THE GRAS SAF PROJECT – OPERATIONAL RADIO OCCULTATION PRODUCTS

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ABSTRACT

The GRAS SAF Project - short for Global Navigation Satellite System (GNSS) Receiver for Atmospheric Sounding (GRAS) meteorology Satellite Application Facility (SAF) - was initiated in 1999 as part of the EUMETSAT network of Satellite Application Facilities. The aim of the project is to deliver operational radio occultation products from the GPS receiver onboard the future EPS/Metop satellites.
The host institute is the Danish Meteorological Institute (DMI) and this will also be the physical location of the operational GRAS SAF facility. The two other project partners are the IEEC (Spain) and the Met Office (UK).
The operational GRAS SAF will receive raw and preprocessed GPS radio occultation data from the GRAS instrument onboard the Metop satellites, process these into vertical height profiles of refractivity, temperature, pressure, and humidity, and distribute these products continuously in near real time (within 3 hours from sensing) to numerical weather prediction users and offline (improved products, within 30 days from sensing) to climate monitoring users. A second objective of the GRAS SAF is to supply software for 4DVAR-assimilation of radio occultation data into numerical weather prediction models. The GRAS SAF will enter into the operational phase and deliver products in the last half of 2006 given the current launch plans for Metop.

The primary input is the GRAS level 1b data from EPS/CGS, this is used to generate and disseminate the products to the end users in both NRT and offline. The archiving of GRAS SAF products is done locally at the host institute, with a user interface to the UMARF archive at EUMETSAT.

New results and examples of data products from the GRAS SAF processor prototype are presented. The prototype has been used on CHAMP data for initial test and validation. The 1DVAR method with additional input from ECMWF has been used to generate the GRAS SAF products. The results have been compared to forecast data from ECMWF and analysed statistically, and show that in most cases the accuracy requirements can be achieved with the CHAMP data. Additionally, a first NWP assimilation impact trial is presented. Approximately 40 profiles were used per data assimilation cycle. The encouraging results show a clear positive impact on the forecasts when also assimilating radio occultation data, but more trials are needed for a full picture.

1. THE GRAS SAF PROJECT – STATUS AND PLANS

The GRAS Meteorology SAF is a Satellite Application Facility being developed under the EUMETSAT programme for SAFs. The GRAS SAF is hosted by DMI with the two partner institutes the Met. Office, UK, and the IEEC, Spain. The GRAS SAF developments were initiated April 8, 1999 and will continue for seven years. The operational GRAS SAF will take over when the first EPS/Metop satellite is launched and providing data in 2006.

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 EPS/Metop (potentially complemented with other low Earth orbiting satellite products providing the same basic atmosphere parameters). One of the prime factors 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. Especially satellite observations will directly influence present classical observables. The role of the GRAS SAF is to facilitate the input from the GRAS instrument on EPS/Metop to NWP and climate change models in order to increase the usage of satellite data in a more effective manner than possible today, see (Offiler et al., 2001) and (Rubek et al., 2003).

The GRAS SAF has finished the preparatory phase by successfully completing the Requirements and Architectural Design Review (RADR), which was split in two parts; RADR-RR (Requirements Review) and RADR-DR (Design Review). The first part of the development phase, including the system design and prototype software developments, is also completed by a successful Critical Design Review (CDR) in March 2003. The second part of the development phase now focuses on the implementation, testing and upgrading of the system and software. To test the performance and accuracy of the GRAS SAF retrieval software the CHAMP radio occultation measurements will be used as an important data source until Metop is launched. During the commissioning of the Metop satellite, planned from second half of 2005 until mid 2006, the GRAS SAF will perform a full validation of the data products, the system and the software deliverables.

The GRAS SAF operational facility will be located at DMI and is being developed for the operational phase, which will start in immediate succession of the Metop commissioning.

2. USER REQUIREMENTS

The raw measurements from the GRAS instrument (Level 0) will be processed into bending angle products as part of the EPS Core Ground Segment (Level 1b). These level 1b data will be the basic input to the GRAS SAF. The GRAS SAF will then process and disseminate the atmospheric products, such as temperature and humidity profiles (Level 2).

Bending angles will be provided for altitudes ranging from 80 km down to 5 km (for both setting and rising occultations), with the expectation that many events will extend to near the surface. The bending angle accuracy requirement is to be better than 1 μrad or 0.4% (whatever is larger). The impact parameter localisation in Earth coordinates is required to be better than 0.01° in longitude and latitude, and better than 6 metres in altitude. The accuracy requirement on the bending angles is actually the design requirement for the GRAS instrument.

We break down the requirements by atmospheric layers; these are defined as:

Lower Troposphere	(LT)	1000hPa to 500hPa	(Surface to 5km)
Higher Troposphere	(HT)	500 hPa to 100 hPa	(5km to 15km)
Lower Stratosphere	(LS)	100 hPa to 10hPa	(15km to 35km)
Higher Stratosphere/Mesosphere	(HS)	10hPa to 1hPa	(35km to 50km)

The GRAS Science Advisory Group (SAG) has identified several classes of users, as noted in (GRAS SAG, 1998). For the purposes of the GRAS SAF, we present user requirements for just two major classes of users – operational meteorology (NWP) and climate. The requirements for operational meteorology, which reflect the limitation of a single GRAS instrument, are summarised in Table 1.

The requirements for climate applications, which also reflect the limitation of a single GRAS instrument, are summarised in Table 2. Both table 1 and 2 are taken from the GRAS SAF User Requirement document (Offiler et al., 2001).

		Temperature	Specific Humidity	Surface Pressure	Refractivity	Bending Angle
Horizontal Domain		Global	Global	Global	Global	Global
Horizontal Sampling		100–2000km	100 – 2000km	100–2000km	100–2000km	100–2000km
Vertical Domain		Sfc–1 hPa	Sfc–100 hPa	Sfc (msl)	Sfc–1 hPa	Sfc–80 km
Vertical Sampling	**LT**	0.3–3km	0.4–2 km	–	0.3–3 km	2–5 Hz
	HT	1–3 km	1–3 km	–	1–3 km	
	LS	1–3 km	–	–	1–3 km	
	HS	1–3 km	–	–	1–3 km	
Time Window		1–12 hrs	1–12 hrs	1–12 hrs	1–12 hrs	1–12 hrs
RMS Accuracy	**LT**	0.5–3 K	0.25–1 g/kg	0.5–2 hPa	0.1–0.5%	1 µrad or 0.4%
	HT	0.5–3 K	0.05–0.2g/kg	–	0.1–0.2%	
	LS	0.5–3 K	–	–	0.1–0.2%	
	HS	0.5–5 K	–	–	0.2–2%	
Timeliness		1-3 hrs	1–3 hrs	1–3 hrs	1–3 hrs	1–3 hrs

Table 1. GRAS/Metop user requirements for operational meteorology.

		Temperature	Specific Humidity
Horizontal Domain		Global	Global
Horizontal Sampling		100–1000 km	100–1000 km
Vertical Domain		Surface to 1 hPa	Surface to 1 hPa
Vertical Resolution	**LT**	0.3–3 km	0.5–2 km
	HT	1–3 km	0.5–2 km
	LS	1–3 km	0.5–2 km
	HS	5–10 km	1–3 km
Time Resolution		3–24 hrs	3–24 hrs
RMS Accuracy	**LT**	0.5–3 K	0.25–1 g/kg
	HT	0.5–3 K	0.05–0.2 g/kg
	LS	0.5–3 K	–
	HS	1–3K	–
Timeliness		30–60 days	30–60 days
Time Domain		> 10 years	> 10 years
Long-term Stability		< 0.1 K/decade	< 2% RH/decade
No. of profiles/ grid box/month		> 10	> 10

Table 2. GRAS/Metop requirements for climate monitoring.

3. DATA AND SOFTWARE PRODUCTS

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. Since this time constraint may mean that processing is simplified, and some ancillary data may not be available in time, NRT products may not represent the optimum possible quality, although it will still meet user requirements for NWP input data.

The GRAS SAF will also re-process the radio occultation data in Offline mode using optimum algorithms and post-processed GNSS and LEO precise orbit determination (POD) 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.
The product domain will be global, and from the surface to a maximum of 80km. The height range of individual Level 2 profiles produced by the SAF critically 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 2km. 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, consistent with the user requirements. The data products are summarised below in Table 3, and details can be found in (Offiler et al., 2002). The algorithms necessary to process the CGS Level 1b products to GRAS SAF Level 2 Products for both NRT and Offline, can be found in the Science Plan (Rubek et al., 2003).

GRAS SAF Products List	Description of product
NRT Data products	
Refractivity profile	The refractive index of the atmosphere in units of $(n-1)10^6$
Temperature profile	Temperature as function of height at tangent point
Pressure profile	Pressure as function of height at tangent point
Specific humidity profile	Specific humidity as function of height at tangent point
Surface pressure	Pressure estimate at surface level
Error covariance matrix	Error covariance matrix as average for all profiles
Offline Data Products	
Bending angle profile	Bending angle as function of impact parameter
Refractivity profile	The refractive index of the atmosphere in units of $(n-1)10^6$
Temperature profile	Temperature as function of height at tangent point
Pressure profile	Pressure as function of height at tangent point
Specific humidity profile	Specific humidity as function of height at tangent point
Error covariance matrix	Error covariance matrix as average for all profiles
Global map of temperature	Global map based on monthly averages of temperature profiles
Global map of specific humidity	Global map based on monthly averages of humidity profiles
Global map of geopotential height	Global map of monthly averages of geopotential height profiles
Software Deliverable Products (ROPP)	
1D-var pre-retrieval software (pre-existing)	Software module used to generate NRT temperature, pressure and humidity products from refractivity and a user's background profile
3/4D-var assimilation software	Forward operators and their adjoints to allow for 3/4DVAR data assimilation of GRAS SAF and level 1b products into existing NWP models
Pre-processing tools	Pre-processing tools to assist the data assimilation of GRAS SAF and level 1b products

Table 3. List of products from the GRAS SAF.

The GRAS SAF will also provide software products (with associated User Guides) which implement procedures to assist in assimilating GRAS 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). The overall content is included in Table 3 above.

Since end-users' operational systems have specific software standards, interfacing requirements and other constraints, the GRAS SAF software deliverables 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.

At DMI a prototype of the GRAS SAF processing system is already running. Figure 1 shows an example of a "dry" temperature profile and a temperature profile processed using 1D-VAR, derived from CHAMP occultation data. The results are compared with ECMWF forecasts. The 1D-VAR temperature curve shows

better agreement with the forecasts than the "dry" temperature, because of the adjustment from background (model) information and presence of water vapour information.
A total of 1810 CHAMP occultations from January 2002 were processed. Figure 2 shows the statistics of 1630 profiles, processed when the 1D-VAR acceptance ratio was set to 2.5, cf. (Lauritsen et al., 2003) for details. These preliminary results show that the user requirements described in (Offiler et al., 2001) can be fulfilled with CHAMP data, and even more so with GRAS/Metop, which will have increased accuracy.

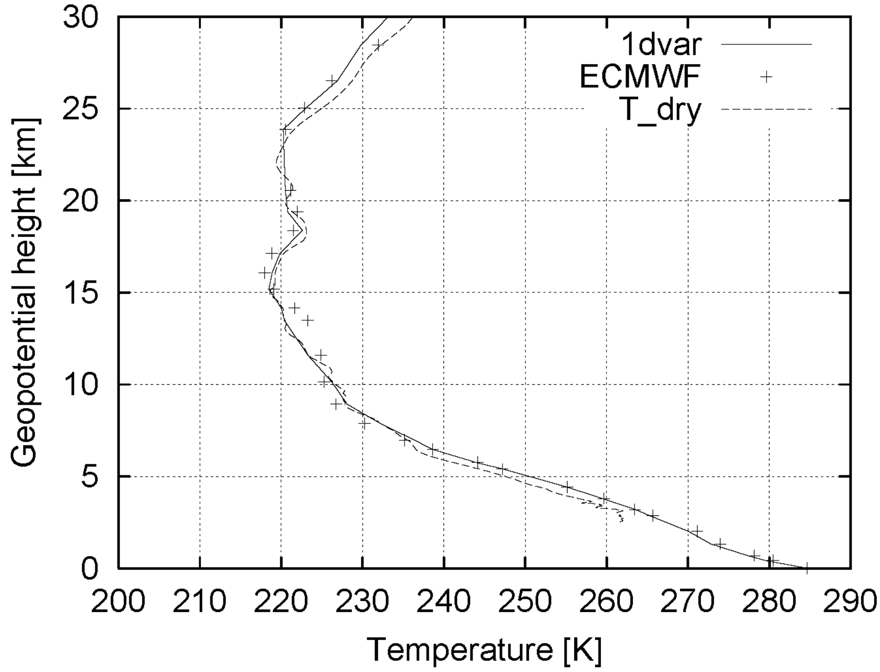

Figure 1. Temperature profile from CHAMP data, processed by the GRAS SAF system prototype.

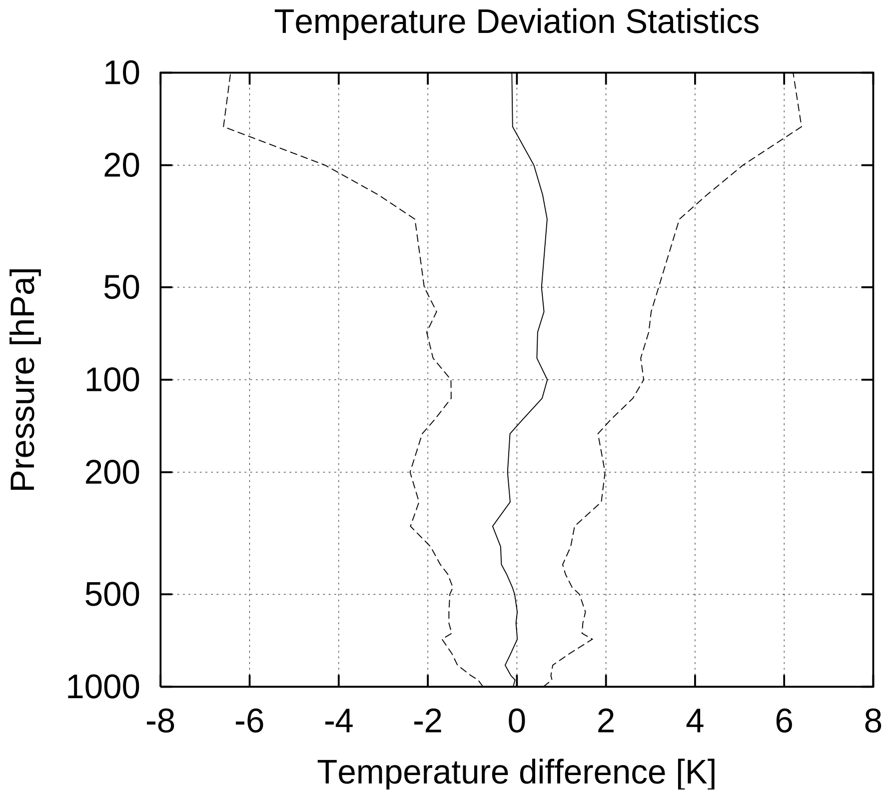

Figure 2. 1D-Var statistics for CHAMP temperature profiles as a function of pressure. The solid curve shows the mean difference between the 1D-Var and ECMWF field, whereas the dashed curves represent +/- the standard deviation.

4. NWP ASSIMILATION IMPACT TRIAL

The 3D-Var and the OPS codes of the ROPP package have been tested in a first impact trial assimilating CHAMP refractivity profiles provided by GFZ. The period used is from May 26, 2001 to June 11, 2001. Each profile contains ~120 refractivity values (150 max), with a vertical separation of 200m. We do not assimilate refractivity below 4km because of the potential bias problems in the measurement. The observation errors are based on Kursinski's 1997 estimates, but we have inflated them to 2% at the surface, falling linearly to 0.2% at 10km. "QC" is based on a 1D-Var calculation. Note, we only obtain ~40 measurements per assimilation cycle.

The control run is defined close to the operational set-up, assimilating radiosondes, ATOVS, SSMI, etc., but without RO data. The impact trial run is defined the same as the control run but now also assimilating RO data obtained from CHAMP. Comparing the NWP forecast fits to the observations (radiosondes) is used to assess the results of the impact trial.

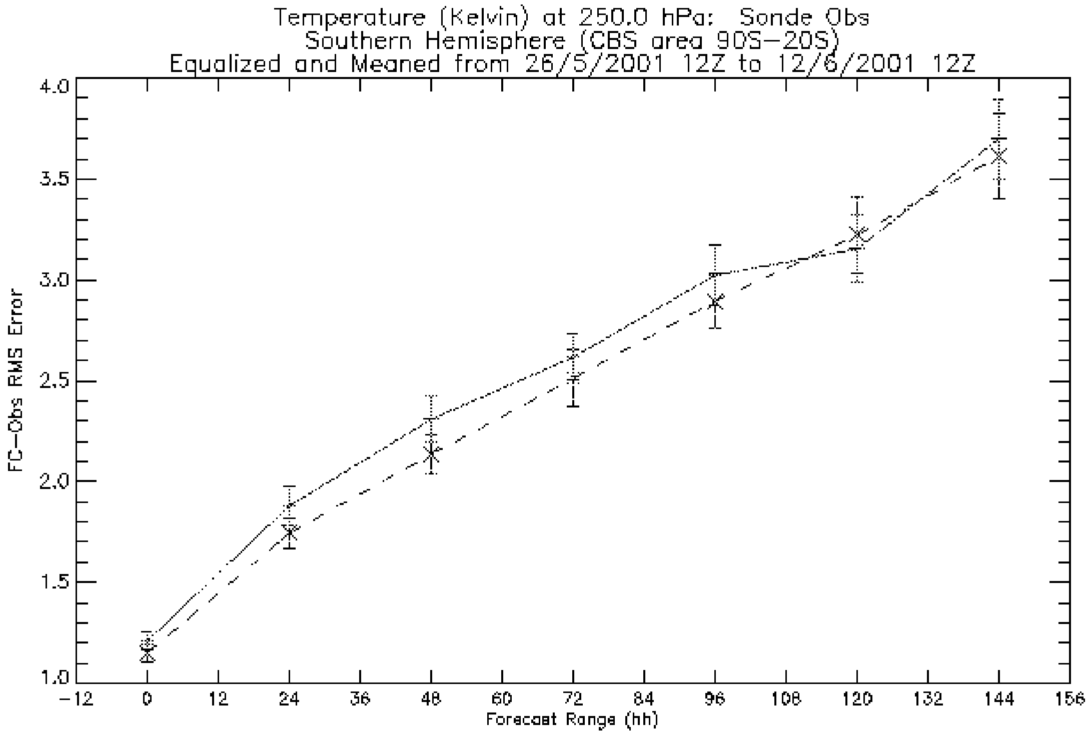

Figure 3. The forecast error of the control run when compared with the actual observed radiosonde measurements is shown as the solid line. The dashed line shows the forecast error of the impact trial when including the CHAMP radio occultation measurements.

We find 0.2% total improvement against observations over the period when assimilating RO data, using as unit an "NWP index", a figure of merit summarising by how much an NWP forecast has been improved/ degraded as a result of new observations. This result would support the case for assimilating the RO data if it was available operationally. Upper troposphere and lower stratosphere show improvements in the 250hPa (Southern Hemisphere) and 50hPa (global) temperature. In Figure 3 the improvements when assimilating the RO data are seen in the 250 hPa temperature in the first four days of forecast. Given the small number of observations these results are very encouraging. The prospects of obtaining measurements from a constellation (e.g. COSMIC, ACE+) are very exciting in the light of these results, which will be published in the near future (Sean Healy, pers. comm.).

5. CONCLUSION

With the first EPS/Metop satellite targeted to be launched in late 2005, GRAS SAF developments are on track and within the planned schedule. The system prototype is running and has been validated against the user requirements using CHAMP data, and a first NWP assimilation impact trial has confirmed the positive prospects of making operational radio occultation systems. Once operational, 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 EPS/Metop satellites, and inclusion of occultation data from other RO satellites (e.g. COSMIC, ACE+, …) in GRAS SAF processing.

6. REFERENCES

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