PROSPECTS OF THE EPS GRAS MISSION FOR OPERATIONAL ATMOSPHERIC APPLICATIONS

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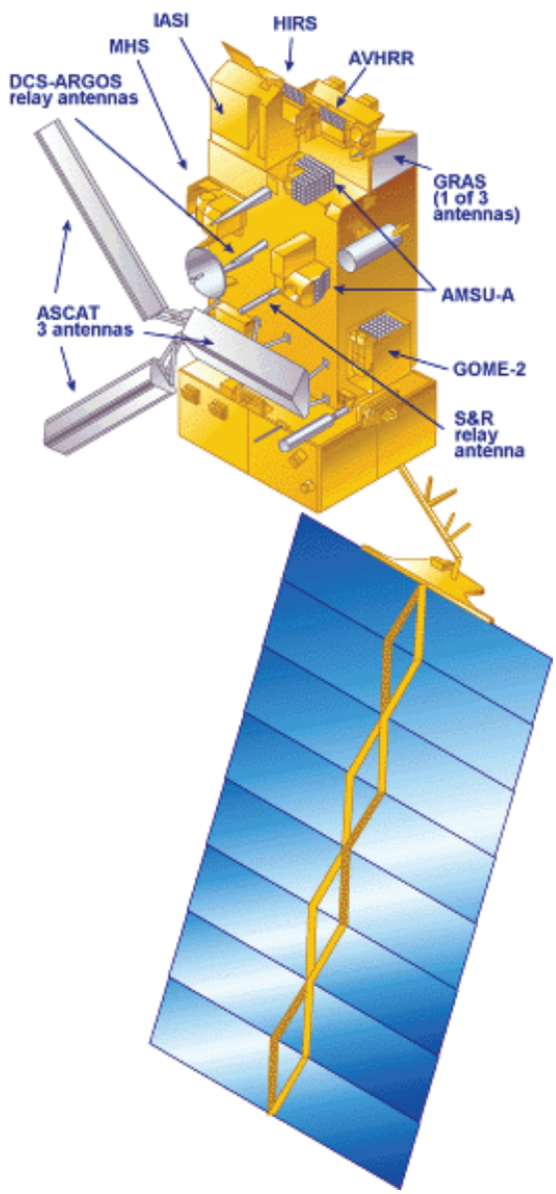

FIG. 1. MetOp satellite and the payload instruments.

Radio occultation receivers on board Europe's new polar orbiting satellites provide very high-quality observations of atmospheric characteristics for operational numerical weather forecasting and climate monitoring.

The GRAS mission will provide operational radio occultation (RO) sounding data to the numerical weather prediction (NWP) user community. Global Navigation Satellite System (GNSS) Receiver for Atmospheric Sounding (GRAS) is one of the payload instruments on board the MetOp satellite series that form the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Polar System (EPS). GRAS is also the first European global positioning system (GPS) receiver that has been designed especially for RO soundings. The objective of the EPS GRAS mission is to provide RO data with unprecedented accuracy and continuity. These characteristics are important both for NWP and climate monitoring applications. The absolute accuracy of RO combined with the over 14-yr duration of the EPS mission will potentially allow GRAS data to be used as a benchmark for other atmosphere sounding missions.

The EPS mission consists of three Meteorological Operation (MetOp) satellites (Fig. 1) that will fly successively for a time period of over 14 yr. EPS is the European contribution to a joint European–U.S. polar satellite system called the Initial Joint Polar System (IJPS) and it is the first European operational meteorological satellite system in a polar orbit. EPS covers the morning (0930 LT) orbit while the satellites operated by the U.S. counterpart, the National Oceanic and Atmospheric Administration (NOAA), will cover the afternoon (1430 LT) orbit.

The first MetOp satellite (*MetOp-A*) was launched successfully in October 2006. A more detailed description of the EPS mission and payload instruments is provided in Klaes et al. (2007).

The GRAS measurement system has been developed to fulfill the stringent requirements for operational NWP applications. The most challenging aspects of the GRAS system design have been to ensure that the GPS and the MetOp Precise Orbit Determination (POD) can be performed in near–real time (NRT) and that the auxiliary data required in the clock correction by differencing will be available. This paper provides an overview of the GRAS system and data products, and presents the prospects of GRAS observations for NWP, climate monitoring, and space weather applications.

RADIO OCCULTATION MEASUREMENT. The scientific basis of the RO technique was developed in the 1960s for soundings of the atmospheric parameters of the other planets in our solar system (e.g., Kliore et al. 1965, 1967; Vinogradov et al. 1968; Fjeldbo and Eshleman 1968, 1969). Approximately at the same time Fischbach (1965) and Lusignan et al. (1969) proposed the use of the same technique for the sounding of the Earth's atmosphere. Later the concept of the RO sounding was analyzed in many publications (e.g., Murray and Rangaswamy 1975; Murray 1977; Rangaswamy 1976; Gurvich et al. 1982; Gurvich and Sokolovskiy 1985; Gorbunov 1988), and tested experimentally from the Salyut-7 space station (Volkov et al. 1987; Grechko et al. 1987). The development of the GPS constellation triggered the first proposals for a global temperature monitoring with a GNSS-based RO system by Melbourne et al. (1988, 1994). These proposals led into the GPS/MET RO concept demonstration mission launched in 1995 (e.g., Ware et al. 1996; Kursinski et al. 1996).

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The RO sounding is based on the refraction of radio waves as they pass through the atmosphere as shown in Fig. 2. The refraction angle is determined by the refractivity gradients normal to the propagation path. The atmospheric refractivity gradients depend on the gradients of density (and hence temperature, pressure, and water vapor) and electron density, and so a measurement of the refraction angle contains information on these atmospheric variables. These effects are most pronounced when the radio wave traverses a long atmospheric limb path, and measurements for a series of such paths at different tangent heights contain information on the vertical profile of refractivity. At radio frequencies it is not possible to measure the refraction angle directly. However, the vertical refraction gradients and the change of the measurement geometry during an occultation measurement introduce an additional Doppler shift into the retrieved signal. This Doppler shift (or the related phase path increase) can be measured very accurately and is directly related to the refraction angle.

A vertical refractivity profile can be retrieved from the RO measurements in multiple ways. A traditional approach is to calculate at first a time series of the refraction angles (also called bending angles) and then apply an Abel transform to invert the angles into the refractivity values (e.g., Kursinski et al. 1997). Above the troposphere the retrieval of the refraction angles can be performed by using a geometrical optics (GO) approximation. In the troposphere atmospheric multipath propagation may cause the GO approximation to produce ambiguous refraction angle solutions for the same impact parameter. In these conditions wave optics (WO)–based retrieval methods can potentially solve for the correct refraction angle profile. The phase transform (PT) presented by Jensen et al. (2004) is a closed-form formulation for a technique solving the atmosphere multipath problem. Two computationally more efficient approximations of the PT principle are the canonical transform (CT) and the full spectral inversion (FSI) methods (Gorbunov and Lauritsen 2004; Jensen et al. 2003).

The refractivity profiles retrieved from RO soundings can be processed into vertical profiles of atmospheric temperature and humidity. In the stratosphere and upper troposphere, where water vapor density is low, refraction variability is dominated by vertical temperature gradients, and the temperature profile can be retrieved accurately by applying the hydrostatic equilibrium assumption. In the lower troposphere, water vapor effects dominate the refraction variability. In this region the water vapor profile can be retrieved with iteration and by using a priori information about the atmospheric temperature (e.g., Kursinski et al. 1995). Alternatively, and preferably, a 1D variational data assimilation (1DVAR) retrieval of temperature and water vapor profiles, and surface pressure can be performed (Palmer et al. 2000; Healy and Eyre 2000). It is also possible to assimilate the RO data directly into NWP systems as refraction angles or refractivity profiles (Eyre 1994; Healy and Thépaut 2006). In the latter two cases a separate retrieval of the temperature or humidity profiles from RO is not necessary.

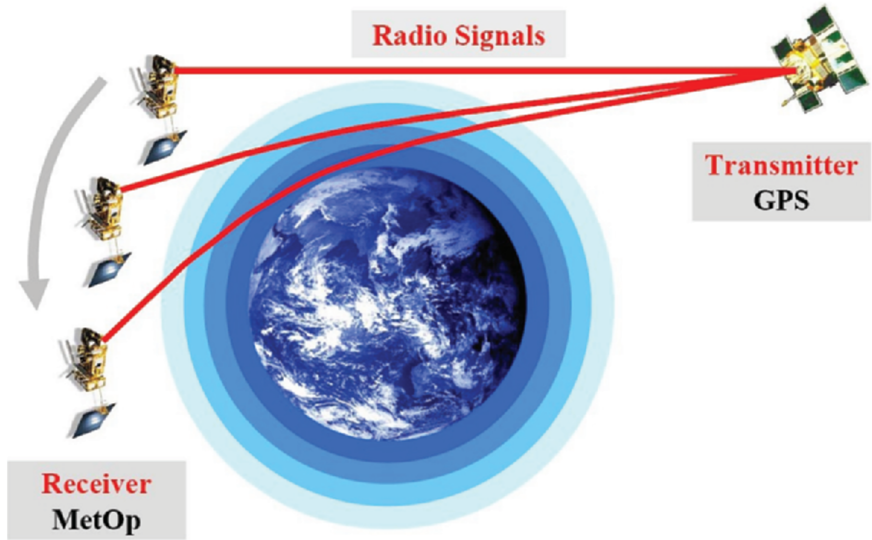

Fig. 2. Geometry of a radio occultation sounding.

The RO sounding of the Earth's atmosphere has been demonstrated several times in various scientific missions. The highly successful GPS/MET mission (Ware et al. 1996) has been followed by a number of other RO missions like Oersted, Challenging Minisatellite Payload (CHAMP; Wickert et al. 2004), Satellite de Aplicaciones Cientificas-C (SAC-C; e.g., Hajj et al. 2004), Gravity Recovery and Climate Experiment (GRACE; Wickert et al. 2005), and Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC; Rocken et al. 2000; Wu et al. 2005; Anthes et al. 2008). The CHAMP and COSMIC mission teams have demonstrated that the processing and dissemination of the RO data within 3-h timeliness is feasible. This has been encouraging for the GRAS system development, because for GRAS the timeliness require-

Table 1. GRAS product accuracy requirements.

		Level 1 products	Level 2 products	
		Bending angle	Specific humidity	Temperature
Coverage		Global	Global	Global
Horizontal sampling		The average distance between individual soundings over a period of 12 h is less than 1,000 km		
Vertical range[a]		Surface–80 km	Surface–100 hPa	Surface–1 hPa
Vertical sampling rate[b]	0–5 km	2–5 Hz	0.4–2 km	0.3–3 km
	5–15 km	2–5 Hz	1–3 km	1–3 km
	15–35 km	2–5 Hz	—	1–3 km
	35–50 km	2–5 Hz	—	1–3 km
RMS accuracy[c]	0–5 km	0.4%	0.25–1 g kg^{-1}[e]	0.5–3 K
	5–15 km	0.4%	0.05–0.2 g kg^{-1}[e]	0.5–3 K
	15–35 km	1 μrad or 0.4%[d]	—	0.5–3 K
	35–50 km	1 μrad or 0.4%[d]	—	0.5–5 K
Timeliness		2 h 15 min	3 h	3 h

[a]Lowest product level is determined by the lowest signal tracking height.
[b]After noise filtering.
[c]With no systematic biases.
[d]Whichever is greater.
[e]Equivalent to a requirement of 5% in relative humidity.

ments are even more stringent (see Table 1). The data from the GRACE mission has been used to show that a receiver with a stable clock oscillator potentially allows refraction angle retrieval without clock differencing (Beyerle et al. 2005). Because the GRAS receiver uses an Ultra Stable Oscillator (USO), this type of retrieval is also possible with the GRAS soundings. Finally, the COSMIC mission has recently started to provide RO soundings in near–real time from a constellation of six satellites. The observations from COSMIC can be used to demonstrate the impact of a large amount of RO information in an NWP system. The COSMIC constellation also has for the first time allowed the estimation of the precision of radio occultation by intercomparison of very closely collocated and coplanar soundings (Schreiner et al. 2007).

GRAS MEASUREMENT SYSTEM. The GRAS receiver has been specifically designated to provide RO soundings for operational meteorological applications (Loiselet et al. 2000). The requirements for the main GRAS data products are presented in Table 1. To meet these requirements, the GRAS receiver has been designed both to produce unprecedentedly high-quality rising and setting occultation observations. The total number of occultation soundings per day from GRAS is over 600. The nominal GPS carrier phase and amplitude sampling rate in the GRAS occultation measurements is 50 Hz. The lowest part of the troposphere is measured with a "raw sampling" (RS) measurement mode (also known as open loop mode). In this mode the output of the correlator of the receiver is sampled at a 1-kHz rate.

The processing of the GRAS measurement data has been split into two parts. The initial processing from raw soundings to bending angle profiles (called level 1 processing) is performed by the EPS Core Ground Segment (CGS) at the EUMETSAT headquarters in Darmstadt, Germany (Luntama 2006). The second part of the processing, that is, the retrieval of the geophysical parameters, is performed by the GRAS Meteorology Satellite Application Facility (SAF). This is called level 2 processing. The GRAS SAF consortium is led by the Danish Meteorological Institute (DMI) with participation by the Met Office, the Institut d'Estudis Espacials de Catalunya (IEEC), and the European Centre for Medium-Range Weather Forecasts (ECMWF).

EUMETSAT provides a permanent archive of all measurement data and level 1 and level 2 data products from the EPS mission. The archived raw data and products are available to the user community via the EUMETSAT Unified Meteorological Archive and Retrieval Facility (UMARF) and the GRAS SAF Archive and Retrieval Facility (GARF) services. These services can be accessed online (http://archive.eumetsat.org/umarf/ and http://garf.grassaf.org/, respectively).

The GRAS Meteorology SAF activities, data processing, and products are described in detail at the SAF Web page (www.grassaf.org/).

GRAS PRODUCT VALIDATION AND EARLY RESULTS. The approach adopted for the GRAS bending angle profile validation is presented by Marquardt et al. (2005). The baseline validation is performed by comparing a NWP background and the retrieved total bending angle profile. The comparison is performed with the 1DVAR technique (Healy and Eyre 2000). The prerequisites for this approach are a forward model for the total bending angle profiles and an error characterization of the measurement data. This validation method tests the correctness of the measurement error characterization. If the error estimates are correct, the 1DVAR finds an assimilation solution within an expected number of iterations. Otherwise the process converges too fast, too slowly, or it may not converge at all. The 1DVAR retrieval provides diagnostics about the convergence of the iterative adjustment of the NWP background, the difference between the measurement and the final solution, correctness of the expected error levels, and a retrieved geophysical data profile. With a global NWP model, every occultation measurement by GRAS can be validated against the model. This enables fast generation of validation statistics.

Another validation planned for the GRAS products is the intercomparison of the noise levels in the measurement data and the theoretically expected noise levels. This validation helps to confirm that the analysis of the measurement system has been performed correctly and that performance of the real system follows expectations. A robust way of performing the noise validation is to use the generalized cross validation (GCV) as presented by Marquardt et al. (2005). GCV is a well-established method for the objective estimation of parameters for smoothing splines when the standard deviation of the noise in the data is not known.

Intercomparisons of the GRAS data products with independent measurements are also going to be used in the GRAS data validation. An independent measurement is considered collocated in the GRAS validation if the measurement location is within 3 h and 300 km from the GRAS sounding. This definition is based on the recommendation of the GRAS Science

Advisory Group (SAG). Radio occultation measurements by other missions (e.g., CHAMP, COSMIC), radiosonde measurements, and geophysical data profiles retrieved from satellite or ground-based remote sensing measurements are potential reference measurements. The intercomparison of RO products and products from other sounding measurements requires that both the measurement and the data processing characteristics are correctly taken into account. Suitable approaches for the direct intercomparison of independent data are discussed as well by Marquardt et al. (2005).

The operational GRAS Product Processing Facility (PPF) is currently undergoing fine tuning with respect to the orbit determination and the calculation of bending angles. Orbit segments are calculated in the operational environment based on 3-min data slices, using a sequential filter. An overview of the bending angle calculation is given in Wilson and Luntama (2007), and a detailed mathematical description of the algorithm is provided in Luntama and Wilson (2004). However, the most recent development uses the geometrical optics retrieval and applies a Savitzky–Golay filter for noise reduction. Ionospheric corrected bending angles are only calculated when dual tracking is available. These constrains limit the current retrievals to ray path tangent point heights above 10 km. Processing of the single frequency tracking data will be included into the PFF in the near future.

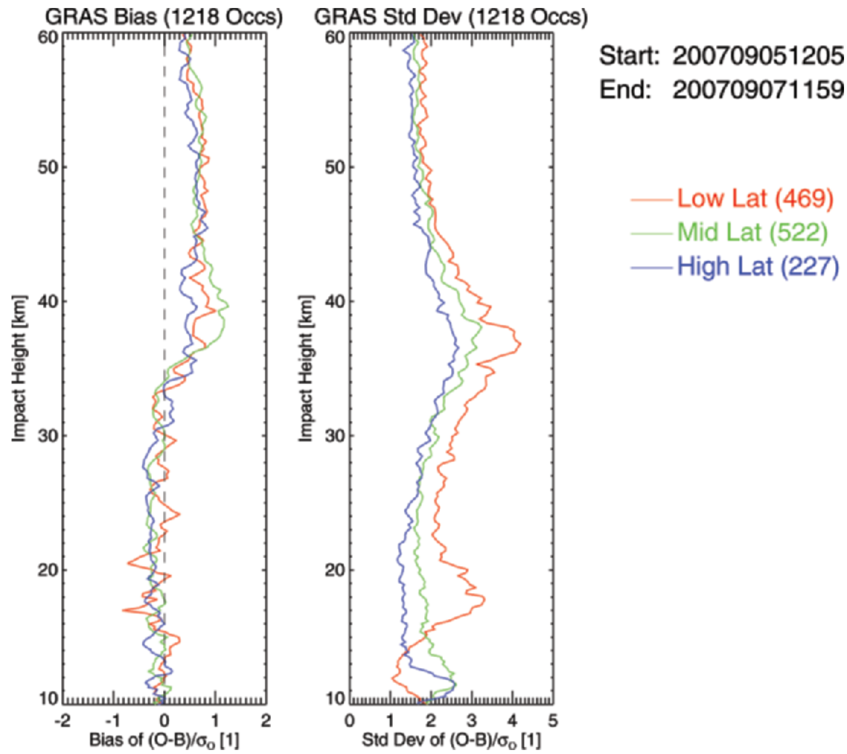

FIG. 3. (left) Bias and (right) std dev of ($O - B$)/σ_O for bending angle profiles retrieved from 1218 GRAS occultations on 5–7 Sep 2007.

Figure 3 shows results from the most recent PPF development. Shown are bias and standard deviation calculated for each occultation from ($O - B$)/σ_O, where O denotes the GRAS observation, B a forward modeled background, and σ_O an expected bending angle error. We use an expected bending angle error of 1 μrad or 1%, whichever is larger. This is roughly in line with the expected errors from GRAS and smaller than errors estimates used in radio occultation assimilation at, for example, ECMWF. For the background we use collocated ECMWF 12-h forecast profiles forward modeled to bending angles using the Radio Occultation Processing Package (ROPP) tool that is available from the GRAS SAF (www.grassaf.org). The results shown are based on data for 2 days within a test period in September 2007, in total more than 1,200 occultations. Latitude bins of 30° are used.

The results show that the current processing gives very good results up to about 33 km, above which a bias is observed in all latitude bands. The bias is down weighted by σ_O since this is constant at altitudes above about 35 km. The bending angle bias at 60-km impact height is about 0.3 µrad. The bias around 40 km is about 0.8 µrad; with respect to the average bending angle around 40 km this is about 1.2%. These biases are probably a combined effect of ECMWF model errors in the stratosphere and the current GRAS processing, for example, a similar bias around 40 km is also found when comparing COSMIC observations to ECMWF model fields. The standard deviation results again show the combined effect of GRAS and ECMWF, for example, for low latitudes around 18 km the impact of gravity waves.

OPERATIONAL AND SCIENTIFIC IMPACT OF GPS RO MISSIONS. The potential of RO measurements both in operational applications and in scientific research has been proven with data from "proof-of-concept" missions like GPS/MET and CHAMP. The GRAS mission can be expected to confirm and extend these results due to the availability of the NRT products for operational applications and the long-term continuity of the sounding over the lifetime of the EPS mission.

NWP. The temperature and humidity profiles retrieved from the GPS/MET and CHAMP RO sounding data have shown that this technique can provide meteorological information over the 7–25-km height range with a very good accuracy (Rocken et al. 1997; Steiner et al. 1999; Wickert et al. 2001; Gobiet et al. 2007; Kuo et al. 2004). The global distribution of the profiles and the all-weather capability of the RO sounding complement the meteorological data received from other sounding systems. It has also been shown with simulation studies that temperature information provided by RO complements the information provided by other instruments such as advanced microwave limb sounders (von Engeln et al. 2001) or infrared sounders (Collard and Healy 2003).

The different strategies for assimilating RO data into NWP systems have been analyzed by Eyre (1994) and Kuo et al. (2000). The main conclusion is that the assimilation of the bending angles is the preferred approach. However, when this is not feasible, the assimilation of refractivity profiles is superior to the assimilation of temperature and humidity profiles derived from the RO measurements. Positive results from assimilation experiments with bending angle profiles from the GPS/MET and CHAMP missions have been presented by Liu et al. (2001) and Zou et al. (2004), but these studies did not assimilate all the other satellite measurements that were available at that time. Healy et al. (2005) has demonstrated a positive impact on stratospheric temperatures in a 16-day trial with the assimilation of CHAMP refractivity profiles into the operational Met Office 3DVAR system. However, Poli and Joiner (2003) reported no significant impact from the assimilation of the 1DVAR retrievals into the Data Assimilation Office model when they assumed that the RO retrievals would have the same error characteristics as radiosondes.

More recently Healy and Thépaut (2006) demonstrated that assimilating CHAMP RO bending angle measurements had a clear positive forecast impact on Southern Hemisphere stratospheric temperatures, in a 60-day forecast impact experiment with the ECMWF 4DVAR system. The successful deployment of the COSMIC satellites increased the number of measurements available for assimilation into NWP models by roughly an order of magnitude. Following extensive preoperational testing, ECMWF began assimilating RO bending angle profiles from COSMIC operationally on 12 December 2006. Assimilating the COSMIC RO measurements has improved lower-/midstratospheric temperature biases in the operational analyses and forecasts. For example, Fig. 4 shows that the RO measurements produced a clear improvement in the short-range forecast and analysis fit to radiosonde temperature measurements at 100 hPa in the Southern Hemisphere. In addition, the RO measurements have improved the mean temperature analysis over Antarctica. The ECMWF temperature analysis over Antarctica has been prone to spurious oscillations in the stratosphere. These are a result of large, systematic temperature increments in the upper stratosphere caused by NWP model error,

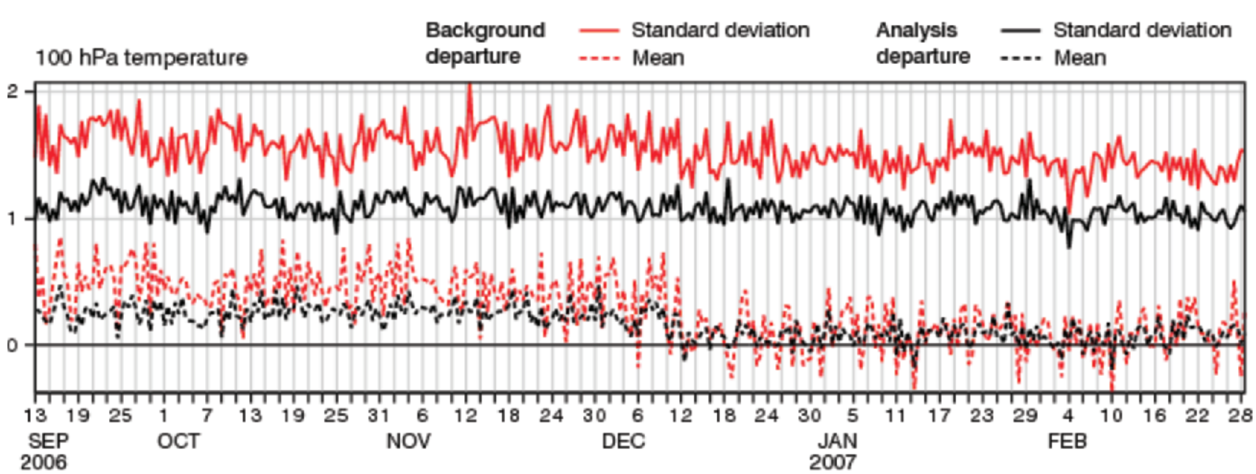

Fig. 4. Time series of the mean and std dev of the short-range forecast and analysis fit to radiosonde temperature measurements in the Southern Hemisphere, for the operational NWP system at ECMWF. The RO measurements were introduced on 12 Dec 2006.

which are propagated downward in the analysis by correlations in the background error covariance matrix. Figures 5a and 5b show the mean temperature analysis state and mean analysis increment, respectively, over Antarctica averaged for January 2007. Assimilating the COSMIC RO measurements removes unphysical oscillations between 200 and 10 hPa, by smoothing the mean increments. The temperature oscillations are in "null space" of satellite radiance measurements, but the RO measurements can resolve and correct them as a result of their superior vertical resolution.

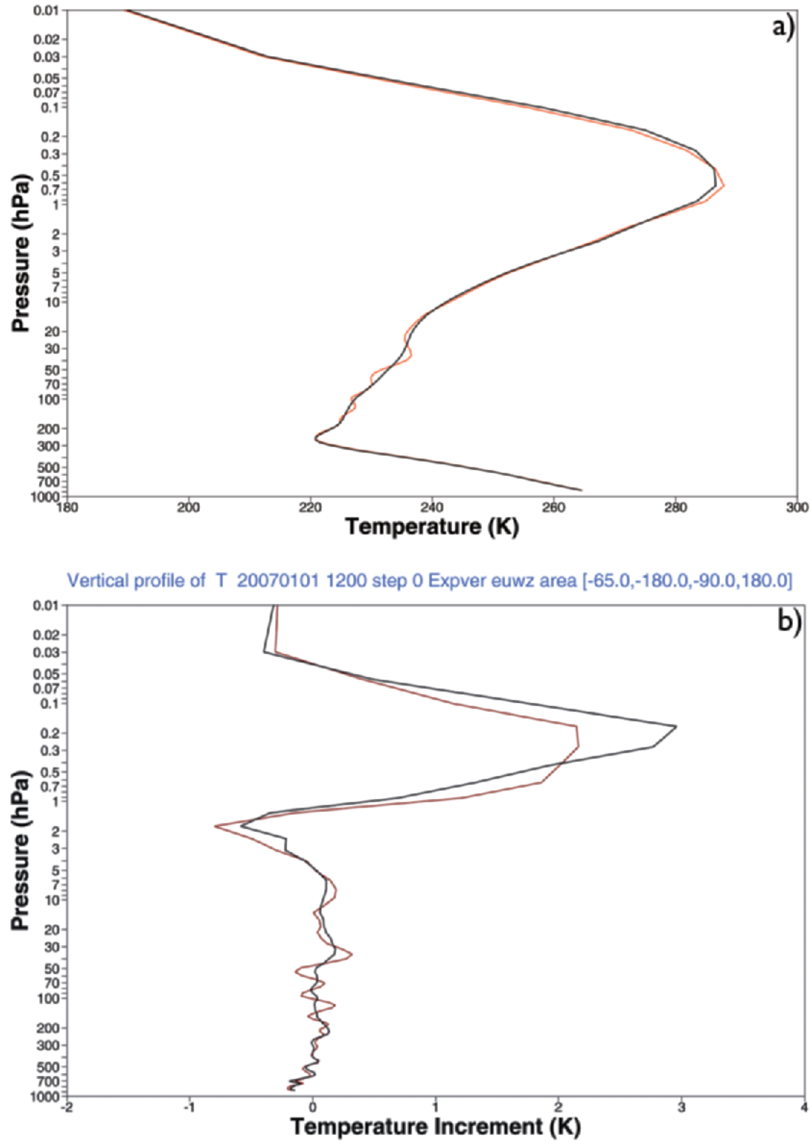

Fig. 5. (a) Mean temperature analysis and (b) mean analysis increment over Antarctica when the RO measurements are assimilated (black) and when they are not used (red). The data are averaged for the period 1–31 Jan 2007.

Climate monitoring and prediction. Radio occultation measurements are potentially extremely well suited for monitoring of the climate due to their weather-independent global coverage, absolute accuracy, and long-term stability. The long-term stability is very important for the detection of trends in global climate as occurring in the free atmosphere. The long-term stability requirement for upper-air temperature observations for climate monitoring has been defined as 0.05 K decade^{-1} for the troposphere, and 0.1 K decade^{-1} for the lower stratosphere, respectively (GCOS 2006). Radio occultation has a very good potential to fulfill the stability requirement for the lower stratosphere, with the region of best temperature retrieval performance being 10- to 30-km altitude (Kuo et al. 2004; Gobiet et al. 2005, 2007). Long-term monitoring of bending angle and refractivity trends from the RO soundings may provide a stable indicator of climate change deep into the troposphere as well, because tropospheric bending angle and refractivity retrieval can be performed without auxiliary information about the atmospheric humidity or temperature.

Use of RO data for climate monitoring has just begun, because databases with sufficiently long-term RO data have only recently been generated. The first experimental RO missions like GPS/MET, CHAMP, and SAC-C have provided very useful data for scientific research and retrieval algorithm development purposes. However, except for CHAMP, the utility of these data for climate monitoring is fairly limited because many changes like onboard software updates have been performed during the missions and the data are only available on a very intermittent basis.

The data from the EPS GRAS and COSMIC missions are expected to be more stable. GRAS data will be especially useful for climate monitoring because they will be provided at least over the lifetime of the EPS mission. All GRAS data will also be permanently archived and made available to users for climate applications.

CHAMP provided the first essentially continuous dataset over more than 5 yr (since September 2001) and enables a good indication of the climate utility of RO data, which will further improve by availability of the COSMIC and the operational EPS GRAS data. For such an indication of climate utility, three examples are briefly discussed here.

Figure 6 illustrates an evaluation of ECMWF analysis data via CHAMP climatologies (Foelsche et al. 2007). The overall agreement is evidently very good (better than 0.5 K in most regions) but also some marked differences exceeding 1 K exist, including a wavelike bias structure at high latitudes, a tropical tropopause bias [except for June–August (JJA) 2006], and a bias above 30-km height. The climate utility of RO data was strongly underpinned in that all three of these salient systematic differences appeared to be mainly attributable to weaknesses in the ECMWF analyses as found by Gobiet et al. (2005) for the high-latitude bias structure, by Borsche et al. (2007) for the tropical tropopause bias, and by Gobiet et al. (2007) for the >30-km bias. Assimilating the COSMIC RO observations since December 2006 has essentially corrected the wavelike bias at ECMWF (as noted in the "Numerical weather prediction" section).

Figure 7 depicts the 2001–06 monthly mean time series of tropical tropopause temperatures and altitudes from CHAMP data, complemented by a few "anchor point" months from the independent satellites SAC-C, GRACE, and COSMIC, in a comparison to corresponding ECMWF and National Centers for Environmental Prediction (NCEP) datasets (for details and more data see Borsche et al. 2007; Foelsche et al. 2008). The comparison shows how NCEP tropopause temperatures somewhat improved from an ~4-K warm bias to ~2 K as of mid-2005, and how an ECMWF cold bias essentially diminished as of February 2006, where a major ECMWF model improvement, from T511L60 to T799L91 resolution, became operational (Untch et al. 2006). The close matching, within sampling error (Pirscher et al. 2007), of anchor points from independent RO data (SAC-C, GRACE, and COSMIC are different instruments in widely different orbits) indicates the level of consistency and homogeneity of RO data.

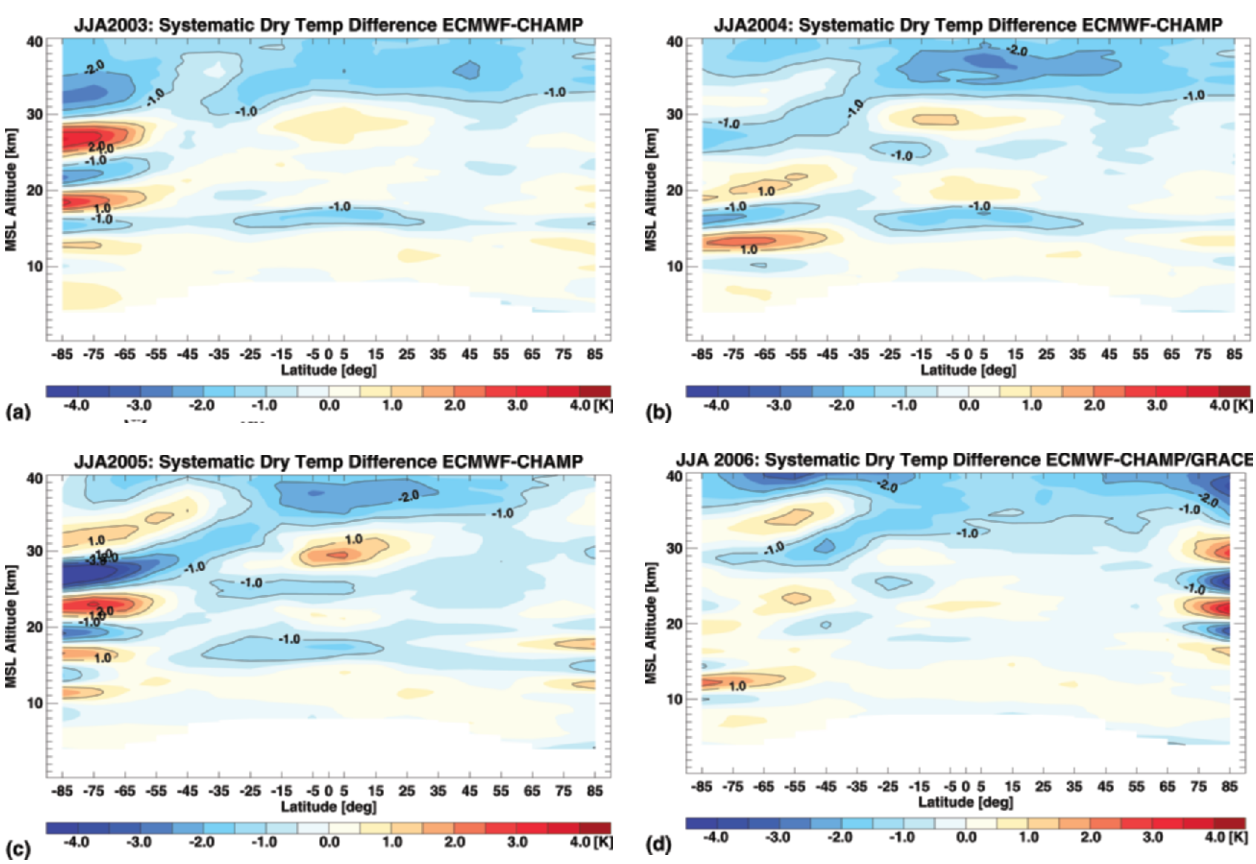

Fig. 6. ECMWF evaluation via CHAMP RO soundings. Systematic differences of seasonal zonal mean climatologies of the summers of 2003–06 are shown.

Figure 8 shows 2001–06 monthly mean time series of Microwave Sounding Unit (MSU)/Advanced Microwave Sounding Unit (AMSU) channel T4 temperature in the lower stratosphere (TLS) temperatures and related anomalies constructed from the CHAMP RO data, compared to the real MSU/AMSU records from the University of Alabama at Huntsville (UAH) and Remote Sensing Systems (RSS) and those constructed from ECMWF analyses and radiosonde data (see Steiner et al. 2007 for details). Regarding absolute TLS temperatures, the shift of ECMWF toward CHAMP as of February 2006 (upgrade to T799L91 resolution) is well visible here also. Regarding TLS anomalies, the very good agreement in intraannual variability of UAH, RSS, ECMWF (except for February 2006 "jump"), and Hadley Centre Atmospheric Temperature (HadAT; increased statistical error) with CHAMP is striking. Regarding multiyear (2001–06) trends, HadAT and CHAMP coincide well, while UAH and RSS exhibit a statistically significant cooling trend difference to CHAMP [about 0.33 K (5 yr^{-1})] stemming mainly from the tropics, where the contribution of known RO-related errors is estimated about an order of magnitude smaller than these trend differences (Steiner et al. 2007).

In summary all three examples (Figs. 6–8) of climate utility of RO indicate that the prospects for EPS GRAS, set to build up a continuous RO climate record until 2020, are very encouraging.

Space weather monitoring. Monitoring of the characteristics of the Earth's ionosphere is feasible with the RO technique because the ionospheric plasma is a dispersive medium for the GPS signals. This means that the residual carrier and code phase delays caused by the ionosphere are different for the two GPS frequencies. The difference in the carrier and code phase delays can be used to derive an estimate of the total electron content (TEC) along the signal propagation path. A 3D electron density map of the ionosphere can be generated by assimilating the carrier and code phase measurements into a numerical ionosphere model (Jakowski et al. 2002; Heise et al. 2002).

The requirements for TEC measurements have had a very small role in the GRAS mission design. The data from the GRAS occultation measurements are only provided when the height of the ray path tangent point is below 80 km. This means that the TEC estimates from the GRAS occultation data contain integrated electron contents from two sides of the ionosphere separated by a section of neutral atmosphere. As a result, the TEC estimates from the GRAS occultation sounding have very limited value in space weather applications (Luntama 2005). However, the navigation measurements from GRAS will provide good TEC estimates of the plasma above the spacecraft at a 3-Hz sampling rate. Because the MetOp orbit height of 840 km is very close to the boundary between the ionosphere and plasmasphere, the GRAS navigation data can be very useful in the validation of

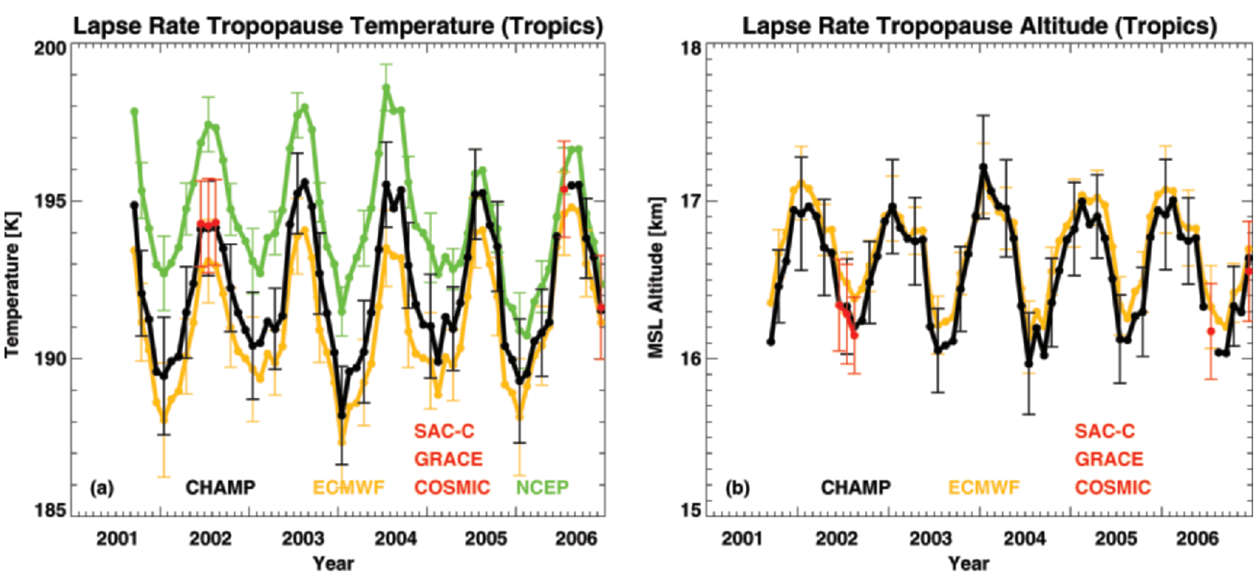

Fig. 7. More than 5 yr of tropical (15°S–15°N) CHAMP data (black) compared to ECMWF (orange) and NCEP (green) data. Anchor point months from SAC-C (JJA 2002), GRACE (Jul 2006), and COSMIC (Dec 2006) are marked with red dots. (a) Monthly mean tropopause temperatures. (b) Monthly mean tropopause altitudes (not available from NCEP). "Error" bars indicate the corresponding (intramonthly) std dev for the center months of each season.

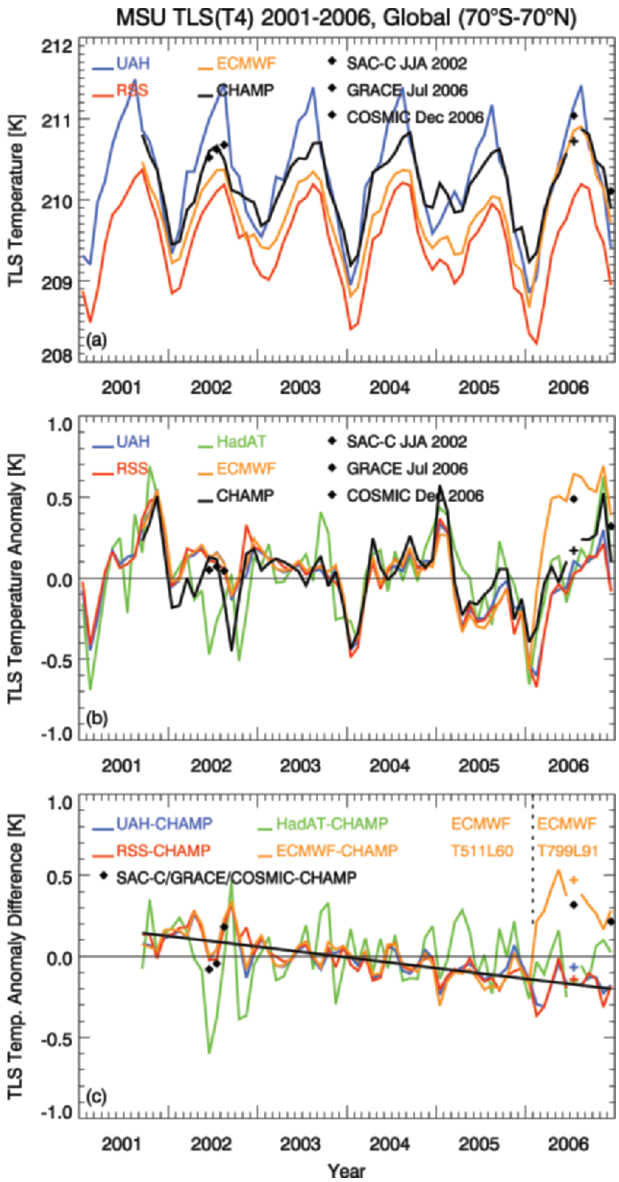

Fig. 8. More than 5 yr of MSU/AMSU–type CHAMP records compared to real MSU/AMSU records (UAH, RSS), and ECMWF as well as HadAT (from radiosondes) records. Anchor point months from SAC-C, GRACE, and COSMIC are marked with red dots. (a) Monthly mean MSU channel T4 (TLS) temperatures. (b) TLS temperature anomalies (2002–05 monthly means, i.e., 4-yr average seasonal cycle, subtracted). (c) Monthly mean anomaly differences (relative to CHAMP).

the electron density models in plasmasphere. GRAS navigation data can naturally also be assimilated into numerical ionosphere–plasmasphere models.

SUMMARY AND CONCLUSIONS. The GRAS measurement system has been designed from the beginning to fulfill the stringent timeliness and accuracy requirements presented in Table 1. Early analysis of the GRAS receiver performance based on offline processing already indicated that these requirements can be fulfilled for the bending angle profiles (Carrascosa et al. 2003).

The GRAS data processing has been distributed to two locations. The level 1 processing producing bending angle profiles is performed at the EUMETSAT headquarters in Darmstadt, Germany. The level 2 processing producing geophysical products (including refractivity, temperature, and humidity profiles) is performed by the GRAS Meteorology SAF hosted by the Danish Meteorological Institute (DMI) (www.grassaf.org/). All GRAS data products are disseminated to the EUMETSAT user community in NRT via the EUMETCast scheme. Selected subsets of GRAS data products are also disseminated via the Global Telecommunications System (GTS) in binary universal format representation (BUFR). The GRAS meteorology SAF will also produce offline data products for climate monitoring applications. All GRAS sounding data and data products are permanently archived and made available to the users through the UMARF and GARF services provided by EUMETSAT and the GRAS Meteorology SAF, respectively.

The GRAS data products are validated with a new concept using a 1DVAR technique with an NWP background. This approach delivers several advantages, for example, the possibility to validate bending angles directly without processing them to higher levels such as temperature, but also to provide measurement error characteristics such as error covariance matrices. These matrices allow NWP users to fully exploit GRAS measurement.

Early validation of the GRAS measurements based on such a 1DVAR approach with an ECMWF background shows that the data quality above 10-km height is very good; below it is currently limited by the geometrical optics approximation. The found differences are a combined effect of deviations between ECMWF and the real atmosphere as well as the current limitations of the GRAS processing.

The GRAS sounding data will be provided to the users over the 14-yr lifetime of the EPS mission, building up a continuous climate record at least until 2020. This will provide an opportunity to continue the climate monitoring that has been started with the RO observations provided by GPS/MET, CHAMP, SAC-C, GRACE, and COSMIC missions. Because of the good long-term stability of the GRAS soundings, this data can potentially serve also as a benchmark for other atmosphere sounding missions for climate applications.

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REFERENCES

Anthes, R., C. Rocken, and S. Sokolovky, 2008: The COSMIC/FORMOSAT-3 Mission: Early results. *Bull. Amer. Meteor. Soc.,* **89,** 313–333.

Beyerle, G., T. Schmidt, G. Michalak, S. Heise, J. Wickert, and C. Reigber, 2005: GPS radio occultation with GRACE: Atmospheric profiling utilizing the zero difference technique. *Geophys. Res. Lett.,* **32,** L13806, doi:10.1029/2005GL023109.

Borsche, M., G. Kirchengast, and U. Foelsche, 2007: Tropical tropopause climatology as observed with radio occultation measurements from CHAMP compared to ECMWF and NCEP analyses. *Geophys. Res. Lett.,* **34,** L03702, doi:10.1029/2006GL027918.

Carrascosa, C., J. Christensen, and M. Loiselet, 2003: Analysis of the performances in retrieved atmospheric profiles with radio-occultation methods by considering different sources of error and different processing techniques. *Proc. Atmospheric Remote Sensing using Satellite Navigation Systems Workshop,* Matera, Italy, URSI.

Collard, A., and S. Healy, 2003: The combined impact of future space-based atmospheric sounding instruments on numerical weather prediction analysis fields: A simulation study. *Quart. J. Roy. Meteor. Soc.,* **129,** 2741–2760.

Eyre, J., 1994: Assimilation of radio occultation measurements into a numerical weather prediction system. ECMWF Tech. Memo. 199, 22 pp.

Fischbach, F., 1965: A satellite method for pressure and temperature below 24 km. *Bull. Amer. Meteor. Soc.,* **46,** 528–532.

Fjeldbo, G., and V. Eshleman, 1968: The atmosphere of Mars analyzed by integral inversion of the Mariner IV occultation data. *Planet. Space Sci.,* **16,** 123–140.

——, and ——, 1969: The atmosphere of Venus as studied with the Mariner IV dual radio-frequency occultation experiment. *Radio Sci.,* **4,** 879–897.

Foelsche, U., M. Borsche, A. K. Steiner, A. Gobiet, B. Pirscher, G. Kirchengast, J. Wickert, and T. Schmidt, 2007: Observing upper troposphere-lower stratosphere climate with radio occultation data from the CHAMP satellite. *Climate Dyn.,* **31,** 49–65.

——, B. Pirscher, M. Borsche, G. Kirchengast, and J. Wickert, 2008: Assessing the climate monitoring utility of radio occultation data: From CHAMP to FORMOSAT-3/COSMIC. *Terr. Atmos. Oceanic Sci.,* in press.

GCOS, 2006: Systematic observation requirements for satellite-based products for climate—Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate. Tech. Rep. GCOS–107, WMO/TD 1338, World Meteorological Organization, WMO, Geneva, Switzerland.

Gobiet, A., U. Foelsche, A. K. Steiner, M. Borsche, G. Kirchengast, and J. Wickert, 2005: Climatological validation of stratospheric temperatures in ECMWF operational analyses with CHAMP radio occultation data. *Geophys. Res. Lett.,* **32,** L12806, doi:10.1029/2005GL022617.

——, G. Kirchengast, G. L. Manney, M. Borsche, C. Retscher, and G. Stiller, 2007: Retrieval of temperature profiles from CHAMP for climate monitoring: intercomparison with Envisat MIPAS and GOMOS and different atmospheric analyses. *Atmos. Chem. Phys.,* **7,** 3519–3536.

Gorbunov, M. E., 1988: Accuracy of refractometric method in a horizontally nonuniform atmosphere. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **2,** 86–91.

——, and K. B. Lauritsen, 2004: Analysis of wave fields by Fourier integral operators and their application for radio occultations. *Radio Sci.,* **39,** RS4010, doi:10.1029/2003RS002971.

Grechko, A. V. G., A. Gurvich, V. Kan, and S. Sokolovskiy, 1987: Recovery of the vertical temperature profile of the atmosphere from refraction measurements made from the Salyut-7 station. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **11,** 914–915.

Gurvich, A., and S. Sokolovskiy, 1985: Reconstruction of a pressure field by remote refratometry from space. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **1,** 7–13.

——, V. Kan, L. Popov, V. Ryumin, S. Savchenko, and S. Sokolovskiy, 1982: Reconstruction of the atmosphere's temperature profile from motion pictures of the Sun and Moon taken from the Salyut-6 orbiter. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **1,** 1–4.

Hajj, G. A., and Coauthors, 2004: CHAMP and SAC-C atmospheric occultation results and intercomparisons. *J. Geophys. Res.,* **109,** D06109, doi:10.1029/2003JD003909.

Healy, S. B., and J. Eyre, 2000: Retrieving temperature, water vapor and surface pressure information from refractive–index profiles derived by radio occultation: A simulation study. *Quart. J. Roy. Meteor. Soc.,* **126,** 1661–1683.

——, and J.-N. Thépaut, 2006: Assimilation experiments with CHAMP GPS radio occultation measurements. *Quart. J. Roy. Meteor. Soc.,* **132,** 605–623.

——, A. M. Jupp, and C. Marquardt, 2005: Forecast impact experiment with GPS radio occultation measurements. *Geophys. Res. Lett.,* **32,** L03804, doi:10.1029/2004GL020806.

Heise, S., N. Jakowski, A. Wehrenpfennig, C. Reigber, and H. Lühr, 2002: Sounding of the topside ionosphere/plasmasphere based on GPS measurements from CHAMP: Initial results. *Geophys. Res. Lett.,* **29,** 1699, doi:10.1029/2002GL014738.

Jakowski, N., A. Wehrenpfennig, S. Heise, C. Reigber, H. Lühr, L. Grunwaldt, and T. Meehan, 2002: GPS radio occultation measurements of the ionosphere from CHAMP: Early results. *Geophys. Res. Lett.,* **29,** 1457, doi:10.1029/2001GL014364.

Jensen, A. S., M. S. Lohmann, H.-H. Benzon, and A. S. Nielsen, 2003: Full spectrum inversion of radio occultation signals. *Radio Sci.,* **38,** 1040, doi:10.1029/2002RS002763.

——, ——, A. S. Nielsen, and H.-H. Benzon, 2004: Geometrical optics phase matching of radio occultation signals. *Radio Sci.,* **39,** RS3009, doi:10.1029/2003RS002899.

Klaes, D., and Coauthors, 2007: An introduction to the EUMETSAT Polar System. *Bull. Amer. Meteor. Soc.,* **88,** 1086–1096, doi:10.1175/BAMS-88-7-1085.

Kliore, A. J., D. L. Cain, G. S. Levy, V. R. Eshleman, G. Fjeldbo, and F. D. Drake, 1965: Occultation experiment: Results of the first direct measurement of Mars' atmosphere and ionosphere. *Science,* **149,** 1243–1248.

——, G. S. Levy, D. L. Cain, G. Fjeldbo, and S. Rasool, 1967: Atmosphere and ionosphere of Venus from the Mariner 5 S-band radio occultation measurement. *Science,* **158,** 1683–1688.

Kuo, Y.-H., S. Sokolovskiy, R. Anthes, and F. Vandenberghe, 2000: Assimilation of GPS radio occultation data for numerical weather prediction. *Terr. Atmos. Oceanic Sci.,* **11,** 157–186.

——, T.-K. Wee, S. Sokolovskiy, C. Rocken, W. Schreiner, D. Hunt, and R. Anthes, 2004: Inversion and error estimation of GPS radio occultation data. *J. Meteor. Soc. Japan,* **82,** 507–531, doi:10.2151/jmsj.2004.507.

Kursinski, E., G. Hajj, K. Hardy, L. Romans, and J. Schofield, 1995: Observing tropospheric water vapor by radio occultation using Global Positioning System. *Geophys. Res. Lett.,* **22,** 2365–2368.

——, and Coauthors, 1996: Initial results of radio occultation observations of Earth's atmosphere using the Global Positioning System. *Science,* **271,** 1107–1110.

——, G. Hajj, J. Schofield, R. Linfield, and K. Hardy, 1997: Observing Earth's atmosphere with radio occultation measurements using GPS. *J. Geophys. Res.,* **102,** 23 429–23 465.

Liu, H., X. Zou, H. Shao, R. Anthes, J. Chang, J.-H. Tseng, and B. Wang, 2001: Impact of 837 GPS/MET bending angle profiles on assimilation and forecast for the period June 20–30, 1995. *J. Geophys. Res.,* **106,** 31 771–31 786.

Loiselet, M., N. Stricker, Y. Menard, and J.-P. Luntama, 2000: GRAS—MetOp's GPS-based atmospheric sounder. *ESA Bulletin,* **102,** 38–44.

Luntama, J.-P., 2005: Ionosphere monitoring with MetOp GRAS mission. *Proc. Second European Space Weather Week,* Noordwijk, Netherlands, European Space Agency, www.esa-spaceweather.net/spweather/workshops/eswwII/proc/Session3/Luntama_poster_Ionosphere_monitoring_with_Metop_GRAS_mission.pdf

——, 2006: The operational EPS GRAS measurement system. *Atmosphere and Climate: Studies by Occultation Methods,* U. Foelsche, G. Kirchengast, and A. Steiner, Eds., Institute for Geophysics, Astrophysics, and Meteorology, University of Graz, Springer Berlin Heidelberg, 147–156.

——, and J. J. W. Wilson, 2004: GRAS level 1 product generation function specification. Tech. Rep. EPS/SYS/SPE/990010, 205 pp. [Available from EUMETSAT, Am Kavalleriesand 31, D-64295 Darmstadt, Germany.]

Lusignan, B., G. Modrell, A. Morrison, J. Pomalaza, and S. Ungar, 1969: Sensing the earth's atmosphere with occulting satellites. *Proc. IEEE,* **4,** 458–467.

Marquardt, C., S. B. Healy, J.-P. Luntama, and E. McKernan, 2005: GRAS level 1b product validation with 1D-VAR retrieval. EUMETSAT Tech. Memo. 12, 106 pp.

Melbourne, W., T. Yunck, L. Young, B. Hager, G. Lindal, C. Liu, and G. Born, 1988: GPS geoscience instrument for EOS and space station. JPL Proposal to NASA AO OSSA-1-88, Jet Propulsion Laboratory.

——, and Coauthors, 1994: The application of spaceborne GPS to atmospheric limb sounding and global change monitoring. JPL Publication 94-18, Jet Propulsion Laboratory, Pasadena, California.

Murray, C., 1977: Recovery of refractivity profiles and pressure and temperature distributions in the lower atmosphere from satellite-to-satellite radio occultation data. NASA Goddard Space Flight Center Tech. Memo. 78020, 65 pp.

——, and S. Rangaswamy, 1975: Recovery of atmospheric refractivity profiles from simulated satellite-to-satellite tracking data. NASA Goddard Space Flight Center Tech. Memo. 71016, 52 pp.

Palmer, P., J. J. Barnett, J. R. Eyre, and S. B. Healy, 2000: A nonlinear optimal estimation inverse method for radio occultation measurements of temperature, humidity, and surface pressure. *J. Geophys. Res.,* **105,** 17 513–17 526.

Pirscher, B., U. Foelsche, B. C. Lackner, and G. Kirchengast, 2007: Local time influence in single-satellite radio occultation climatologies from sun-synchronous and non sun-synchronous satellites. *J. Geophys. Res.,* **112,** D11119, doi:10.1029/2006JD007934.

Poli, P., and J. Joiner, 2003: Assimilation experiments of one-dimensional variational analyses with GPS/MET refractivity. *First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies,* C. Reigber, H. Luhr, and P. Schwintzer, Eds., Springer-Verlag, 515–520.

Rangaswamy, S., 1976: Recovery of atmospheric parameters from the Apollo/Soyuz-ATS-F radio occultation data. *Geophys. Res. Lett.,* **3,** 483–486.

Rocken, C., and Coauthors, 1997: Analysis and validation of GPS/MET data in the neutral atmosphere. *J. Geophys. Res.,* **102,** 29 849–29 866.

——, Y.-H. Kuo, W. S. Schreiner, D. Hunt, S. Sokolovskiy, and C. McCormick, 2000: COSMIC system description. *Terr. Atmos. Oceanic Sci.,* **11,** 21–52.

Schreiner, W., C. Rocken, S. Sokolovskiy, S. Syndergaard, and D. Hunt, 2007: Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission. *Geophys. Res. Lett.,* **34,** L04808, doi:10.1029/2006GL027557.

Steiner, A. K., G. Kirchengast, and H. P. Ladreiter, 1999: Inversion, error analysis, and validation of GPS/MET occultation data. *Ann. Geophys.,* **17,** 122–138.

——, ——, M. Borsche, U. Foelsche, and T. Schoengassner, 2007: A multiyear comparison of lower stratospheric temperatures from CHAMP radio occultation data with MSU/AMSU records. *J. Geophys. Res.,* **112,** D22110, doi:10.1029/2006JD008283.

Untch, A., M. Miller, M. Hortal, R. Buizza, and P. Janssen, 2006: Towards a global meso-scale model: The high-resolution system T799L91 and T399L62EPS. *ECMWF Newsletter,* No. 108, ECMWF, Reading, United Kingdom, 6–13.

Vinogradov, A. P., U. A. Surkov, and C. P. Florensky, 1968: The chemical composition of the Venus atmosphere based on the data of the interplanetary station Venera 4. *J. Atmos. Sci.,* **25,** 535–536.

Volkov, A., G. Grechko, A. Gurvich, V. Kan, and S. Sokolovskiy, 1987: Recovery of the vertical temperature profile of the atmosphere from refraction measurements made from the Salyut-7 station. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.,* **11,** 914–915.

von Engeln, A., S. Buehler, G. Kirchengast, and K. Kuenxi, 2001: Temperature profile retrieval from surface to mesopause by combining GNSS radio occultation and passive microwave limb sounder data. *Geophys. Res. Lett.,* **28,** 775–778.

Ware, R., and Coauthors, 1996: GPS sounding of the atmosphere from low Earth orbit: Preliminary results. *Bull. Amer. Meteor. Soc.,* **77,** 19–40.

Wickert, J., and Coauthors, 2001: Atmosphere sounding by GPS radio occultation: First results from CHAMP. *Geophys. Res. Lett.,* **28,** 3263–3266.

——, T. Schmidt, G. Beyerle, R. König, C. Reigber, and N. Jakowski, 2004: The radio occultation experiment aboard CHAMP: Operational data analysis and validation of vertical atmospheric profiles. *J. Meteor. Soc. Japan,* **82,** 381–395.

——, G. Beyerle, R. König, S. Heise, L. Grunwaldt, G. Michalak, C. Reigber, and T. Schmidt, 2005: GPS radio occultation with CHAMP and GRACE: A first look at a new and promising satellite configuration for global atmospheric sounding. *Ann. Geophys.,* **23,** 653–658.

Wilson, J. J. W., and J.-P. Luntama, 2007: Advanced processing algorithms for GRAS instrument data. *Proc. IEEE International Geoscience and Remote Sensing Symposium,* Barcelona, Spain, IEEE, 1049–1054.

Wu, B.-H., V. Chu, P. Chen, and T. King, 2005: FORMOSAT-3/COSMIC science mission update. *GPS Solutions,* **9,** 111–121, doi:10.1007/s10291-005-0140-z.

Zou, X., H. Liu, R. Anthes, H. Shao, J. Chang, and Y.-J. Zhu, 2004: Impact of CHAMP radio occulation observations on global analyses and forecasts in the absence of AMSU radiance data. *J. Meteor. Soc. Japan,* **82,** 533–549.