CHAMP, GRACE, SAC-C, TerraSAR-X/TanDEM-X: Science results, status and future prospects

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ABSTRACT

More and more satellites apply the GPS (Global Positioning System) radio occultation (RO) technique for precise sounding of the Earth's atmosphere and ionosphere on a global scale. A milestone for the recognition of this quite new remote sensing method was reached, when ECMWF and MetOffice started operational assimilation of GPS occultation data to improve global weather forecasts in 2006. Currently the major part of the operational available RO data is provided by the six satellite U.S.-Taiwan constellation FORMOSAT-3/COSMIC (FORMOsa SATellite mission-3/Constellation Observing System for Meteorology, Ionosphere and Climate). Data from the European operational Metop satellite (GRAS - GNSS Receiver for Atmospheric Sounding, launched 2006) are expected to be available in the near future. However, besides these dedicated RO missions, the operation of several GPS RO receivers is based on a mission-of-opportunity (MoO) concept. These missions, e.g., the German CHAMP, brought significant progress for the GPS RO technique and its break through. We briefly review the status of the current MoO missions, which provide GPS RO measurements, and summarize related science results.

1 Introduction

The application of the GPS Radio Occultation (GPS RO) technique aboard Low Earth Orbiting (LEO) satellites allows for the derivation of vertical atmospheric profiles on a global scale. The main characteristics of GPS RO measurements are: all weather capability, calibration free operation, and high accuracy and high vertical

Figure 1: GPS radio occultation missions of opportunity: CHAMP (launch July 15, 2000), GRACE-A (March 17, 2002), SAC-C (November 21, 2000), TerraSAR-X (June 15, 2007), and TanDEM-X (currently scheduled for September 2009).

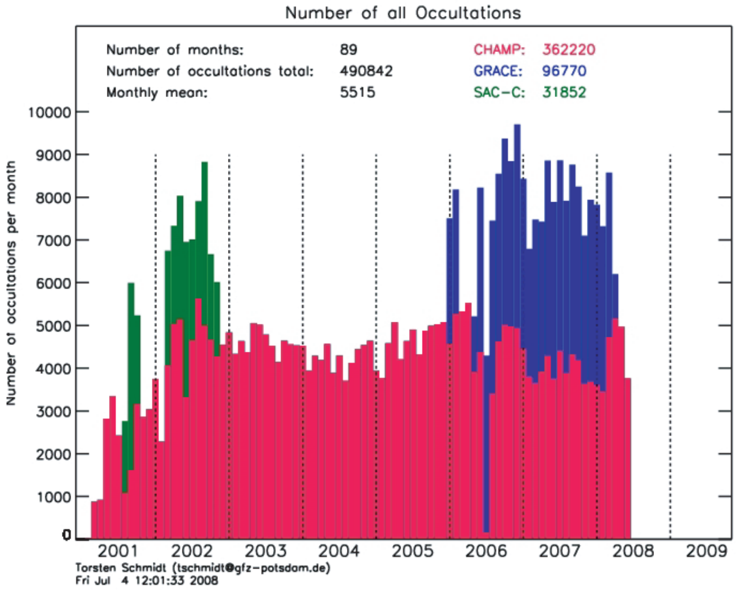

Figure 2: Number of monthly vertical atmospheric profiles, derived from CHAMP, GRACE-A and SAC-C GPS occultation measurements (GFZ processing) as of July 4, 2008.

resolution products. A detailed introduction to GPS RO is given, e.g., by Kursinski et al. (1997). Currently GPS RO is continuously applied aboard various satellites. Beside the dedicated operational missions FORMOSAT-3/COSMIC (six satellites launched on April 14, 2006; see, e.g., Anthes et al. (2008)) and Metop (launch October 18, 2006; operational data provision since April 2008, see, e.g., v. Engeln et al. (2008)) several MoO concept RO missions contribute to the currently available data base of RO measurements. We briefly introduce and overview the status of these missions: CHAMP, GRACE, SAC-C, TerraSAR-X/TanDEM-X (Fig. 1).

2 Mission status

2.1 CHAMP

The German CHAMP (CHAllenging Minisatellite payload) satellite was mainly designed for the determination of the Earth's gravity and magnetic field (Reigber et al. 2005). It reached its 8th anniversary in orbit on July 15, 2008. Initial RO measurements from CHAMP's BlackJack GPS receiver were available on February 11, 2001 (Wickert et al. 2001). As of July 4, 2008 more than 360,000 globally distributed vertical atmospheric profiles were provided (Fig. 2). These measurements form the first and unique long-term set of GPS RO data. According to recent orbit decay predictions and taking into account a final orbit uplift manoeuvre (currently foreseen for spring 2009) the end of the CHAMP mission is expected for end of 2009.

2.2 GRACE

The German-U.S. GRACE (Gravity Recovery and Climate Experiment) twin satellite mission was started on March 17, 2002. Due to a microwave link (Ku-band), connecting both satellites, a significant increased accuracy of the derived geoid parameters is reached, compared to CHAMP (Tapley and Reigber 2004; Dunn et al. 2003). Both satellites are equipped with CHAMP-like BlackJack GPS flight receivers. Initial occultation measurements aboard GRACE-B were recorded in July 2004 (Beyerle et al. 2005; Wickert et al. 2005), but continuous RO (aboard GRACE-A) was activated about two years later, on May 22, 2006 (for more details see

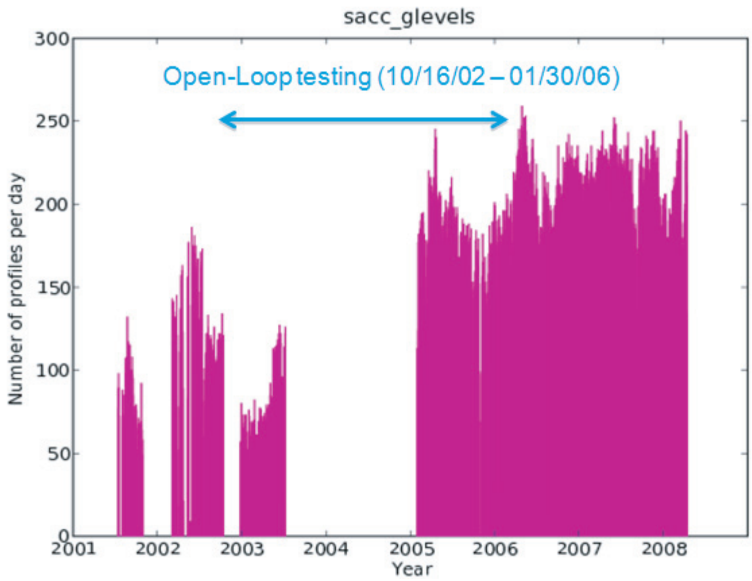

Figure 3: Daily GPS occultation measurements from SAC-C (JPL processing). The blue arrow indicates the period of OpenLoop testing.

Wickert et al. (2008)). As of mid June 2008 about 100,000 vertical profiles are available from GRACE-A (Fig. 2). Currently the lifetime of GRACE is expected to due at least until 2014.

2.3 SAC-C

SAC-C (Satelite de Aplicaciones Cientificas - C) is an international mission with main contributions from Argentina and U.S.. The satellite was launched on November 21, 2000. Main instruments are multi-spectral cameras, therefore the satellite is in a sun-synchronous orbit. GPS radio occultation measurements are recorded from a BlackJack receiver. Initial measurements from SAC-C were compared with CHAMP to assess the accuracy of the GPS RO technique in general (Hajj et al. 2004). The satellite was also used for first application and test of OpenLoop signal tracking between October 16, 2002 and January 30, 2006 (see, e.g., Ao et al. (2008); Sokolovskiy et al. (2006)) to improve the RO data quality in the lower troposphere also as preparation for the FORMOSAT-3/COSMIC mission. Currently more than 200 daily profiles are available from SAC-C, which are recorded in Open Loop mode (JPL offline processing, see Fig. 3).

2.4 TerraSAR-X/TanDEM-X

The German TerraSAR-X satellite (see Fig. 1) was launched on June 15, 2007. The main science instrument aboard is a new generation X-band radar (9.65 GHz) for Earth observation with up to 1-2 m resolution (spotlight mode). GFZ (together with University Texas) is operating an IGOR (Integrated GPS and Occultation Receiver) with fore and aft-looking COSMIC-like occultation antennas, which is currently in the commissioning phase. Together with the German satellite TanDEM-X (identical construction, launch currently planned for September 2009) TerraSAR-X will fly in a tandem-satellite constellation to capture interferometric radar images for precise digital elevation models (DEM) of the Earth's surface. This constellation (both satellites will fly very close to each other) provides also a potential opportunity for a long-term RO-in-orbit-calibration constellation, as nearly the same RO profile will be measured with identical receiver soft-and hardware by two different, but identical in construction, satellites. From the long-term analysis of the deviations between these twin-profiles detailed information on the RO error budget for different conditions can be derived (e.g., influence of diurnal, seasonal and solar cycle or the geographical region).

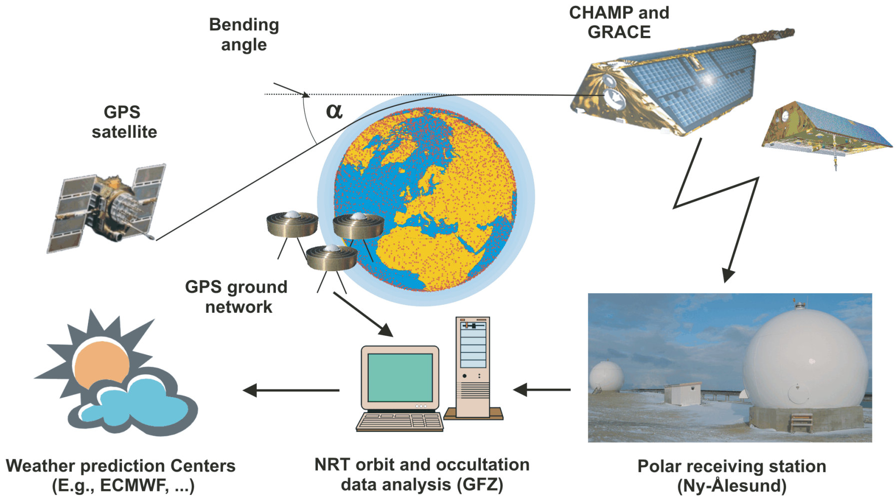

Figure 4: Overview of the GFZ ground infrastructure for operational handling and processing of NRT occultation data from CHAMP and GRACE. The facilities include the global GPS ground network, which is operated jointly with JPL, and the polar satellite receiving station at Ny–Ålesund, Spitsbergen, which is operated by GFZ.

3 Near real-time data provision

GFZ's research mandate includes the operation large-scale facilities. One of these is a quite complex ground infrastructure to operate satellite missions, which is the base to provide occultation data from CHAMP and GRACE-A in near real-time (see Fig. 4). Crucial components of this infrastructure are a globally distributed low-latency GPS ground station network (operated jointly with JPL), the polar satellite receiving station at Ny–Ålesund, Spitsbergen (two antennas operated by GFZ) and the automated satellite orbit (GPS and LEO) and occultation processing systems (for more details see, e.g., König et al. (2005); Wickert et al. (2004)). Initial effort to provide NRT occultation data from CHAMP was already made, when designing the processing systems before the launch of the satellite in 2000. Due to these activities an average mean delay between measurement aboard CHAMP and provision of corresponding RO analysis results (bending angle and refractivity profiles) of ∼5 hours was continuously reached already in February 2003 (Wickert et al. 2004). An international research project "Near Real-Time - Radio Occultation" (NRT-RO) within the GEOTECHNOLOGIEN programme of the German Ministry for Education and Research was started in 2005 to further reduce this delay and therefore pushing the operational use of RO data to improve global numerical weather forecasts. The main focus of NRT-RO was the development of dedicated near real-time orbit and occultation analysis software and the optimization of the interplay of the ground infrastructure from GFZ (see Fig. 4). As a major result of these activities the mean delay between RO measurements aboard CHAMP and GRACE-A and provision of corresponding bending angle and refractivity profiles was reduced in two steps to less than four (since Nov. 28, 2005) and two hours (since April 17, 2007). Fig. 5 provides an impression on recent delays. The NRT-RO project therefore contributed significantly to the begin of the operational GPS RO data assimilation at MetOffice and ECMWF in 2006 (e.g., Healy et al. (2007)) and by additional weather centers in 2007, e.g., MeteoFrance (Poli et al. 2008).

Currently a joint activity of NASA (National Aeronautics and Space Administration) JPL, CONAE (Comision Nacional de Actividadaes Espaciales), UCAR (University Corporation of Atmospheric Research) and GFZ is aimed to provide also data from the SAC-C satellite in NRT (more than 200 profiles daily, see Fig.3). In addition the reception of three satellites in parallel (CHAMP, GRACE-A, TerraSAR-X) was already successfully tested at the Ny Ålesund receiving station in autumn 2007, the base for future NRT data provision also from TerraSAR-X.

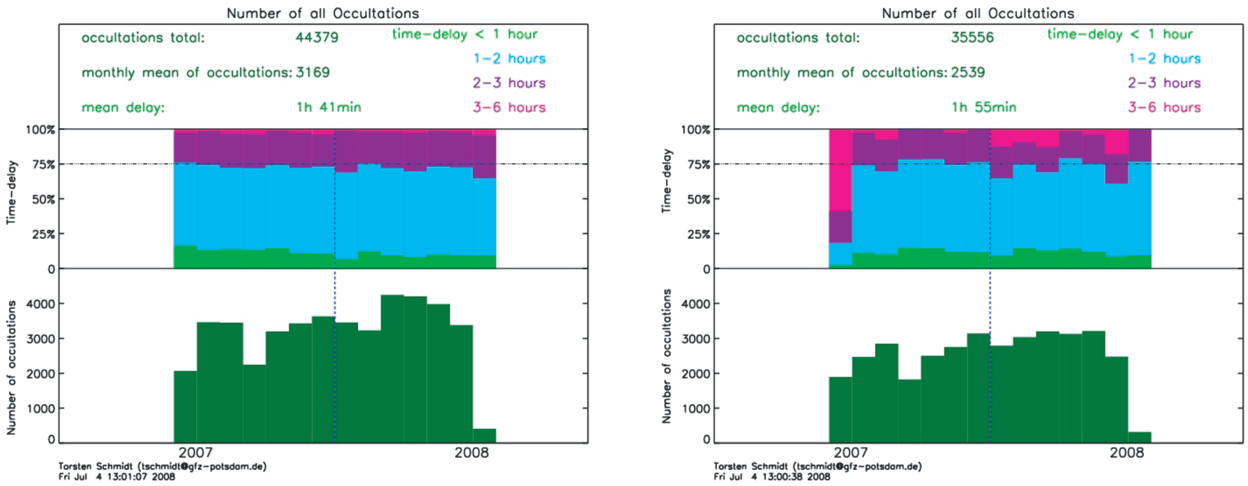

Figure 5: Delay (top) and monthly number (bottom) of NRT data from CHAMP (left) and GRACE-A (right) provided by GFZ since April 2007 (activation of recent NRT mode) as of July 4, 2008. The mean delay for CHAMP is 1 h 41 min, for GRACE-A slightly worse 1 h 55 min. Around 75% of the data for both satellites are provided within two hours after the corresponding measurement, nearly all profiles within three hours. To eliminate outliers we've only taken into account profiles, which are provided with less than six hours latency.

4 Selected recent science results

The mission-of-opportunity GPS RO satellites CHAMP, GRACE and SAC-C brought significant progress for the GPS RO technique, compared to the pioneering proof-of-concept mission GPS/MET (GPS/Metorology) between 1995–1997 (Rocken et al. 1997). Significant progress was reached to improve and simplify the GPS data analysis, e.g., by the initial application of single- and zero difference techniques (Beyerle et al. 2005; Wickert et al. 2002). Based on the analysis of CHAMP and SAC-C measurements and simulation studies a deeper understanding of the lower troposphere bias problems was reached, e.g., (Ao et al. 2003; Beyerle et al. 2006) and advanced signal tracking and analysis techniques were developed and applied (Sokolovskiy et al. 2006; Jensen et al. 2003) to improve the RO data quality in the lower troposphere. The data were also used to prepare for future, more advanced and dedicated missions, as, e.g., FORMOSAT-3/COSMIC or Metop. Data from CHAMP and GRACE-A are also provided in near real-time via GTS (Global Telecommunication System) for weather centers (Wickert et al. 2008). The long-term set of RO data from CHAMP is unique and in use by numerous groups world-wide for various scientific investigations. Here we give examples for recent science RO results from GFZ.

4.1 Long term data set from CHAMP

The CHAMP RO data record covers already a period of ∼8 years (see sec. 2.1). The measurements are globally distributed, weather independent and exhibit a high accuracy and vertical resolution. Consequently the data base can be used for initial climatological studies on a global scale. One example are investigations of the tropopause region. Changes of the tropopause height are considered as a parameter for the detection of climate change processes. Therefore the continuous identification and monitoring of this parameter is an important goal in climate research. Within a recent study by Schmidt et al. (2008), based on the CHAMP data set, global LRT (Lapse Rate Tropopause) height trends between 39–66 m/decade were derived, which are in good agreement with radiosonde observations. For all geographical regions positive tropospheric and negative stratospheric correlations between LRT height and temperature anomalies at different pressure levels were found, whereas the extra-tropical correlations are higher compared to the tropics (see Fig. 6). Another example for long-term studies based on CHAMP data are investigations related to the global distribution and climatological variation

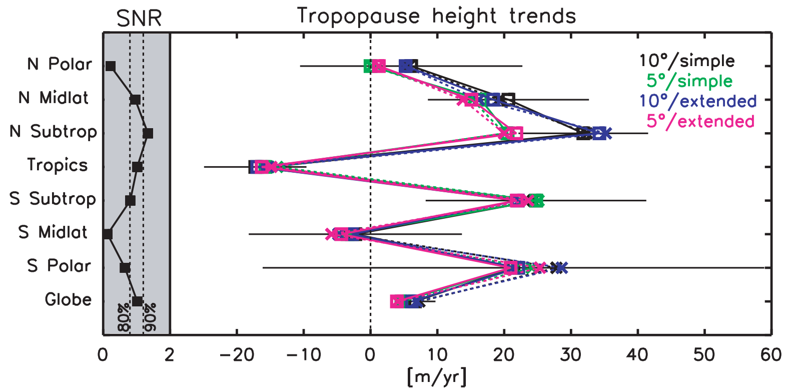

Figure 6: Lapse Rate Tropopause height trends (m/yr) derived from CHAMP data between May 2001 and December 2007 (80 months) for different binning methods and tropopause determination algorithms. Error bars (2-sigma confidence intervals). Left: SNR with the one-sided 80% and 90% confidence intervals (from Schmidt et al. (2008)).

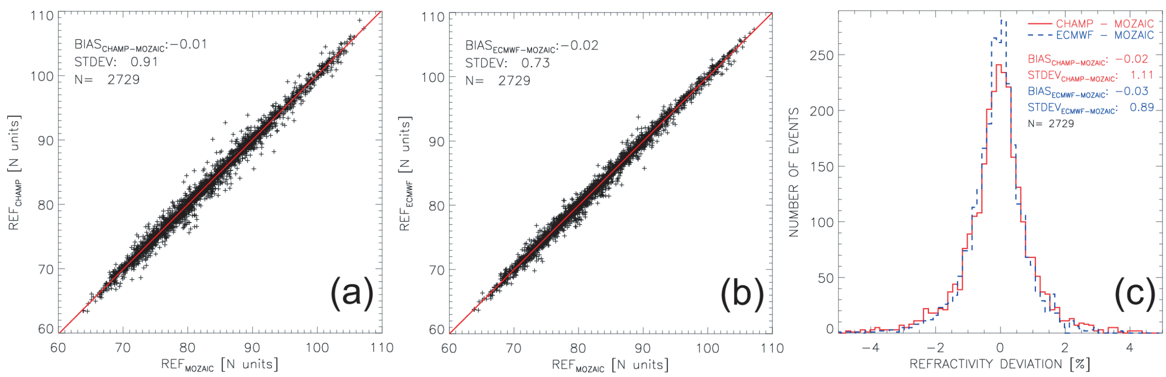

Figure 7: Comparison of refractivity data from MOZAIC above 300 hPa with a) CHAMP, b) ECMWF and c) CHAMP and ECMWF (from Heise et al. (2008)).

of atmospheric wave activity (e.g., de la Torre et al. (2006)).

4.2 Comparison of CHAMP with aircraft data

A recent validation study with CHAMP data demonstrated for the first time that aircraft measurements of pressure, temperature, and humidity provide a valuable source of information for GPS RO validation in the troposphere region (Heise et al. 2008). Data from the MOZAIC (Measurement of OZone and wAter vapor by Airbus Inservice airCraft) program, which currently includes five aircrafts performing up to 2,500 flights per year, were used for this study. These data are not assimilated to ECMWF analyses and consequently provide an opportunity to assess, whether GPS RO data could provide, e.g., significant additional water vapor information compared to ECMWF data without assimilating RO. One of the conclusions of the authors is, that CHAMP derived humidity data between around 300 and 650 hPa could provide this additional information. Also refractivity and temperature data can be compared. As an example for this, Fig. 7 shows results of refractivity comparisons at cruise altitudes of the aircrafts (above the 300 hPa pressure level). Within the follow-on program of MOZAIC, IAGOS (Integration of routine Aircraft measurements into a Global Observing System, currently under preparation) the number of aircrafts will be increased to 10-20. This will significantly improve the global coverage of the measurements, especially in the Pacific region.

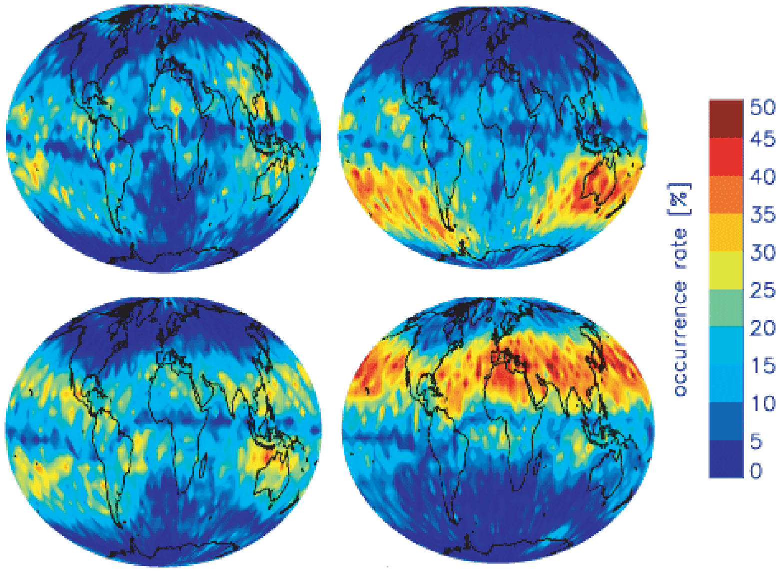

Figure 8: Seasonal occurrence of sporadic E-layers, derived from CHAMP, GRACE-A and FORMOSAT-3/COSMIC GPS RO measurements with a spatial resolution of 5°×5°. The upper row contains plots for northern hemisphere autumn 2006 (September, October, November) on the left and winter 2006/2007 on the right (December, January, February). The plots in the lower row contain data from spring 2007 (March, April, May) on the left and summer 2007 (June, July, August) on the right (from Arras et al. (2008)).

4.3 Ionospheric irregularities

The derivation of vertical atmospheric profiles in the neutral part of the atmosphere is based on the analysis of 50 Hz dual-frequency GPS tracking data (L-Band) during the occultation events. The data cover altitudes from the Earth's surface up to around 120 km (all mentioned satellites including FORMOSAT-3/COSMIC, except Metop with upper altitudes of ∼80 km). This allows for a further important application of the RO data.

The lower ionospheric E-region (between 90 and 120 km) sometimes features areas of enhanced electron density, called sporadic E-layers (E_s). E_s consists of a considerable amount of metallic ions which are transported by wind shears, especially produced by tides, in the upper atmosphere. Such layers can be identified based on a dedicated GPS RO data analysis (Arras et al. 2008). Fig. 8 shows the global sporadic E distribution in 2006/2007. The maps contain E_s information, derived from CHAMP, GRACE-A and FORMOSAT-3/COSMIC. E_s occur mainly during daytime in the mid latitudes of the summer hemisphere with maximum occurrence rates of 45%. In winter E_s activity is generally low and during the equinoxes a moderate activity was found in lower latitudes.

The information on E_s can be used in atmospheric research, e.g., to investigate vertical coupling processes between different atmospheric layers. E_s monitoring is also useful to assess the error budget of navigation and communication systems, which are disturbed by sporadic E layers.

5 Summary and future prospects

The status of several mission-of-opportunity GPS RO missions was briefly reviewed. Such missions provide an excellent chance to fly GPS RO receivers at low costs compared to dedicated single-satellite missions or constellations. Data from the described missions brought significant progress for the GPS radio occultation technique during the last years and currently also contribute to the operational available occultation data, e.g., to continuously improve global weather forecasts. Further missions are already close to be launched, as, e.g., KOMPSAT-5 (Korea, with IGOR receiver) or the Indian remote sensing satellite OCEANSAT-2, with ROSA, the Italian GPS radio occultation receiver.

In parallel to these activities the realization of several ideas for dedicated multi-satellite RO mission is currently in progress. This concept uses the major advantage of the GPS RO technique: Small receivers, which can be integrated to potential constellations of a large number of small and very small satellites, allowing for low-cost multi-satellite missions with high numbers of provided occultation events (see, e.g., Yunck et al. (2000)). Such GPS RO constellations thereby can be combined with new applications, as, e.g., GPS-Reflectometry/Scatterometry or the quite established spectrum of ionosphere sounding techniques to exploit, in combination with ground based measurements, the full potential of GPS techniques for atmospheric remote sensing (see, e.g., Wickert et al. (2007)). Such constellations also will profit from additional signal sources (Navigation satellites) as from GALILEO (Europe), GLONASS (Russia) or BEIJDOU (China). The additional signals will significantly increase the number of occultations, but new signal structures will also allow to increase the accuracy of the GPS (and more general GNSS, Global Navigation Satellite System) data. Examples for current multi-satellite projects are the FORMOSAT-3/COSMIC follow on mission Thundersat (Taiwan, U.S.), Cicero (U.S.), or MicroGEM (Germany), which are currently in process to get funding. A key challenge hereby is the development and improvement of appropriate and cost-effective GNSS receivers optimized for remote sensing.

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