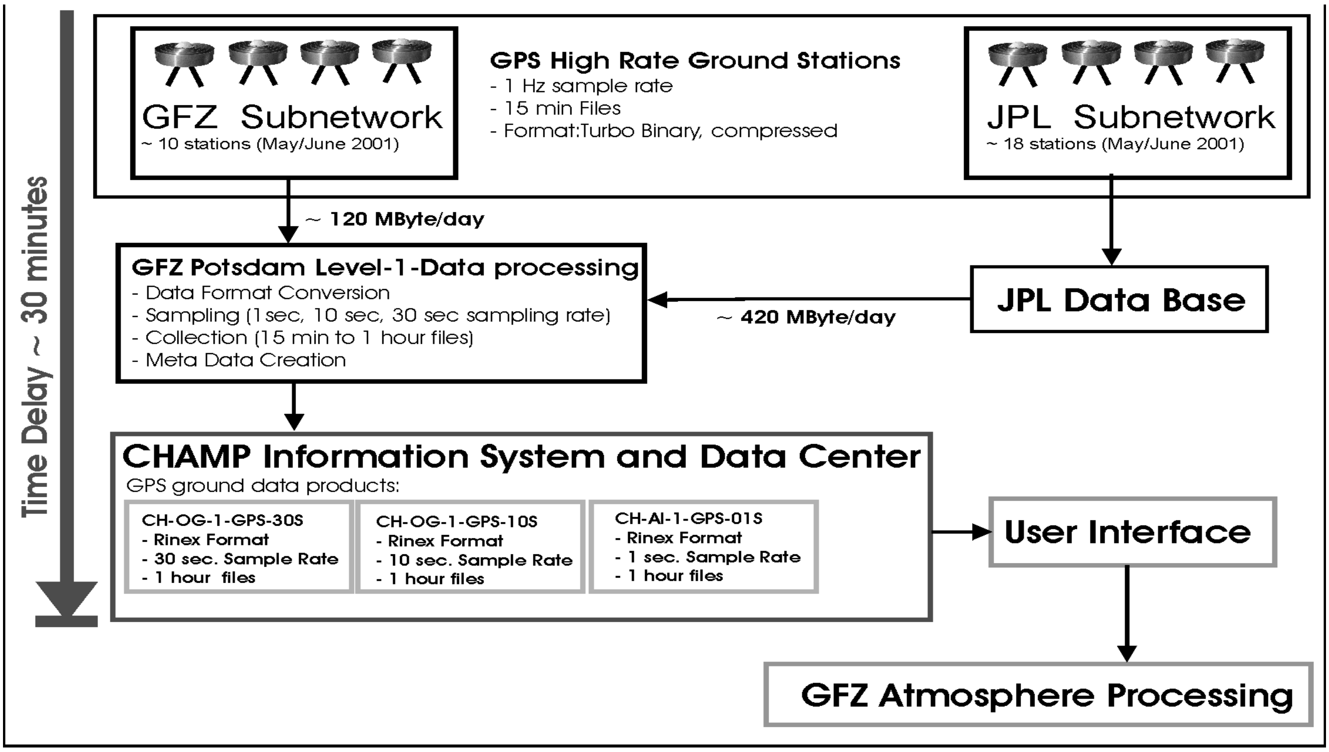

Fig. 3. Data flow of the "High Rate Low Latency GPS Ground Tracking network" for CHAMP. As of May/June 2001 the network consists of 28 stations, operated by JPL and GFZ.

generated. Here, hourly RINEX (Receiver INdependent EXchange format) files are generated and transferred to the CHAMP Information System and Data Center ISDC). In addition, the data are sampled to lower acquisition rates to generate GPS ground station data products according to different user requirements; e.g. for the Precise Orbit Determination of CHAMP data files with a sampling rate of 10 s are required. For all data products a set of metadata is generated, containing additional information about the product files (e.g. version of the processing software, generation date etc.). The time delay between measurement and data provision is currently between ~30 min and ~70 min. Due to the use of 15 min time intervals for the data transmission from the ground stations to the Level-1 processing center, these delays can be further minimized down to about 15-30 min.

4 Data analysis

The investigations within this study were performed with GFZ's operational occultation processing system. The system is briefly described by Wickert et al. (2002a), a more detailed description is given by Wickert (2002).

The operational data analysis is based on a double difference method for deriving the atmospheric excess phase, the geometric optics approximation for ray propagation of the GPS signals and the assumption of spherical symmetry of the atmosphere for the derivation of the refractivity (for technical details of GPS occultation data processing see also Hajj et al., 2002; or Schreiner et al., 1998).

Four types of input data are required for the processing: GPS occultation data from CHAMP, GPS ground station data of the fiducial network and precise orbit information of the satellites involved in the double differencing (occulting, referencing GPS and CHAMP). The GPS and CHAMP orbit ephemeris (Rapid Science Orbits, RSO) are provided by GFZ's Precise Orbit Determination for CHAMP. Currently (April 2002) the 3-D position accuracy for CHAMP-RSO is ~10 cm (Michalak et al., 2002). Recently, the delivery of near-real-time orbits with 3 hour period has been demonstrated (Ultra rapid Science Orbits, USO; Reigber et al., 2002). The fourth data type are the meteorological data (6 hourly operational analyses from European Center for Medium-Range weather Forecast, ECMWF), which are required to derive vertical humidity profiles (see e.g. Marquardt et al., 2001).

The analysis software for the occultations is embedded in a dynamically configurable and extendable system for operational data processing and product generation (Wehrenpfennig et al., 2001). This system enables the provision of the input data, coordinates the work of the scientific data analysis software modules (e.g. double differencing or inversion) and also provides the interface to GFZ's data archive (ISDC) for providing the output data, the atmospheric data products. The scientific data users have access to the analysis results via the ISDC (http://isdc.gfz-potsdam.de/champ). The automatic processsing system is currently improved to aim at an near-real time data product provision within the GASP research project (Schmidt et al., 2002).

The analysis and processing software is implemented in FORTRAN, C++ and Perl programming languages. The main processing computer is currently a SUNFIRE 280R server (2 UltraSparc III processors 750~MHz, 4 GB RAM).

The following investigations (chap. 5-7) were performed using a set of 5,585 CHAMP occultation events during May 15 - June 9, 2001 (Doy 2001, 135-160). The occultations were processed using all appropriate and available ground stations. The data of 24 ground stations were used for the study, the average data availability of these stations was 91.2%.

5 Redundancy of ground station data for CHAMP occultation processing

A major disadvantage of the GPS/MET occultation experiment was the restricted number of six GPS ground stations (Ware et al., 1996) providing 1 Hz data for double difference processing. The GPS receiver onboard the satellite only recorded occultations, for which at least one of the existing ground stations could be used for double differencing. The result was an incomplete and irregular global coverage of the occultation events (Wickert, 2002). The global distribution of a set of 6,465 GPS/MET occultations was analysed. It was found that the distribution in latitude was not symmetric to the Equator and in longitude not symmetric to Greenwich meridian. At eastern longitudes and southern latitudes the number of occultations was smaller than the number at western longitudes and northern latitudes. This was related to the insufficient number and non-uniform global distribution of the GPS ground stations for double differencing.

Already before the launch of CHAMP it was shown, that the fiducial ground network allows for processing of all occultation events. Furthermore, it was demonstrated that the network enables occultation data processing with a redundancy of ~4 different ground stations per occultation event (Wickert et al., 2001a).

Here we confirm these findings with real CHAMP occultation data within the period during May/June 2001

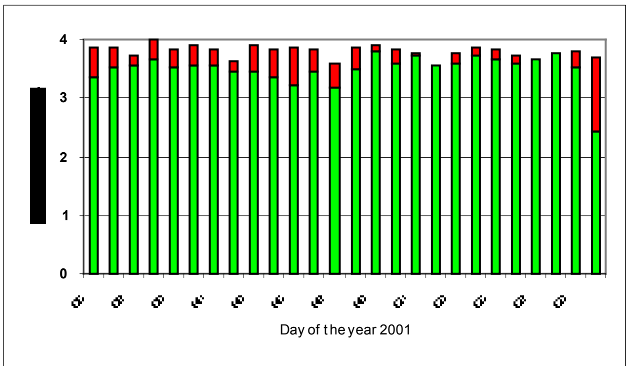

Fig. 4. Average ground station redundancy for CHAMP occultation processing per day (light grey: real, light + dark grey: simulated) during May 15 - June 9, 2001.

(see chap. 4). In parallel to the analysis of the measurements, simulations with the ROST software tool using the configuration of the 24 ground stations were performed, the elevation cut-off angle for the ground based measurements was set to 15 degrees. From the simulations the "theoretical" possible number of ground stations assuming 100% ground station availability was determined. The deviation between this "theoretical" and the real number of ground stations, which could be used for double differencing, is a measure for the data availability from the network. The main reasons for a loss of data, which will reduce this availability, are hardware problems at the ground station sites or data transmission failures from the ground stations to the Level-1 processing center at GFZ.

Fig. 4 shows the simulated and real average ground station redundancy for CHAMP occultation processing per day. The simulated redundancies are for each day about 4. The real redundancy is on average about 3.5 ground stations per day. The "day to day" variations are stronger as for the theoretical redundancies, which reflects different availability of ground station data for the different days. For Doy 152 of 2001 nearly all possible ground station data were available, the theoretical and real redundancy are almost identical. Problems in the ground station data provision were noticed on Doy 160 of 2001, the real redundancy was only about 2.5.

The analysis of the average redundancy provides no information, if a complete global coverage of occultations by the ground station configuration could be reached. Therefore, the global distribution of the redundancy was determined. The number of ground stations, which was used for the processing of each occultation was assigned to the location of the event. Then, for a grid with an area of 10x10 degrees in latitude/longitude the average number of ground stations for all occultations within the particular pixel was calculated. The resulting contour plot is shown in Fig. 5. On average ~4 ground stations were available for processing, e.g. over North Atlantic or Europe. Areas with lower redundancy were found as well, e.g. India or South Africa with ~2 ground stations per occultation. Areas with higher-than-average redundancy with up to 7 ground stations per occultation exist within the Equatorial Pacific region. Despite of this non-uniform global redundancy on average a minimum of ~2 ground stations for the pro-

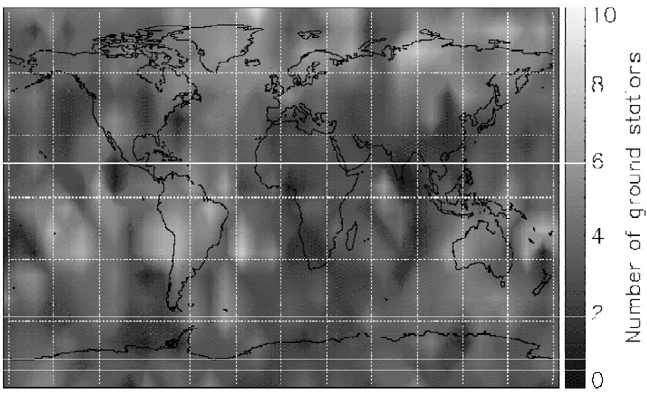

Fig. 5. Global distribution of ground station redundancy for CHAMP occultation processing during May 15 - June 9, 2001.

cessing of each occultation is available using the established network configuration.

6 Percentage in double differencing

The percentage of occultations, processed using data of each particular ground station is shown in Fig. 6. The light grey color indicates the real percentage whereas light and dark grey color indicate the simulated percentage (with the ROST software tool). The deviation between simulated and real percentage gives an information about the reliability of the ground station within the regarded time interval.

The majority of the ground stations is involved in the overall data processing with a percentage of 12-15 %, e.g. Goldstone (gold) and Tidbinbilla (tidb) with ~ 15 % or Quezon City (pimo) and Christiansted (cro1) with ~12 %. Significantly more occultations can be processed using the near-polar ground stations as Fairbanks (fair) with ~23.5 %, Mc Murdo (mcmz) with 28 % or My Alesund (nya2) with ~29.5%. This means that e.g. using only the Ny Alesund GPS ground station about one third of the CHAMP occultations can be processed applying the double difference technique. Furthermore, assuming a "Mini-network" consisting of only two near-polar ground stations (one at South-polar region as McMurdo and one at North-polar region as Ny Alesund) allows to process more than the half of all CHAMP occultations.

The best performance of data availability within the analysis period is reached by the Ny Alesund (nya2) station. For 99.7% of the possible cases the data for double differencing were provided. In contrast, only 37.2% of the Santiago de Chile (sant) station data were available. The average data availability for all ground stations is 91.7 %.

7 Occultations without ground station data

Only very few (1-4) occultations on some days are left unprocessed due to missing ground data. For all days with remaining occultations the data availability of the ground network was below the average, e.g. Doy 160 (20 unprocessed occultations) with 63.7% and Doy 135 (4 unprocessed) with 82.8%. But also on Doy 149 with 95.5% data availability one occultation left unprocessed due to missing ground station data.

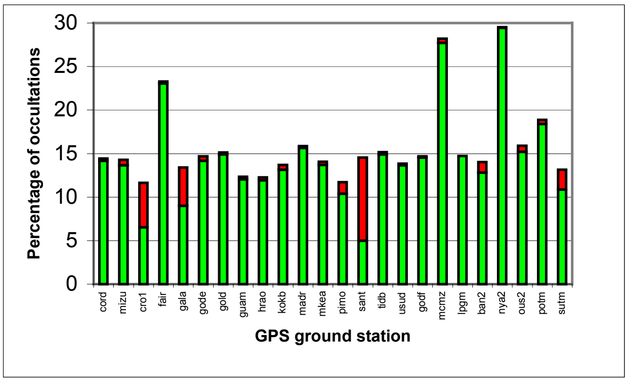

Fig. 6. Percentage of occultations processed using a particular ground station (light grey: real; light & dark grey: simulated) during May 15 - June 9, 2001. 4th column from left: Fairbanks (fair); 7th column from right: McMurdo (mcmz); 4 column from right: Ny Alesund (nya2).

8 Acquisition rate of the ground data

An acquisition rate of 1 Hz was selected for the installation of the fiducial ground network. This rate was necessary to correct for the short time variations in the GPS clocks, which were introduced by the Selective Availability (SA) of the GPS (Wickert et al. 2001a; Ware et al., 1996). SA was part of the intentional degradation of the GPS user's navigation solution (see e.g. Graas and Braasch, 1996) and implies that GPS transmitter clocks varied by about 10^{-7} s (tens of meters in units of length) over timescales of 100 s, with rates on the order of 1 m/s. These clock rates are unacceptable for precise atmospheric profiling. They can be corrected for by applying the double difference technique to process the GPS occultation data (e.g. Rocken et al., 2000).

As a result of the termination of SA on May 2, 2000 the amplitude of the described errors in the transmitter clocks was reduced by orders of magnitude, which made the clocks more predictable (Zumberge and Gendt, 2001).

A first result of the termination of SA is the feasibility of the application of the space-based single difference technique using 5-min precise GPS clock solutions for precise occultation data processing. This was recently successfully demonstrated by Wickert et al. (2002b). The application of the space-based single difference technique yielded a set of vertical temperature profiles, which exhibits statistically almost identical deviation to corresponding ECMWF analyses as an reference data set, generated utilizing the double difference technique. But the authors also concluded, that further analysis is needed to find the reasons for the statistical deviations between single and double difference temperature profiles of the order of 0.5 K below 20 and 1.0 K below 30 km. This deviations are not insignificant for the GPS radio occultation technique, with accuracy potential of the sub-kelvin order below 40~km and 0.2~K at tropopause level (Kursinski et al., 1997).

A second result is the possible reduction of the required acquisition rate for the double differencing without loss of information for the occultation processing. This was proposed already before the activation of the CHAMP radio occultation experiment by Wickert et al. (2001a) or Zumberge and Gendt (2001) analyzing 1 Hz GPS ground station data and the variations in time of precise GPS clock solutions. The authors suggested a reduction of the acquisition rate down to 1/10 or even 1/30 Hz. The rate of 1/30 Hz is the standard of the globally distributed GPS network of the International GPS Service (IGS). A rate reduction would significantly decrease the amount of ground data necessary for the data processing, which at 1 Hz rate is about 540 MByte per day in Turbo Binary format for 28 ground stations (May/June 2001, see Fig. 3).

CHAMP provided first GPS occultation data after the termination of SA and therefore, the impact of an acquisition rate reduction to the accuracy of the vertical atmospheric profiles can be investigated for the first time with real occultation data.

A set of 436 occultations during April 19-21, 2001 was processed with an average redundancy of ~3.5 ground stations per event using ground station acquisition rates of 1 Hz, 1/5 Hz, 1/10 Hz and 1/30 Hz respectively.

The resulting 1,400 dry temperature profiles for every specific acquisition rate were compared with each other, using the 1 Hz profiles as reference. The results are shown in Fig. 7. All three comparisons show practically not noticeable mean deviations over the entire height interval up to 30 km. The standard deviations at 20 km are 0.2 K (1/5 and 1/10 Hz) and 0.4 K (1/30 Hz) respectively. At 30 km standard deviations of 0.3 K (1/5 Hz), 0.5 K (1/10 Hz) and 0.8 K (1/30 Hz) were observed. A detailed discussion of these deviations, which are small, but not insignificant for the accuracy potential of the GPS radio occultation technique (see above), will take us outside the scope of this paper. We relate the deviations to the interpolation of the GPS clocks using different numbers of data points. A discussion of this was given by Wickert et al. (2001a) for the data analysis within a case study using the data of a specific ground station. They found, that the interpolation results for occultation processing (clock rates) are identical, when the acquisition rate is reduced down to 1/10 Hz. Our study shows, that for a larger number of occultations using various ground stations deviations already can be observed, if the acquisition rate is reduced to only to 1/5 Hz. Higher noise level of the ground station data (in relation to the ground station used for the single case study) is one possible reason for the observed deviations.

In addition, all 4 sets of temperature profiles were compared with corresponding ECMWF profiles as an independent data source (interpolated 6 hourly operational analyses, see Fig. 8). Vertical profiles of mean and standard deviations in relation to the analyses were calculated for each of the four data sets (see e.g. Wickert et at. (2002b) for a discussion of the deviations between CHAMP and ECMWF). Then, these "mean and standard deviation profiles" of the 1/5 Hz, 1/10 Hz and 1/30 Hz data sets were compared with the "mean and standard deviation profile" of the 1 Hz set, used as a reference. The result is shown in Fig. 8. The intention was, to find eventually different statistical behavior of the occultation profiles, which were generated with reduced (in relation to the standard 1 Hz) ground station acquisition rate, in relation to ECMWF. We found, that deviations in the statistical behavior of all 4 data sets in relation to the analyses (mean and standard deviation) are practically not noticeable (Fig. 8). A slight deviation of 0.1 K at 30 km is observed between the standard deviations of the 1/30 and 1 Hz data set in relation to ECMWF. We conclude, that the GPS occultation processing using reduced (in relation to the standard 1 Hz) acquisition rates of 1/5, 1/10 and 1/30 Hz results in sets of vertical temperature profiles, which exhibit statistical almost identical deviations to corresponding ECMWF analyses as the reference data set, generated using 1 Hz ground station data.

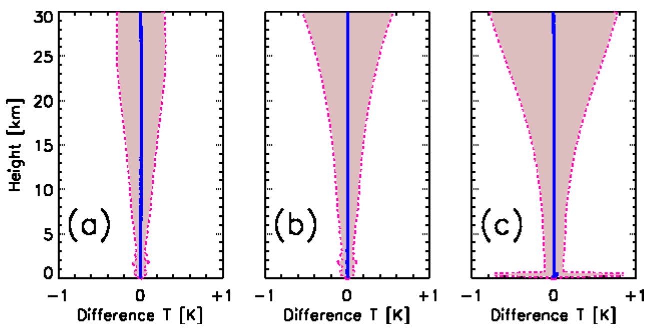

Fig. 7. Statistical comparison of 1,400 vertical temperature profiles (436 occultations during April 19-21, 2001 with in average 3.5 ground stations per event) derived using reduced acquisition rates of 1/5 Hz (a), 1/10 Hz (b) and 1/30 Hz (c) respectively, with the corresponding 1 Hz reference profiles. The solid black line indicates the mean deviation of the profiles, whereas the grey, dashed line shows the standard deviation between the respective data sets.

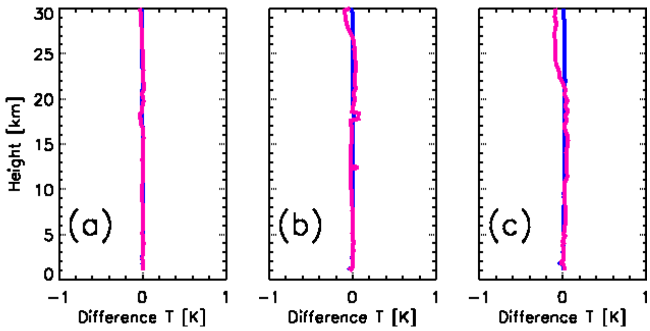

Fig. 8. Validation with an independent data source. Four sets of 1,400 dry temperature profiles (generated using 1, 1/5, 1/10 and 1/30 Hz ground station acquisition rate for double differencing) were compared with corresponding ECMWF analyses. Vertical profiles of the mean and standard deviation in relation to the analyses were determined for each data set, these are not shown here. They are between 0 and 2 K e.g. within the height interval from 5-30 km (e.g. Wickert et al., 2002b). The figures depicted here, indicate the differences of the mean (black) and standard (grey) deviation vertical profiles (in relation to ECMWF) of the 1/5 Hz (a), 1/10 Hz (b) and 1/30 Hz (c) data set related to the mean and standard deviation profiles of the 1 Hz data set, used as a reference (see text). There should be no difference of the mean deviation profiles (black, see Fig. 7), but even the difference of the standard deviations is negligible.

9 Summary and conclusions

The joint GFZ & JPL "High Rate Low Latency GPS Ground Tracking Network for CHAMP" enables the processing of globally distributed radio occultation events using double differencing technique with an average redundancy of about 4 ground stations per occultation event. The redundancy is globally non-uniform. Areas with lower-than-average redundancy were found, e.g. India or South Africa with ~2 ground stations per occultation. Areas with higher-than-average redundancy with up to 7 ground stations per occultation exist within the Equatorial Pacific region. Unprocessed Occultations occur due low ground network data availability, a disadvantage of the double difference method.

The time delay for providing the ground station data (hourly RINEX files) via the CHAMP Information System and Data Center is currently between ~30 to ~70 min. That delay allows for operational occultation processing. The delay can be further reduced since the data are transmitted from the ground station sites as files covering 15 min intervals. These files are transferred to the network processing centers with maximum time delay of ~15 min.

For the first time different reduced acquisition rates of the ground station data were applied to GPS occultation data processing after the termination of SA. Data sets of 1,400 vertical temperature profiles from CHAMP were generated, using the double differencing method with ground station acquisition rates of 1, 1/5, 1/10 and 1/30 Hz, respectively. These data sets show almost identical statistical behavior (mean and standard deviation) in relation to corresponding ECMWF analyses. These results indicate that after termination of the SA mode of the GPS a reduction of the acquisition rate in relation to the standard rate of 1 Hz is possible.

We conclude, that the High Rate and Low Latency network, jointly operated by GFZ and JPL, fulfills the requirements for an operational occultations data processing to provide globally distributed information about vertical structure of the atmosphere.

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