TOWARDS OPERATIONAL RADIO OCCULTATION PRODUCTS

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ABSTRACT

In 1999 EUMETSAT initiated the GRAS SAF Project (short for Global Navigation Satellite System (GNSS) Receiver for Atmospheric Sounding (GRAS) meteorology Satellite Application Facility (SAF)) as part of its network of Satellite Application Facilities. The aim of the project is to deliver operational radio occultation products from the GRAS occultation sensor 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, process these into vertical height profiles of refractivity, temperature, pressure, and humidity, and distribute these products continuously in NRT (near real time, within 3 hours from sensing) to numerical weather prediction users. Furthermore, the GRAS SAF will process and distribute offline (improved products, within 30 days from sensing) to climate monitoring users. Another 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. Currently, GRAS SAF demonstration products are produced using radio occultation data from the CHAMP satellite, and we present a statistical analysis of the differences between GRAS SAF demonstration products and analysis fields from ECMWF global fields.

The basic principle in the GRAS SAF project is the radio occultation method where 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 standard methods for retrieving atmospheric quantities from radio occultation measurements assume that the measured signal at a given time consists of a single ray. However, in cases where the atmosphere contains dense water vapor layers, which is typical for the lower troposphere in the tropics, the signal arriving at the satellite will consist of more than one ray. We discuss recently developed retrieval methods that are able to handle cases with this so-called multi-ray propagation.

1. THE GRAS SAF PROJECT

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 in 1999 and will span seven years. The operational GRAS SAF will take over when the first 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, see Figure 1. 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. 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.

The GRAS SAF has finished the preparatory phase by completing the Requirements and Architectural Design Review (RADR). The Critical Design Review (CDR) in March 2003 completed the first part of the development phase, including the system design and prototype software developments. 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 CHAMP radio occultation measurements are used as an important data source until Metop is launched. During the commissioning of the Metop satellite, planned from the beginning of 2006 until mid 2006, the GRAS SAF will perform a full validation of the data products, the system and the software deliverables. Currently, the GRAS SAF system is in the middle of the component test phase. During this phase the individual software and hardware modules of the system will be tested independently, along with the first tests of the EPS Primary NRT User Terminal (interface to EPS, for reception of pre-processed input data from the Metop satellite) and the UMARF CORBA Client (interface to EUMETSATs central archiving facility UMARF, for archiving of products and handling of product orders from users). The next project milestone will be the Infrastructure Readiness Review in December 2004, ending the component test phase.

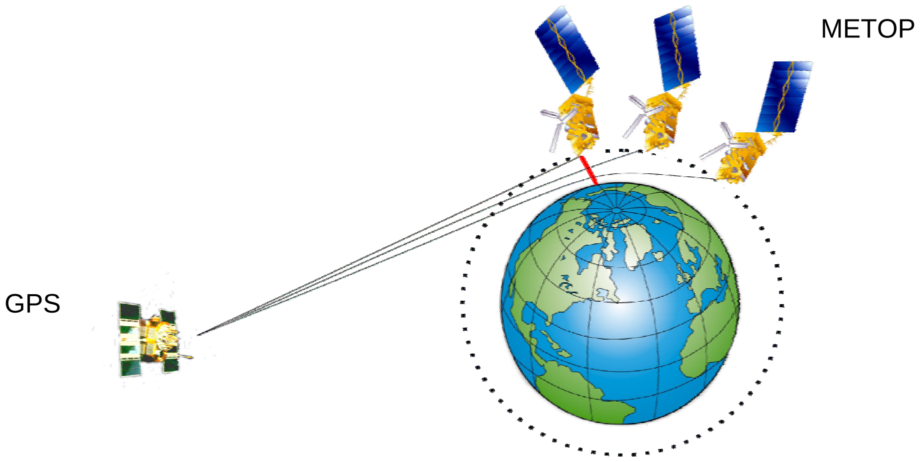


Figure 1. The basic principle behind the radio occultation (RO) technique. Radio signals from the GPS satellite are received by the orbiting Metop satellite, shown at three consecutive times. The ray path is characterized by its incoming impact parameter and the bending angle. The inversion of the measured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

2. USER REQUIREMENTS

The raw measurements of phase and amplitude 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 longitudes and latitude, and better than 6 meters in altitude. The accuracy requirement on the bending angles is the basic design requirement for the GRAS instrument. We specify the requirements by atmospheric layers, defined as follows:

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

The GRAS Science Advisory Group (SAG) has identified several classes of users, as noted in Ref. [GRAS SAG, 1998]. For the purpose of the GRAS SAF, we present user requirements for 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]. In Figure 2, we show the global distribution of GRAS SAF profiles within 24 hours obtained by a simulation.

		Temperature	**Specific Humidity**	**Surface Pressure**	**Refractivity**	**Bending Angle**
Horizontal Domain		Global	Global	Global	Global	Global
Horizontal Sampling		100–2000 km	100–2000 km	100–2000 km	100–2000 km	100–2000 km
Vertical Domain		Sfc–1 hPa	Sfc–100 hPa	Sfc (msl)	Sfc–1 hPa	Sfc–80 km
Vertical Sampling	**LT**	0.3–3 km	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	0.05–0.2 g/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.

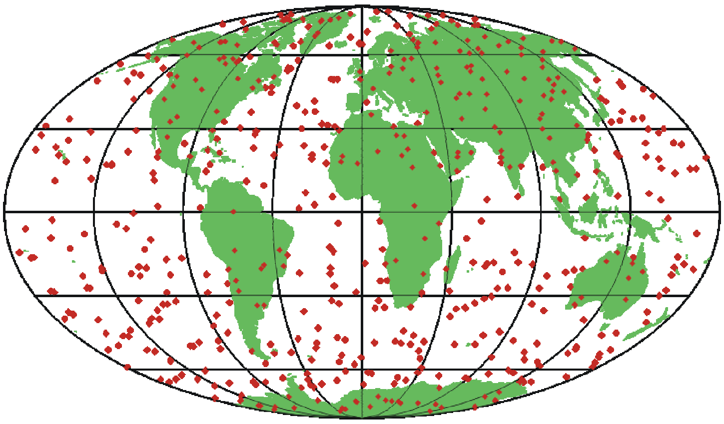


Figure 2. Global distribution of radio occultation profiles during 24 hours (about 500 profiles).

		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	1–3 K	–
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 user requirements for climate monitoring.

GRAS SAF Products List	Description of product
NRT Data products	
Refractivity profile	The refractive index of the atmosphere
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
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	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 3/4D-Var 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 data and software products from the GRAS SAF.

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. 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 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 80 km. 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 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, consistent with the user requirements. The data products are summarised in Table 3, and details can be found in [Offiler et al., 2002]. The GRAS SAF will also provide software products (with associated User Guides) that 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.

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 running. Figure 3 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 global analysis 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. Figure 4 shows the statistics of the analysis of 8700 Champ profiles (from Jan-Feb 2003), processed with the 1D-Var routine [Lauritsen et al., 2003]. The 1D-Var retrieved profiles are obtained using ECMWF global analysis fields as backgrounds. These profiles are next compared with the same ECMWF fields in order to generate the statistics displayed in Figure 4. The results thus indicate that the user requirements can be fulfilled with CHAMP data, and even more so with GRAS/Metop, which will have an increased accuracy.

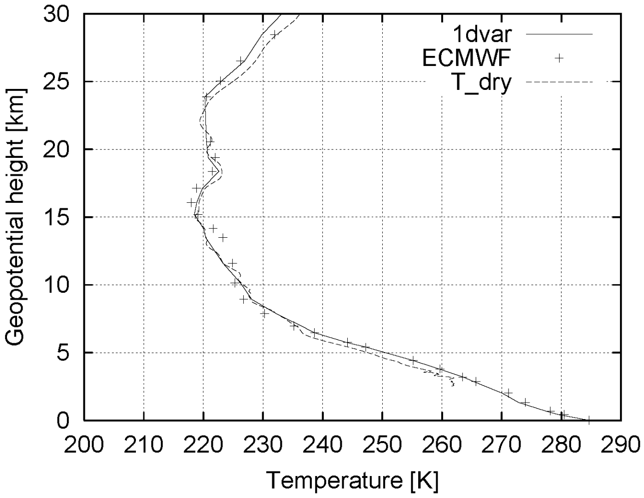


Figure 3. Temperature profile retrieved from CHAMP occultation data, compared with the ECMWF background profile used in the 1D-Var algorithm.

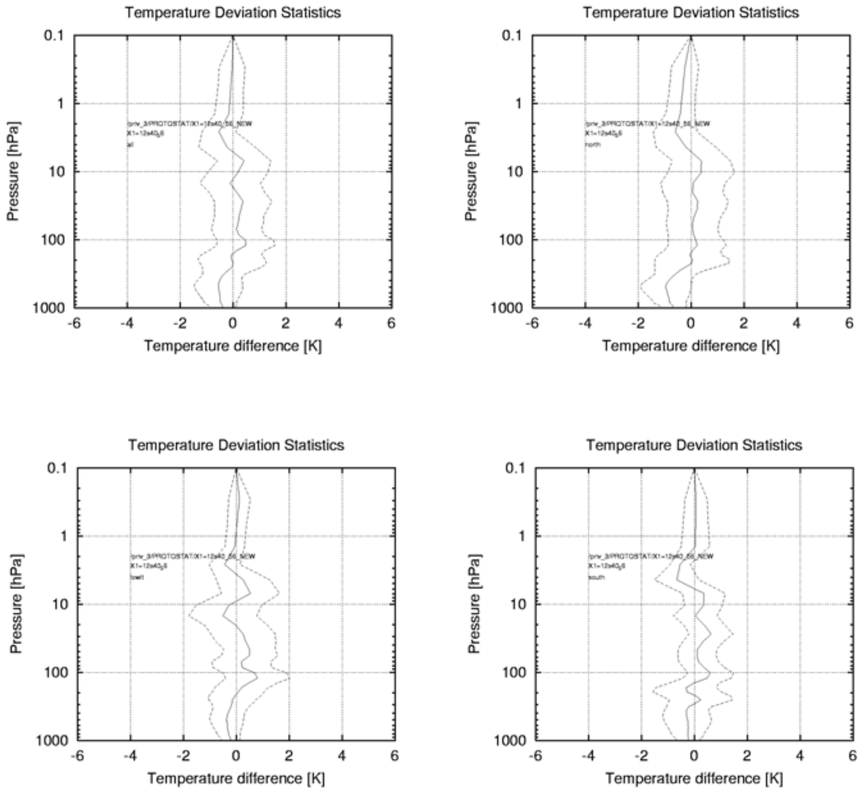


Figure 4. Statistics for retrieved temperature profiles as a function of pressure. The solid curve shows the mean difference between the retrieved 1D-Var and ECMWF fields whereas the dashed curves represent plus/minus the standard deviation. The panel at the upper left shows the global distribution whereas the other panels show the northern hemisphere (upper right), tropics (lower left), and southern hemisphere (lower right).

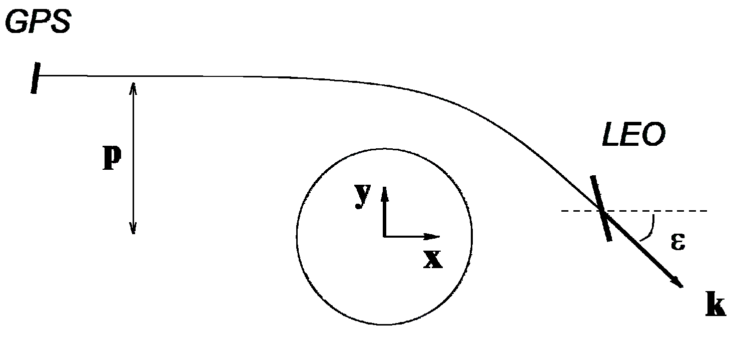


Figure 5. Schematic drawing of the radio occultation geometry. The rays from the GPS satellite are characterized by their impact parameter, p, and their total bending angle, ε.

4. ATMOSPHERE MULTIPATH

The standard methods for retrieving atmospheric quantities from radio occultation measurements assume that the measured signal at a given time consists of a single ray (see Figure 5). However, in cases where the atmosphere, characterized by an index of refraction n(r), contains dense water vapour layers, which is typical for the lower troposphere in the tropics, the signal arriving at the satellite will consist of more than one ray (see Figure 6). Analyzing such a signal by the standard methods result in a bending angle that will lead to a negative bias in the retrieved values for the refractivity profile. In order to reduce this negative bias, the signal has to be analyzed by methods designed to be able to invert signals with multiple rays. It should be noted that receiver tracking, horizontal gradients and critical refraction may also contribute to a negative refractivity bias.

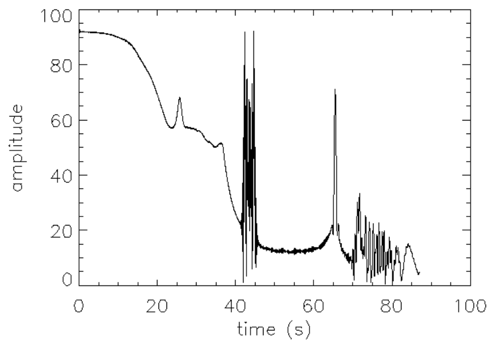
The so-called canonical transform (CT) and full-spectrum inversion (FSI) methods have been developed to handle situations with multipath behavior [Gorbunov, 2002; Jensen et al, 2003; Gorbunov-Lauritsen, 2003]. In these methods the basic idea is to assume that the impact parameter, p, uniquely will define a given ray. This implies that any given physical quantity (e.g., the bending angle, $\varepsilon(p)$) can be calculated as a function of the impact parameter. The assumption is fulfilled for a spherically symmetric atmosphere but even for situations with small horizontal gradients it will be approximately fulfilled. The measured signal is transformed to the impact parameter representation by applying a Fourier integral operator and thereafter the bending angle is obtained from the derivative of the phase of the transformed signal. Simulations performed with global atmospheric fields for cases with strong water vapour gradients that give rise to multipath propagation show that the canonical transform method can unfold multipath behavior, thereby leading to more accurate retrieved atmospheric quantities. The CT and FSI methods provide high accuracy and resolution (about 50 m) in the reconstruction of bending angle profiles. In Figure 7, we show an example of retrieved impact parameter and bending angle for a simulation based on a high-resolution radio sonde profile.

The original CT method uses back-propagation as a pre-processing tool [Gorbunov, 2002]. Another approach, as used in the FSI [Jensen et al, 2003] and CT2 [Gorbunov-Lauritsen, 2003] methods, is to directly map the measured field to the impact parameter representation. The simplest formulation of these methods applies to a radio occultation with a circular geometry (i.e., spherical satellite orbits in the same vertical plane, spherical Earth and spherically symmetrical atmosphere). The methods are based on a Fourier transform applied to the complete record of the measured, complex field $u(t)$ as function of observation time t or another parameterization of the observation trajectory such as the satellite-to-satellite angle θ. The advantage of such methods is that they do not assume stationarity of the GPS satellite. Furthermore, these methods allow for efficient numerical implementations based on FFTs by mapping to an approximate impact parameter representation.

The field measured at the METOP satellite can be written as $u(t) = A(t)\exp(i\Psi(t))$, where A is the amplitude and Ψ the phase. Generically, the canonical transform methods are based on mapping the time-dependent field to the impact parameter representation by a Fourier integral operator (FIO). This type of mapping generalizes the Fourier transform. The FSI and CT2 methods uses some approximations and a phase model, $f(Y)$, where Y now is a generic coordinate which can be time, satellite-to-satellite angle, or something else. The resulting mapping can be written as:

$$w(\tilde{p}) = \hat{\Phi}_2 u(\tilde{p}) = a_2(\tilde{p}, Y_s(\tilde{p})) \int \exp(-ik\tilde{p}Y)\exp\left(ik\int_0^Y f(Y')dY'\right)u(Y)dY$$

where $\tilde{p}$ is an approximation for the impact parameter and a_2 the amplitude function of the operator (k is the wave vector). The transformed field can be written $w(\tilde{p}) = A(\tilde{p})\exp(ik\Psi(\tilde{p}))$, and from the derivative of its phase, $d\Psi(\tilde{p})/d\tilde{p}$, it is possible to obtain the bending angle as a function of impact parameter.



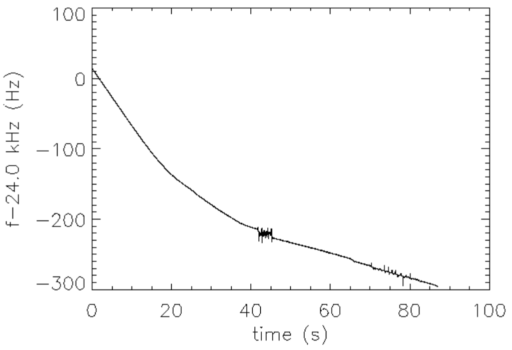


Figure 6: Simulated example with a wave optics propagator showing amplitude of a radio signal at the LEO orbit (left), and the Doppler frequency shift (right). One observes strong focusing resulting in multipath behavior with 3 interfering rays appearing around the time 42-46 seconds.

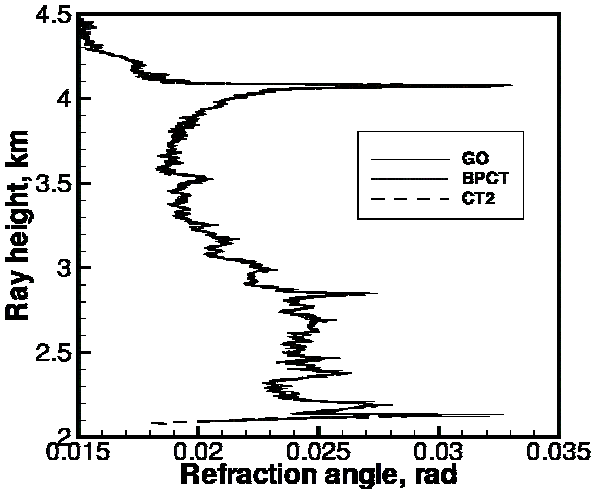


Figure 7: Comparison of refraction (bending) angle as a function of ray height (impact parameter minus Earth's curvature radius) obtained by three different methods: geometric optics (GO), CT and back-propagation (BPCT) and the CT2 retrieval method.

5. CONCLUSION

The GRAS SAF system prototype is running and occultation results have been analyzed using CHAMP data. 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 outcome of an NWP assimilation impact trial has confirmed the positive prospects of assimilating radio occultation measurements operationally. 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 the GRAS SAF processing.

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