THE GRAS SAF PROJECT:
RADIO OCCULTATION PRODUCTS FROM METOP

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Abstract

The GRAS SAF is part of EUMETSATs network of Satellite Application Facilities (SAFs) under the EUMETSAT Polar System (EPS). The objective of the GRAS SAF is to deliver operational radio occultation products from the GRAS occultation instruments (Global Navigation Satellite System Receiver for Atmospheric Sounding) onboard the three MetOp satellites. The Leading Entity is the Danish Meteorological Institute (DMI) and this is also the physical location of the operational GRAS SAF processing and archiving center. The other project partners are the IEEC (Institute d’Estudis Espacials de Catalunya, Barcelona, Spain), the Met Office (Exeter, UK), and the European Center for Medium-range Weather Forecasts (ECMWF, UK). The GRAS SAF started the operational phase in March 2007 and will start to deliver validated products in 2007. The archiving of GRAS SAF products is done locally at DMI.

We present the GRAS SAF Processing and Archiving Center and describe the different meteorological products, their formats, and ways of dissemination. The primary input to the processing center is the GRAS level 1b data from EPS/CGS, received through a EUMETCast terminal. This data type is used to generate the products, which are archived and disseminated to the end users. The NRT product dissemination is through both RMDCN (Regional Meteorological Data Communication Network, WMO Region 6 GTS) and EUMETCast. The archiving of GRAS SAF products is done locally at DMI and users are able to obtain archived data through the GRAS SAF web interface (www.grassaf.org). Alternatively, archived data can also be obtained through the UMARF archive facility at EUMETSAT. Offline products are made available via FTP or sent out on DVD, depending on the end users’ preferences.

Because raw GPS radio occultation data are calibration free and the assumptions are known, RO data is also well suited for climate monitoring and climate research. The self-calibrating property should allow for relatively easy inter-comparison of data from different satellites and RO instruments, which is required to construct long time series covering many years and even decades. The offline products – bending angle, refractivity, temperature, and humidity – will regularly be processed into global and regional climate data in support of these activities. We are currently undertaking studies on how to best exploit the GRAS data, both for construction of an accurate single-source climate data base with known error characteristics of the data and for provision of global climate monitoring. We also discuss how to derive climate data from the RO profiles, and how to estimate the error characteristics – random observational/sampling errors and systematic biases – of such climate data.

1. INTRODUCTION

The basic principle of the radio occultation (RO) method is that a receiver onboard a low-orbiting satellite tracks GPS signals as the transmitting satellite sets or rises behind the Earth. Due to refraction in the ionosphere and the neutral atmosphere the signal is delayed and its path bent, enabling calculation of the index of refraction (or refractivity) and subsequently temperature and humidity as a function of height.

The operational GRAS SAF Processing and Archiving Center (GPAC) receives raw and preprocessed GPS radio occultation data from the GRAS instrument, processes these into vertical height profiles of refractivity, temperature, pressure, and humidity, and distributes these products continuously in NRT (near real time,
within 3 hours from sensing) to numerical weather prediction users. The primary NRT input to the processing system is the GRAS level 1b data from EPS/CGS. In addition, offline products (improved products, within 30 days from sensing) are produced for climate monitoring users. The offline products take advantage of data not available within the NRT timeliness constraints, like e.g. precise satellite orbits, NWP reanalysis. A third objective of the GRAS SAF is to supply the software package ROPP (Radio Occultation Processing Package) for 3D/4D-VAR assimilation of radio occultation data into numerical weather prediction models. The results of several NWP assimilation impact trials using RO data from e.g. the German CHAMP and the US/Taiwanese COSMIC satellites show a clear positive impact on NWP forecasts in the upper troposphere and lower stratosphere [Healy and Thepaut, 2006].

Pre-operational data from GRAS are now being received and processed at the GRAS SAF Processing Center. The data are not yet scientifically validated and therefore not available to users yet, but preliminary results show that the data are of very good quality. As also presented at the 2007 conference by EPS/EUMETSAT, the first analyses show that the GRAS instrument delivers high-quality data with low noise levels in accordance with specifications, see also [Luntama et al, 2007].

2. THE GRAS SAF

The GRAS SAF is a Satellite Application Facility (SAF) developed under the EUMETSAT program for SAFs. The GRAS SAF is hosted by DMI with the three partner institutes ECMWF (Reading, UK), Met Office (Exeter, UK) and the IEEC (Barcelona, Spain). The development phase started in 1999 and spanned eight years. The GRAS SAF Processing and Archiving Center is now operational and will start providing data in 2007.

The scope of the GRAS SAF activities is to deliver products in near real time (NRT) as well as offline, at the level of geophysical parameters, based on the GPS radio occultation measurements by the GRAS instrument on Metop (see Figure 1). One of the prime ways for improving present operational NWP analysis and products is the effective implementation and exploitation of satellite observations in the evolving NWP models for weather forecasts and climate change monitoring. The role of the GRAS SAF is to facilitate the input from the GRAS instrument on Metop to NWP and climate change models in order to increase the usage of satellite data in a more effective manner than possible today. For the user requirements, which the processing system is designed to comply with, we refer to our paper [Lauritsen et al, 2006].

Figure 1. The basic principle behind the radio occultation (RO) technique: radio signals from the GPS satellite (left) are received by the orbiting Metop satellite, shown at three consecutive times. The ray path is characterized by its impact parameter and bending angle. The inversion of the measured signal leads to vertical profiles of atmospheric parameters (indicated by the short, red line).
3. DATA AND SOFTWARE PRODUCTS

3.1. Product Overview

The GRAS SAF’s primary products are the Level 2 products, which consist of profiles of refractivity, pressure, temperature and humidity, processed in near-real time (NRT), within 3 hours of observation. This time constraint may mean that processing is simplified and some ancillary data may not be available in time. Therefore, NRT products may not represent the optimum possible quality although it will still meet user requirements for NWP input data. However, the GRAS SAF will also re-process the radio occultation data in offline mode using optimum algorithms and post-processed GPS and Metop precise orbit information and including other auxiliary data, which may not have been available on the time scale of the near-real time product. Offline products will be available to users within 30 days of observation time. Table 1 shows the processing steps in the GRAS SAF system. Details about the Canonical Transform method (“CT2”) can be found in [Gorbunov, 2005], [Gorbunov and Lauritsen, 2006], and [Gorbunov et al, 2006].

The product domain will be global, and from the surface to a maximum height of 80 km. The height range of individual Level 2 profiles produced by the SAF depends on the output of the GRAS instrument and processing up to Level 1b within the CGS. However, a large fraction of the profiles are expected to extend below 2 km. The geographical and temporal coverage of SAF products will be limited only by the characteristics of the radio occultation instrument and not by the processing algorithms. Data in the form of profiles will be provided as a function of height (ellipsoidal height, height above mean sea level, geopotential height and pressure), or as a function of time. Details about the products can be found in the Detailed Products Description Document [GRAS SAF, 2002] and the User Requirements Document [GRAS SAF, 2001].

The GRAS SAF will provide monthly, seasonal, and annual averages of temperature, geopotential heights, humidity, and refractivity, primarily in low-resolution 3D gridded and zonally gridded formats, but also in the form of global and hemispheric averages and as graphical products. The climate data will be delivered together with estimates of the error characteristics, where the observational errors (or instrumental errors) will be estimated through a validation procedure that will include other observational data sets, whereas the sampling errors will be estimated through a simulation process (see Section 5.3).

The GRAS SAF will also provide software products (with associated User Guides) that implement procedures to assist in assimilating RO profiles into NWP and other models. The software products are developed by the Met Office and will be supplied as a library of software modules grouped into one package: the Radio Occultation Processing Package (ROPP). Since end-users’ operational systems have specific software standards, interfacing requirements and other constraints, the ROPP software deliverable cannot be treated as ‘black box’ modules. The GRAS SAF software deliverables will have the status of example, fully working, but non-operational code, with stand-alone test harnesses and supporting test datasets. Some modification by users for their specific operational environment is to be expected.

3.2. GRAS SAF Archive and Retrieval Facility

The interface with the end users is through the GRAS SAF Archive and Retrieval Facility GARF (web site: www.grassaf.org). NRT products are disseminated to the subscribing end users through the Regional Meteorological Data Communication Network RMDCN (WMO Region 6 standard on GTS) as well as via the EUMETCast network. Offline products are made available through subscription or on individual request at the GARF FTP server or they can be mailed on DVDs. The planned climate data products will be available in the same way as the offline products.

The GARF will have an extensive web site where users can register and search, browse, select and order archived data. Alternatively, archived GRAS SAF products can be ordered through EUMETSAT’s UMARF service (Unified Meteorological Archive and Retrieval Facility). UMARF and GARF both offer search capability for end user requests for all archived GRAS SAF products. UMARF registers users and provides ordering forms, price information and invoices to the users, and sends the product ordering forms to GARF, which is responsible for delivery of the requested products.
4. ASSIMILATION OF RO DATA IN NUMERICAL WEATHER PREDICTION

The radio occultation method should be regarded as complementary to passive atmospheric sounders; it has a high vertical resolution in atmospheric regions where passive techniques are marginally useful, and it operates on completely different measurement principles. The fact that RO measurements do not merely reproduce other measurements is clearly shown within the field of NWP, where assimilation of RO data has a substantial positive impact (see below). Within the field of climate monitoring – and particularly for detection of climate change – the possibilities to accurately observe climate trends and to make bias corrections from independent measurements based on completely different measurement principles, are very important, see e.g. [Leroy et al., 2006]. One of the key advantages of RO measurements is that they can be assimilated without bias correction. Therefore, they can potentially improve the assimilation of satellite radiance measurements by correcting model biases and providing “anchor points”, to prevent adaptive, variational bias correction schemes drifting towards the NWP model climatology.

RO measurements are globally distributed, have an all-weather capability and very good vertical resolution. The “proof of principle” GPS/MET experiment [Rocken et al., 1997] demonstrated that the technique provides temperature information with sub-Kelvin accuracy between heights of 7 km to 25 km. Theoretical information content studies have shown that the RO measurements provide temperature information near
the tropopause and in the lower/mid stratosphere with better resolution and accuracy characteristics than can be derived from advanced infrared sounder radiance measurements [Collard and Healy, 2003]. Furthermore, forecast impact experiments using operational NWP systems to assimilate refractivity [Healy et al, 2005] and bending angle profiles [Healy and Thepaut, 2006] have demonstrated a clear positive impact, despite the relatively low number of RO observations, when compared with the amount of data that is already assimilated. These results demonstrate that the RO measurements provide information that is complementary to that provided by the other observing systems, and that they are a highly useful addition to the global observing network. As a result, RO measurements are now assimilated operationally at ECMWF, the Met Office, NCEP, JMA, and others.

5. RO BASED CLIMATE DATA

5.1. Background and Rationale

Many of the characteristics of RO data suggest them as a near-ideal resource for climate studies, particularly the global coverage, the all-weather capability, and the self-calibrated nature of the RO data [e.g., Leroy et al., 2006; Foelsche et al., 2007]. The latter property – which distinguishes RO from most other satellite observational techniques – should allow for inter-comparison of data from different satellites and RO instruments, which is required to construct long time series covering many years and even decades. Global coverage and long time series are essential to improve our understanding of the Earth’s climate system.

The EUMETSAT Polar System (EPS), with its planned series of three Metop satellites, now provides an opportunity to create RO based global climatologies of high quality. This will help us meet the requirements of both the scientific community and a wide range of climate data users. For this purpose, and also for climate monitoring purposes, the GRAS SAF will provide global and regional climate data on a regular basis. The climate data include refractivity, temperature, humidity, and geopotential heights of fixed-pressure surfaces, but also estimates of observational and sampling errors – systematic and random – which is essential for a correct use of such data.

5.2. Spatial and Temporal Sampling

Each day, around 600 vertical profiles will be observed by the GRAS/Metop instrument (Figure 2), giving a total number of roughly 18,000 profiles per month. The profiles will be irregularly distributed across the globe, providing a good overall spatial coverage. The spatial density of RO profiles will be nearly constant in longitude, whereas in latitude the spatial density will vary by a factor of 2 (per square degree) or by a factor of 5 (per square kilometer). Hence, the number of RO profiles per month in 10x10 degree equal-angle grid boxes will on average range from about 40 at mid-latitudes to 20 in the tropics and near the poles.

This is the ideal case where no profiles are deemed bad. In reality, we could expect a loss of RO data at low altitudes in the tropics. Nevertheless, the spatial sampling of the climate system appears to be good enough to produce monthly means with a low spatial resolution, or seasonal means with a somewhat better resolution. For the resulting climate data, there is a trade-off between spatial resolution and random errors. Hence, the spatial resolution that can be attained depends on the observational errors, i.e. the errors of the individual profiles, and on the temporal sampling characteristics in relation to the variability of the climate system, predominantly the synoptic variability and the diurnal cycle.

A common characteristic of observations from a polar, Sun-synchronous orbit is a good spatial sampling combined with temporal under-sampling, particularly of the diurnal cycle [Pirscher et al., 2007]. In Figure 3, we show the scatter of simulated GRAS/Metop observations for a full month. We find that over a broad mid-latitude interval, the climate system is sampled at two local times separated by 12 hours whereas at high latitudes, either day-time or night-time observations tend to dominate.

The sampling characteristics are more important for the construction of climate data than for the meteorological data. The fundamental reason for this is the higher sensitivity of climate data to small, but long-term and consistent, variations in observational biases. As an example, the current focus on detection of human influences on the climate requires temperature trends of the order of 0.01 K/year to be detected in the troposphere. A careful consideration of sampling biases, and an understanding of how they change over time, is needed to reliably discern such weak trends against a background of climate variability.
Figure 2. (a) Spatial distribution of simulated RO events observed by the GRAS/Metop instrument during a day. There will be around 600 such events per day giving a total number of 18,000 per month. (b) The number of RO events per month in 10x10 degree equal-angle grid boxes ranges from around 20 in the tropics and in the polar regions to 40 at mid-latitudes.

Figure 3. Scatter of simulated GRAS/Metop RO events in local time, longitude (left) and latitude (right). These characteristics are typical for observations from a satellite in a polar, Sun-synchronous orbit. At low and mid latitudes, the observations twice a day separated by 12 hours may result in biases if the diurnal cycles are far from sinusoidal. At high latitudes, the uneven distribution between day and night may also cause biases in the climate data.

5.3. Construction of Climate Data and Estimation of Sampling Errors

Figures 4 and 5 show how the climatologies may be constructed and indicate a means to estimate the associated errors through simulation. Using the straight-forward method of averaging into equal-angle grid boxes, we simply take all observed RO profiles that fall within a grid box and within a suitable averaging time interval – 1 month, 3 months, or a year – and average them into a climatology profile. The averaging needs to be done on the same geopotential heights or, alternatively, on the same mean-sea level heights.

In Figure 4, we have constructed a set of “sim-observed” data by sampling the ERA-40 reanalysis data set at the locations and times of GRAS occultations during a full month. “Sim-observed” climate data are then constructed by binning these data into 10x10 degree latitude-longitude grid boxes followed by a computation of monthly means within each grid box. If the ERA-40 data have the same statistical properties as the real data, the “sim-observed” climate data will be affected by the same sampling errors as the real observations. The true data is hidden to us, but as we know the “sim-true” data, we may compute the errors introduced by an incomplete sampling. This procedure, although in a constrained form, can be used to estimate the sampling errors of the actual observations. Note that this kind of simulation only includes the sampling errors – the observation errors needs to be independently estimated and incorporated into the simulations.
6. CONCLUSIONS AND OUTLOOK

The GRAS SAF Processing and Archiving Center is part of EUMETSATs network of Satellite Application Facilities. The objective of the GRAS SAF is to deliver operational radio occultation products from the GRAS occultation instruments onboard the three Metop satellites.

Outcome of NWP assimilation impact trials have confirmed the positive prospects of assimilating radio occultation measurements operationally. Once operational (ultimo 2007), the GRAS SAF will supply continuous, operational radio occultation data for weather forecasts (in near-real time) and climate research as an integrated part of EUMETSATs EPS system. Future growth potential includes e.g., GALILEO reception capability on future Metop satellites and inclusion of occultation data from other RO satellites (e.g. COSMIC) in the GRAS SAF processing.

GPS radio occultation data are calibration free and therefore well suited for climate studies and monitoring. We are currently undertaking studies on how to best exploit the GRAS data, both for construction of a single-source climate data base with accurate error characteristics and for provision of global climate monitoring.

7. ACKNOWLEDGMENTS

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GRAS SAF User Requirement Document (URD), V2.1 (2001), Ref. SAF/GRAS/METOFFICE/RQ/URD/001

GRAS SAF Detailed Products Description Document (DPDD), V1.0 (2002), Ref. SAF/GRAS/METOFFICE/RQ/DPD/01


