Atmosphere sounding using GPS radio occultation

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Introduction

On July 17, 1995 the U.S. Air Force announced " .. that today the Global Positioning System (GPS) satellite constellation has met all requirements for Full Operational Capability". Apart from precise positioning GPS signals also can be used to derive characteristic properties of the propagation medium (neutral atmosphere and ionosphere).

Onboard the Low-Earth-Orbiting MICROLAB-1 satellite (launched on April 5, 1995) GPS signals were recorded, which were transmitted by a setting GPS satellite and tangentially travelled the Earth's atmosphere (GPS occultation measurements within the GPS/MET-Experiment, Ware et al., 1996). Globally distributed vertical profiles of atmospheric temperature, water vapor and electron density were successfully derived, the GPS radio occultation technique as an innovative remote sensing method became reality.

The properties of the calibration-free atmosphere limb sounding technique (e.g. all-weather-capability, high accuracy, high vertical resolution, low cost realization) offer great potential for atmospheric and ionospheric research, improvement of numerical weather forecasts, space weather monitoring and climate change detection (e.g. Anthes et al., 2000; Hajj et al., 2000; Kuo et al., 2000; Kursinski et al., 1997).

Measurement principle

The GPS radio occultation technique is based on precise dual-frequency phase measurements (L-band; 1.2 and 1.5 GHz) of a GPS receiver in a Low-Earth-Orbit 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. A double difference technique is used to eliminate satellite clock errors: the signals from the occulting satellite are differenced with those from a reference GPS satellite. These satellite data then are synchronized with simultaneously recorded data, provided by a fiducial ground network. Details of the excess phase calibration are given by Hajj et al. (2002), Wickert (2002) or Wickert et al. (2001b).

Atmospheric bending angles are derived from the time derivative of the calibrated atmospheric excess phase after appropriate filtering. The ionospheric correction is performed by linear combination of the L1 and L2 bending angle profiles (Vorob'ev and Krasilnikova, 1994). Vertical profiles of atmospheric refractivity can be retrieved from the ionosphere corrected bending angle profiles by Abel inversion. For dry air, the density profiles are obtained from the known relationship between density and refractivity. Pressure and temperature ("dry temperature") are obtained from the hydrostatic equation and the equation of state for an ideal gas (e.g. Melbourne et al., 1994).

When water vapor is present, additional information is required to determine the humidity and density from refractivity profiles. Temperature profiles from operational meteorological analyses (e.g. of the European Centre for Medium-Range Weather Forecasts, ECMWF) are used to derive humidity profiles from the calculated refractivity in an iterative procedure (standard procedure, Gorbunov and Sokolovskiy, 1993). This algorithm suffers from a high sensitivity to even small errors in the analyses temperatures, resulting in large uncertainties of the derived water vapor profiles (Marquardt et al., 2001). More elaborate retrieval methods based on optimal estimation of both temperature and humidity including the error characteristics of the measurement and the "background" information (e.g. Healy and Eyre, 2000) show more potential for obtaining water vapor profiles with high accuracy. More details of the derivation of atmospheric parameters from GPS radio occultation data are given by e.g. Hocke (1997), Kursinski et al. (1997), or Melbourne et al. (1994)

GPS radio occultation with CHAMP

The German GPS radio occultation activities were started within the CHAMP satellite project (CHAllenging Minisatellite Payload, launch on July 15, 2000, Reigber et al., 2003a) and the HGF strategy funds (German's Helmholtz Association's instrument of competition) project GASP (GPS Atmosphere Sounding Project, 1999-2002, Reigber et al., 2003b; 1998). GASP was a project of the HGF centers AWI (Alfred Wegener Institut für Polar- und Meeresforschung), DLR (Deutsches Zentrum für Luft- und Raumfahrt), GKSS (Gesellschaft für Kerntechnik in Schiffbau und Schifffahrt) with GeoForschungsZentrum Potsdam (GFZ) as the project leading institution.

CHAMP, the German geoscience satellite, is in orbit and excellent condition now already for about 3 years (as of April 2003). In addition to measurements for the determination of the Earth's gravity and magnetic field, the data from a state-of-the-art GPS flight receiver ("BlackJack", provided by Jet Propulsion Laboratory, JPL) are used to derive precise information about the vertical temperature, humidity and electron density distribution on a global scale using the GPS radio occultation technique (Jakowski et al., 2002, Wickert et al., 2001a).

Within GASP, beside GPS radio occultation as a space-based method, also the application of ground-based techniques for GPS atmosphere sounding (estimation of vertically integrated water vapor content with high accuracy) were evaluated (see e.g. Reigber et al., 2002; Dick et al., 2001). The interdisciplinary research project combined the expertise of GPS experts, atmospheric physicists, meteorologists and climate experts. The main project goals were: installation of an infrastructure for the operational provision of space- and ground-based GPS atmospheric data and the assessment of their value for various applications in research and practice. For the first time continuous and rapid provision of GPS radio occultation data products (globally distributed vertical temperature profiles and atmospheric excess phases) with latencies between measurement and provision of 4-7 hours was demonstrated. Total water vapor content, derived from ground-based measurements at ~130 locations in Germany, is provided continuously with maximum delay of ~1.5 hours. Extensive validation studies with independent atmospheric/ionospheric data sets (meteorological analyses from ECMWF, radio sondes, ionosondes) were performed, techniques for assimilation of the GPS based atmospheric data were developed and applied (Reigber et al., 2002).

Here the GPS radio occultation experiment aboard CHAMP is briefly focussed to. Together with the U.S. Argentinean SAC-C satellite (launched on November 21, 2000, Hajj et al., 2003), CHAMP succeeds GPS/MET (1995-1997, Rocken et al., 1997). The measurements of both satellites and the improved (in relation to GPS/MET) infrastructure for GPS radio occultation data reception, transfer, analysis and provision brought significant progress for the GPS radio occultation technique.

CHAMP's GPS radio occultation experiment was activated on February 11, 2001. 7 occultation measurements during an one hour period were recorded by the GPS receiver onboard the satellite. Temperature and water vapor profiles were derived, the results were validated with meteorological analyses from ECMWF (Wickert et al., 2001a). Already these early results have shown, that, in spite of the activated Anti-Spoofing (AS) mode of the GPS, CHAMP allows for precise atmospheric sounding. This became feasible by the use of the state-of-the-art GPS flight receiver ("BlackJack", provided by JPL), combined with favourable antenna characteristics. The continuous availability of GPS occultation data is a significant progress in relation to GPS/MET (data analysis focussed to periods with deactivated AS, Rocken et al., 1997) and precondition for operational data processing and provision of atmospheric data, especially for applications within the numerical weather forecast. Further improvements are: first successful application of a space-based single differencing technique for precise occultation processing (Wickert et al., 2002) and demonstration of using reduced ground station acquisition rates (in relation to the standard 1 Hz) for double difference occultation processing (Wickert et al., 2003a). These improvements became feasible after the termination of the Selective Availability (SA) mode of the GPS on May 2, 2000 and simplify the GPS occultation processing. Using the radioholographic technique for the data analysis characteristic frequency shifts of direct and reflected GPS signals have been determined in the CHAMP observations. It was shown that these frequency shifts can be exploited to obtain information on ground elevation at the reflection point and ground-level refractivity (Beyerle et al., 2002).

Within 578 days in 2001 and 2002 CHAMP recorded more than 118,000 occultations (duration >20s), about 74,000 vertical atmospheric profiles of good quality are provided to the scientific community via GFZ's Information System and Data Center for CHAMP (ISDC, http://isdc.gfz-potsdam.de). Since March 10, 2002 (update of the flight receiver software) ~260 measurements per day are performed. Since the CHAMP mission is estimated to last at least until 2007, an unprecedented long-term-set of GPS occultation data is expected.

The occultation measurements of CHAMP are also used to derive vertical profiles of electron density, a key parameter to characterize the ionosphere. These data contribute to operational data sets of the global electron density distribution for developing and improving global ionospheric models and to provide operational space weather information (e.g. Hajj et al., 2000). The first 189 ionospheric radio occultations were performed on April 11 and 12, 2001 (Jakowski et al., 2001). In total about 77,000 measurements were recorded during 2001 and 2002. More than 48,000 electron density profiles were derived and are provided via GFZ's data center (ISDC, http://isdc.gfz-potsdam.de) to the scientific community. Additional ionospheric information is derived from the GPS navigation measurements. An assimilation technique is applied to reconstruct 3D electron density distribution of the upper ionosphere and plasmasphere near the CHAMP orbit plane (Heise et al., 2002).

Occultation infrastructure for CHAMP

The main components of the operational infrastructure for data generation, transfer, analysis and archiving are: the GPS receiver onboard the CHAMP satellite and the ground segment. It consists of the near polar downlink station at Ny Alesund, Spitsbergen (79.0° N, 11.5° E), the fiducial GPS ground network ('High Rate and Low Latency Network', Galas et al., 2001; currently consisting of about 40 stations), the Ultra rapid Precise Orbit Determination facility (König et al., 2002), the operational occultation processing system and, for archiving and distribution, the CHAMP Information System and Data Center. A second downlink station at DLR Neustrelitz, Germany (53.1° N, 13.1° E) serves as backup. The GPS ground network is operated in cooperation between GFZ and JPL, the other components are maintained by GFZ.

Operational data analysis

At GeoForschungsZentrum Potsdam an operational data analysis system has been established to process satellite orbit data (König et al., 2002), GPS ground station observations (Wickert et al., 2001b) and radio occultation data in an operational manner (Wickert et al., 2001a). The operational analysis of the ionospheric occultations is performed by DLR Neustrelitz (Jakowski et al., 2002; Wehrenpfennig et al., 2001).

Validation and provision of atmospheric data

Vertical profiles of refractivity, dry temperature and water vapor were validated with ECMWF meteorological analysis and radio sonde data (Beyerle et al., 2003b, Schmidt et al., 2003). Data, derived using earlier analysis software version were validated by Marquardt et al. (2003). The results indicate that stratospheric temperatures agree well with the analyses and sonde data. Between the upper troposphere and about 25 km altitude mean temperature deviations are <1 K and rms errors fall within the 2–4 K range. The biases at these heights could be either due to ECMWF or the CHAMP retrievals. A negative refractivity bias in the lower troposphere at low latitudes is observed in the CHAMP retrievals (Ao et al., 2003). It can be significantly reduced by using a modified canonical transform method (Beyerle et al., 2003a; Gorbunov, 2002), which is not yet included in the operational data analysis. The quality of the derived water vapor profiles suffers from the observed negative refractivity bias, dry biases up to 30% at low latitudes were observed in relation to ECMWF.

The GPS occultation data of CHAMP and the results of the operational data analysis are provided via the CHAMP ISDC (http://isdc.gfz-potsdam.de/champ/). Information about the status of the operational occultation processing can be found at the homepage of the GPS Atmosphere Sounding project , hosted by GFZ:http://www.gfz-potsdam.de/pb1/GASP/GASP2/index_GASP2.html.

The currently available data and analysis results are: GPS occultation measurements from CHAMP (neutral atmosphere and ionosphere), GPS ground station data of the fiducial network, the GPS and CHAMP orbit ephemeris, occultation tables, atmospheric excess phases for each occultation event, vertical atmospheric parameters (temperature/water vapor), vertical electron density profiles and relative TEC (Total Electron Content) data of the ionosphere occultation satellite link.

Summary and outlook

The innovative GPS radio occultation technique for precise sounding of the Earth's atmosphere was established in Germany within the CHAMP satellite mission and the GPS Atmosphere Sounding Project (GASP). The radio occultation experiment aboard CHAMP brought significant progress for the GPS occultation technique. About 200 globally distributed vertical profiles of temperature and water vapor daily are provided via the CHAMP data center in an operational manner. Since the CHAMP mission is estimated to last at least until 2007, an unprecedented long-term-set of GPS occultation data is expected. The preparation of the future multi-satellite occultation missions profits from the CHAMP data. These missions are: ACE+ (Atmosphere and Climate Explorer; Hoeg and Kirchengast, 2002), COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate; Anthes et al., 2000) or METOP (METeorology Operational; Edwards and Pawlak, 2000; Loiselet et al., 2000). These missions will operationally provide up to ~5,000 (for ACE+) precise and globally distributed vertical atmospheric profiles daily and will establish the GPS occultation technique as a standard method for remote sensing of the Earth's atmosphere on a global scale.

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