by Kent Bækgaard Lauritsen

SYMBOL OF THE OCCULT

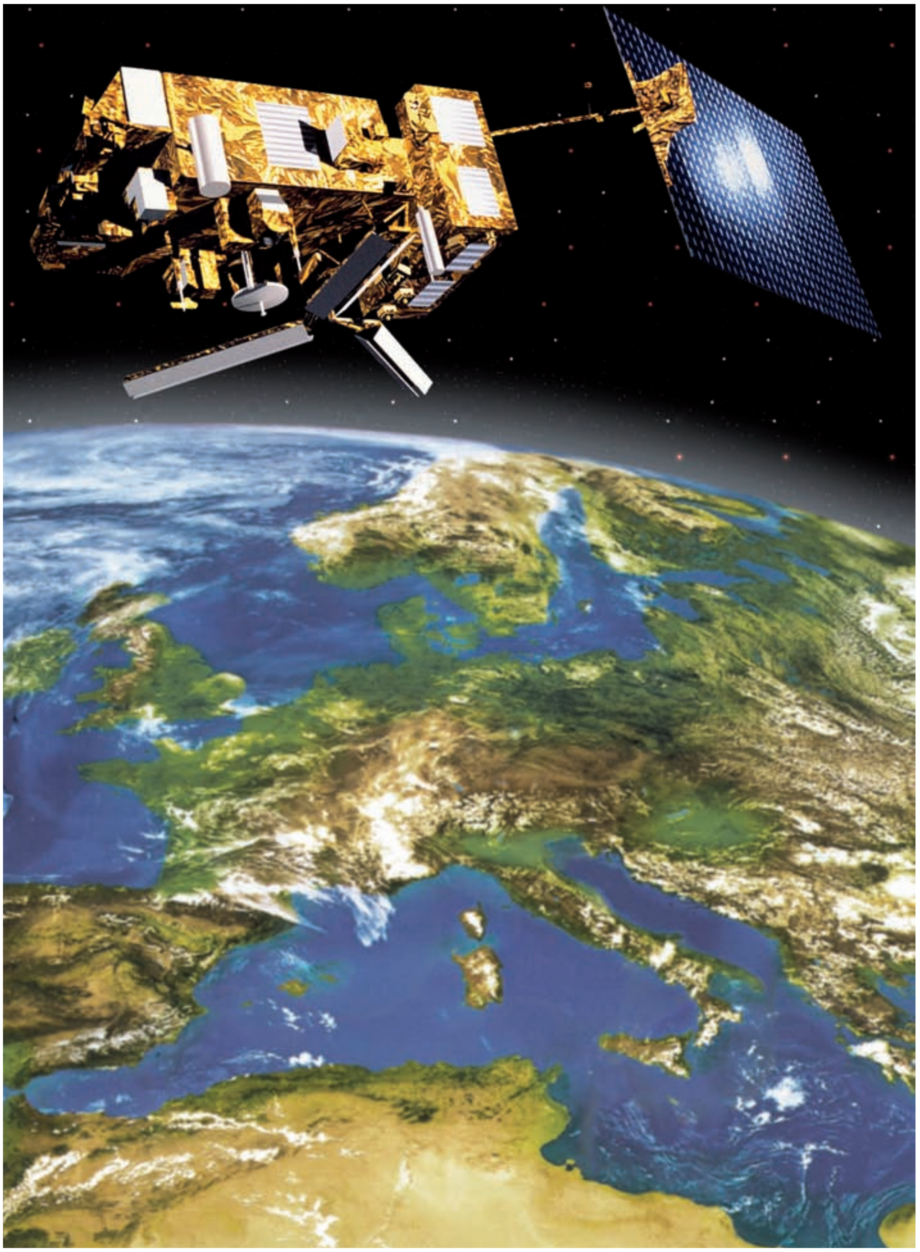
The GRAS SAF project and radio occultations

Using satellite observations more effectively will improve weather forecasting. Radio occultation data is becoming increasingly important for these applications

Radio occultation (RO) uses the radio signals continuously transmitted by GPS satellites to measure the phase change as the radio signal path skirts Earth's atmosphere on its way from the transmitting GPS to a receiver on another orbiting satellite. The phase measurements can be processed into radio occultation products comprising vertical profiles of atmospheric parameters, such as refractivity, temperature, pressure, and humidity. RO is a new application of GPS signals and RO instruments are currently in orbit on operational and research satellites. Using satellite observations more effectively will improve weather forecasting as well as climate change monitoring. RO data is becoming increasingly important for these applications.

The Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS) is an RO instrument on board the Metop-A satellite, operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). GRAS has occultation antennae looking forward and backward relative to Metop's flight direction, and both are able to track two GPS satellites simultaneously. With the current GPS constellation of around 30 satellites, more than 650 occultations are tracked every day. The profiles are irregularly distributed across the globe, providing good overall spatial coverage. GRAS is capable of tracking in 'phase-locked loop' (at 50Hz) and in 'raw sampling mode', also called 'open-loop' (at 1,000Hz). The resulting data profiles extend from the lowest part of the atmosphere up to about 80km.

Metop-A was launched in October 2006 and is part of the EUMETSAT Polar System (EPS). In total there will be three Metop satellites, each with an expected lifetime of five years. EPS will provide data for at least 14 years. All Metop satellites will fly in a sun-synchronous orbit, at an altitude of



around 820km. The EPS is designed for operational data provision, which means that observations are rapidly made available to users. The requirement is availability to users within two hours 15 minutes after sensing time. Each orbit of data (about 100 minutes) is downlinked over Svalbard (at 78°N midway between mainland Norway and the North Pole), processed at EUMETSAT and disseminated to users. Users include Numerical Weather Prediction (NWP) centers worldwide. The data is also processed further at the Satellite Application Facilities (SAF), which are specialized development and processing centers in member states of EUMETSAT. The timescale on operational SAF products is three hours.

Leading light

The GRAS SAF is one of EUMETSAT's SAFs. The leading entity is the Danish Meteorological Institute (DMI), which is also the physical location of the operational GRAS SAF processing and archiving center. The other project partners are the European Center for Medium-range Weather Forecasts (ECMWF, UK), the Institute d'Estudis Espacials de Catalunya (IEEC, Spain), and the Met Office (UK). The objectives of the GRAS SAF are to deliver operational RO products from the GRAS instruments onboard the Metop satellites, and to supply the Radio Occultation Processing Package (ROPP) containing modules for pre-processing and assimilation of the RO data into NWP models. The near real-time GRAS SAF data products consist of profiles of refractivity, temperature, pressure and humidity; planned off-line and reprocessing products will also include bending angles.

An important purpose of the GRAS SAF is to facilitate the input of GRAS data into NWP and climate change models. RO data is useful for climate monitoring and climate research since it is based on a measurement of time and the RO technique is therefore self-calibrating. This property enables relatively straightforward inter-comparison of data from different satellites and RO instruments, which is required to construct long time series covering many years and even decades. Additionally, RO data can be used to calibrate other long-term measurement records. Within the field of climate monitoring and for detection of climate change, accurately observing climate trends is very important.

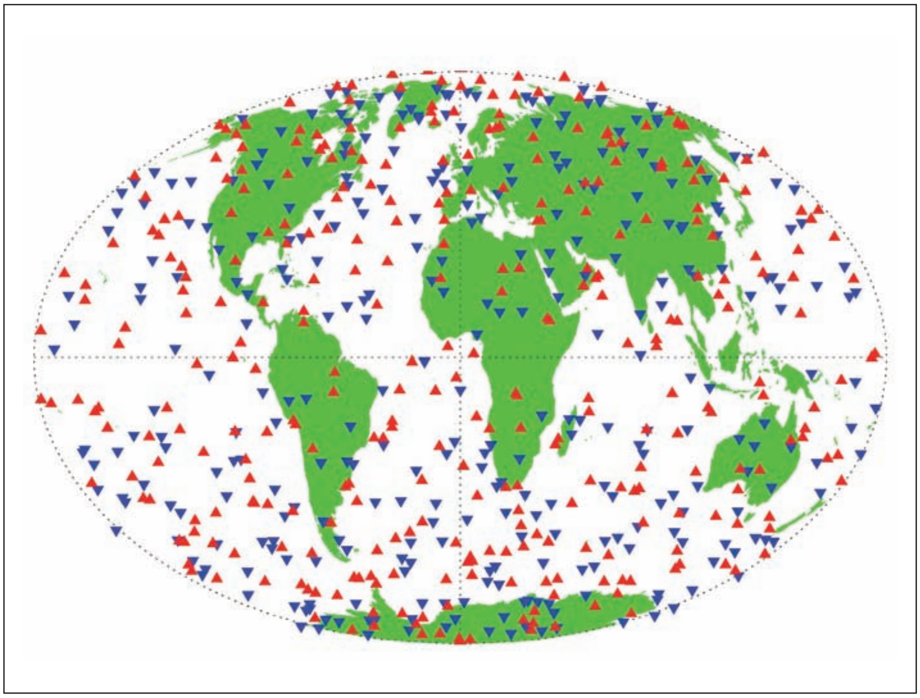


FIGURE 1: **Distribution of the 647 radio occultations measured by GRAS on January 13, 2008. Red triangles indicate so-called rising occultations, blue triangles indicate setting occultations**

> "Using the Abel transform algorithm that relates the ray bending and refractivity, a vertical profile of refractivity values is obtained"

Radio occultation method

The basic principle of the RO method is that a GPS receiver onboard a low-orbiting satellite tracks GPS signals as the transmitting satellite sets or rises behind Earth. All radio signals are delayed and bent due to refraction in the ionosphere and atmosphere. The degree of bending depends on various properties of the air mass along the ray path. The principle can be seen in Figure 2.

Using the Abel transform algorithm that relates the ray bending and refractivity, a vertical profile of refractivity values is obtained. Refractivity is directly related to the density of the atmosphere. By using the refractivity and an estimate of the background atmospheric field, together with their error co-variances, one obtains statistically optimal temperature and humidity profiles of the atmosphere as a function of height or pressure. This is referred to as one-dimensional variational (1DVar) retrieval. Figure 3 shows an example of a temperature profile obtained from a GRAS RO measurement in combination with a forecast from the European Centre for Medium-range Weather Forecasts (ECMWF).

The RO method should be regarded as complementary to passive atmospheric sounders on satellites; 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

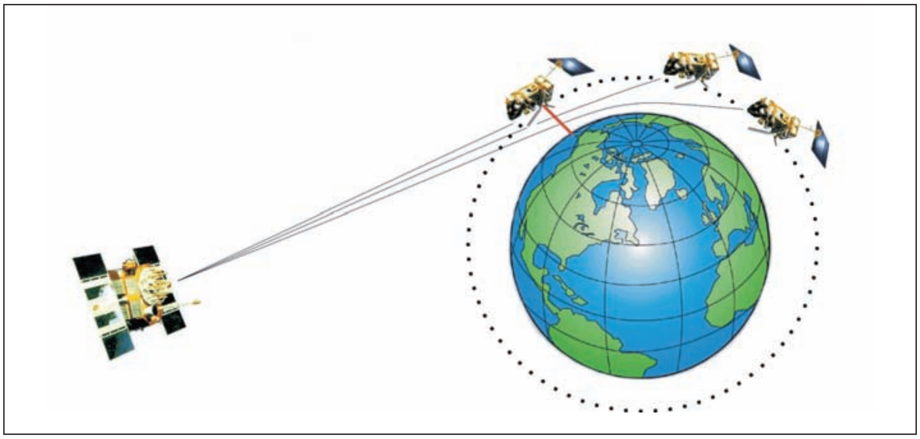


FIGURE 2: **The basic principle behind the RO technique. Radio signals from the GPS satellite (left) are received by the orbiting Metop satellite, shown at three consecutive times. The ray path is characterized by its bending angle. The mathematical inversion of the measured signal leads to vertical profiles of atmospheric parameters**

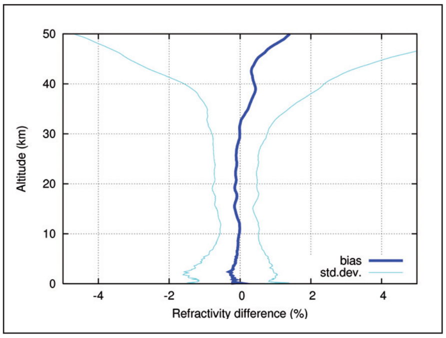


FIGURE 4: **Statistical comparison between GRAS RO refractivity observations and ECMWF forecasts for the first 10 days of April 2009. The thick blue line indicates the mean difference; the thinner cyan lines indicate one standard deviation on both sides**

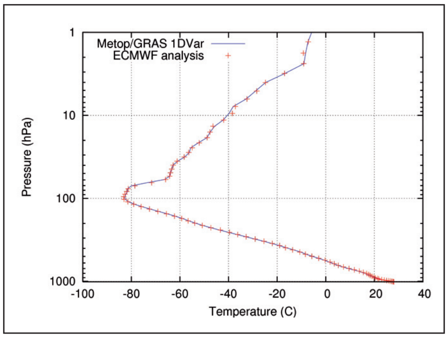
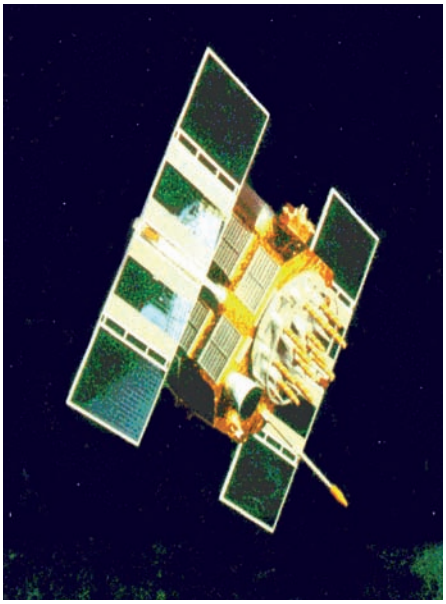


FIGURE 3: **Example of a GRAS temperature profile obtained via a one-dimensional variational (1DVar) approach using an ECMWF forecast (at position 15.75 S, 6.48 W on April 9, 2009). Also shown is the corresponding ECMWF analysis**

data has a substantial positive impact. Forecast impact experiments using operational NWP systems to assimilate refractivity and bending angle profiles have demonstrated a clear positive impact, despite the relatively low number of RO observations used.

These results demonstrate that RO provides information complementary to other observing systems, and that it is a highly useful addition to the existing global observing network. As a result, RO measurements are now assimilated operationally at many NWP centers worldwide. One of the key advantages is that RO can be assimilated without bias correction. Therefore it can potentially also improve the assimilation of satellite radiance measurements by correcting model biases and providing 'anchor points', to prevent adaptive, variational bias correction schemes drifting toward the NWP model climatology.

When characterizing the accuracy of RO data one typically compares it to NWP background fields, which can be forecast fields from ECMWF. Figure 4 shows an example of such a comparison. The figure shows the percentage difference between the observed refractivity and the corresponding refractivity obtained from ECMWF forecasts as a function of altitude above mean sea level. The bias and standard deviation in such a comparison gives an indication of the accuracy of the RO measurements, although one should bear in mind that ECMWF forecasts also contain errors. Figure 5 shows the difference between the RO 1DVar temperature and the corresponding temperature from ECMWF analyses as a function of geopotential height. The difference between RO/1DVar temperature profiles and those of ECMWF analyses is generally less than about 1 K up to a height of about 30km.



A GPS receiver onboard a low-orbiting satellite tracks GPS signals as the transmitting satellite sets or rises behind Earth

Climate data

Many of the characteristics of RO data suggest it could be a near-ideal resource for climate research, particularly the global coverage, the insensitivity to clouds, and the fact that there is no need to inter-calibrate RO instruments. The latter property distinguishes RO from most other satellite observational techniques. Inter-comparison of data from different satellites and RO instruments is relatively straight-forward, and is required to construct climate time series covering many years and even decades.

EPS, with its planned series of three Metop satellites, now provides an opportunity to establish an RO-based global climatology of high quality covering a long time-span. Together with RO data from other missions such as CHAMP, GRACE-A and COSMIC, this will help meet the requirements of a wide range of climate data users and the scientific community in general.

The GRAS SAF plans to generate monthly, seasonal and annual averages of temperature, geopotential heights of fixed pressure levels, humidity, refractivity and bending angle, primarily as a low-resolution zonal (latitude-level) grid, but also in the form of global and hemispheric averages. This climate data will be provided as numerical and graphical products. The GRAS SAF will also provide estimates of the observational and sampling errors, which are essential for correct use of such data. The observational errors (including measurement and processing errors) are estimated through a validation procedure that includes other observational data sets, whereas the sampling errors are estimated through a simulation process.

Even though straightforward in practice, some effort is needed to ensure that climate data is as free as possible from biases or systematic errors. Such biases can arise from the selection of data based on some quality criteria. They can also arise from the retrieval procedure itself. Another source of bias comes from the fact that Metop is a single satellite in a near-polar, sun-synchronous orbit at a low altitude, resulting in temporal under-sampling, particularly of the diurnal cycle.

These limitations are more important for the construction of climate data than for the corresponding 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 0.1 K/decade, or 0.01 K/year to be detected. A careful consideration of selection, processing and sampling biases, and an understanding of how they may change over time, is needed to reliably discern such weak trends against a background of natural climate variability. ◗

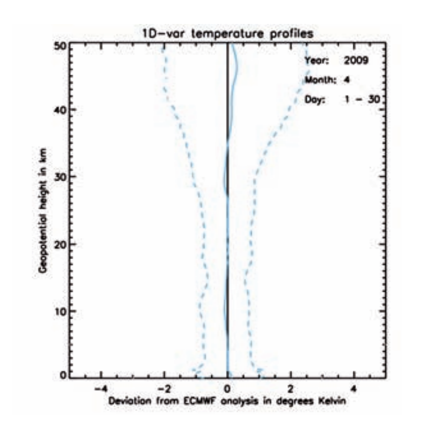


FIGURE 5: **Statistical comparison between GRAS RO 1DVar temperature retrievals and ECMWF analyses for April 2009. The solid blue line indicates the mean difference and the dashed lines indicate one standard deviation on both sides.**

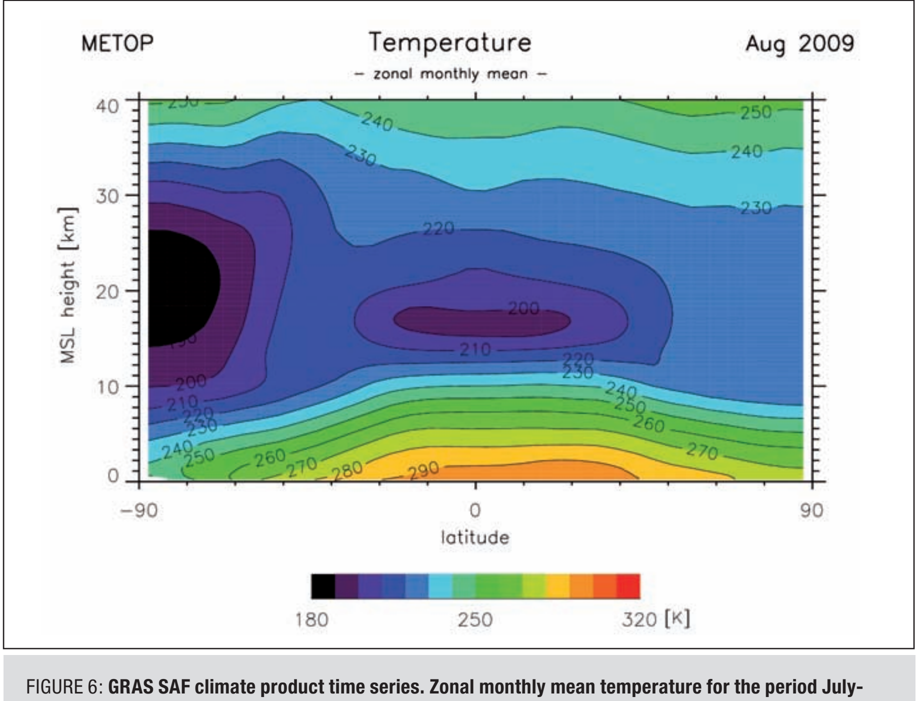


FIGURE 6: **GRAS SAF climate product time series. Zonal monthly mean temperature for the period July-October 2009 generated from GRAS bending angle measurements**

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