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Prepared by EUMETSAT
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RECENT DEVELOPMENTS IN RADIO-OCCULTATION OBSERVATIONS WITH GRAS

GRAS operational geometric optics processing is now performed at EUMETSAT with an improved processor; this has introduced several improvements, among them deeper penetration of occultations into the troposphere, use of improved GPS orbits/clocks, and a reduction of degraded data due to orbit convergence periods.

In parallel, an offline prototype has been developed that combines geometric and wave optics processing. The offline processor also has the option to include GPS Navigation Bits in the processing. Validation of the prototype was performed within a European ESA study; different centres provided wave optics processed GRAS data. Results show generally good agreement in terms of bias; standard deviations do depend on the selected smoothing / filtering of the data. The validation also confirms that GRAS is capable to track all the way down to the lowest altitudes, even under highly variable atmospheric conditions.

The validation also shows that processing options do have a fairly large impact on the found bias structure at lower altitudes and that further comparisons are required to optimize the use of any radio occultation instrument in the lower troposphere.

A best-effort (i.e. non operational) based wave optics processed bending angle data stream from this offline processor is scheduled to be provided close to Near-Real-Time in October 2010. This will allow for early identification of possible short-comings in the processor, which will then be fed into the in parallel ongoing development of the operational processor (scheduled to be available in 2011).

Action/Recommendation proposed:
CGMS is invited to comment.

Recent developments in radio-occultation observations with GRAS

1 INTRODUCTION

GRAS (GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding) is a radio occultation instrument onboard of Metop. The instrument observes GPS signals either in closed loop (CL) or raw sampling (RS) mode. CL describes a tracking technique where a replicate of the GPS satellite signal is generated onboard of the receiver and then correlated to the received GPS signal. The atmosphere will lead to a bending of the ray; this bending will show up as a Doppler frequency shift of the received electromagnetic signal in addition to the geometric Doppler contribution. CL tracking works fine under sufficiently high SNR conditions, but usually breaks down in the mid troposphere where increased water vapour abundance causes strong fluctuations in the signal's phase and amplitude. The GRAS receiver then replaces the closed feedback loop with an onboard Doppler model ("open loop", for GRAS called RS), and collects data at a higher rate (1 kHz vs. 50 Hz in CL).

For bending angle processing, accurate knowledge on the GPS and Metop orbits and clocks is required. This GPS information is coming in Near-Real-Time (NRT) into the EUMETSAT ground segment in 3 hour segments for orbits and 15 minute segments for clocks, provided by the GRAS Ground Support Network (GSN). Data collected at higher altitudes can be processed based on "Geometric Optics" (GO), the GO algorithm work under the assumption that the GPS signals received are composed from a single Doppler frequency ("tone") only. Water vapour in the lower troposphere will lead to atmospheric multipath, causing the crossing of individual rays on their way through the atmosphere. Thus, tropospheric signals consist of multiple tones present at the same time, requiring more complex algorithms to "disentangle" the different signals. Traditionally, these algorithms are called "Wave Optics" WO algorithms. Since WO and the RS mode are both used when variability in the atmosphere is high, it is generally required to treat these together.

This document first gives a short overview on recent operational GO processing development, the GO/WO prototype, outlines the processing differences between GRAS and other radio occultation receivers flying, summarises the recent developments regarding the GRAS WO bending angles processing, and outlines the next steps in the processor development.

2 GEOMETRIC AND WAVE OPTICS PROCESSING AT EUMETSAT

2.1 Recent Developments

The last updates to the GO processing running operationally are:

- PPF (Product Processing Facility) 2.16 became operationally on 01.07.2010, enhancing four processing aspects: (1) allowing extrapolation of the bending angles measured on the GPS L2 frequency, thus extending the range of the neutral bending angle to lower altitudes; (2) providing thinned bending angle data in the original PFS format; (3) reducing the time bending angle data is flagged as degraded from 8 hours to 4 hours during an orbit convergence period; (4) allowing to use higher quality GSN data.
- The GRAS instrument configuration was changed for a week in December 2009, assessing the GPS satellite tracking down to very low altitudes. In addition, the switch

from RS tracking to CL tracking was moved to higher altitudes in this configuration change. This removes short, unrecoverable GRAS data gaps in the mid-troposphere. The configuration was switched back after user consultation, requiring the above mentioned extrapolation of L2 data in order not to lose useful data in the troposphere.

The most recent developments regarding GO and WO prototype processor development are:

- The reconstruction of the GRAS CL and RS data to product level 1A has been developed and validated within an ESA study that focused on the RS data.
- A generated reconstructed data set was delivered to participants of the ESA study to run it through their GO and WO processing algorithms.
- The existing EUMETSAT prototype has been streamlined and harmonized to allow GO and WO processing following very similar steps.
- The prototype has been extended to use either externally provided GPS Navigation Bits, or rely on an internal estimation.
- WO processing of a test data set has been performed with the prototype, demonstrating GRAS tracking to the lowest km, well into the Planetary Boundary Layer. It however also shows the need for further processing and filtering fine tuning at lower altitudes.
- The EUMTETSAT prototype GO processing has been tested by participating in the RO Trends project, where about 8 years of CHAMP data are processed by several centres worldwide to assess structural uncertainty, in particular with respect to trends.

2.2 GRAS processing vs. other RO receivers

There is a considerable difference between GRAS and receivers based on the US/JPL (Jet Propulsion Laboratory) architecture (CHAMP, SAC-C, COSMIC, TerraSAR-X, Tandem-X). For GRAS, the lowest possible data level (raw correlator output and data from the individual instrument components which in total define the measured amplitude, phase, and tracking loop behaviour) is delivered to the ground for CL and RS data, where it needs to be “reconstructed” to obtain the actually measured signal. In contrast, JPL-based receivers used on, e.g., COSMIC, perform this reconstruction on board, resulting in the need for frequent firmware updates if the data handling onboard is implemented incorrectly. Note that JPL required more than 4 years to fully implement open loop data handling in their onboard software, starting from the initial attempts to obtain open loop data on SAC-C in late 2002 until finally providing working open loop measurements on COSMIC in early 2007.

A EUMETSAT funded study was started with the UCAR/COSMIC team, where they were asked to process GRAS observations from raw (level 0) measurements for a test period in September, October 2007. Preliminary results from their processing have just been received. The figures below show comparisons of the number of occultations processed per day by EUMETSAT and UCAR (Figure 1) and of the bias and standard deviation with respect to ECMWF (Figure 2). More occultations per day are provided by the EUMETSAT processor, and it also achieves lower noise at higher altitudes.

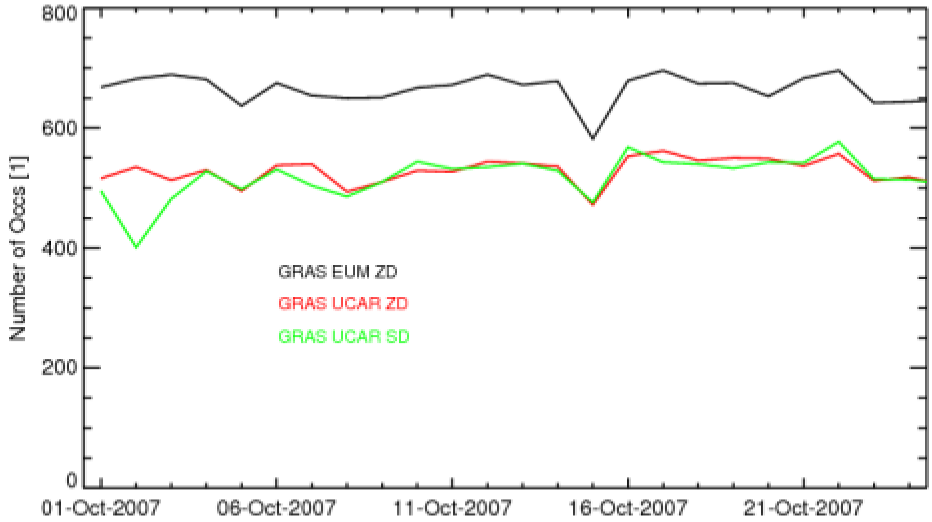

Figure 1 Number of daily occultations provided by EUMETSAT and UCAR processing of GRAS occultations in October 2007. ZD: Zero differencing, SD: Single differencing.

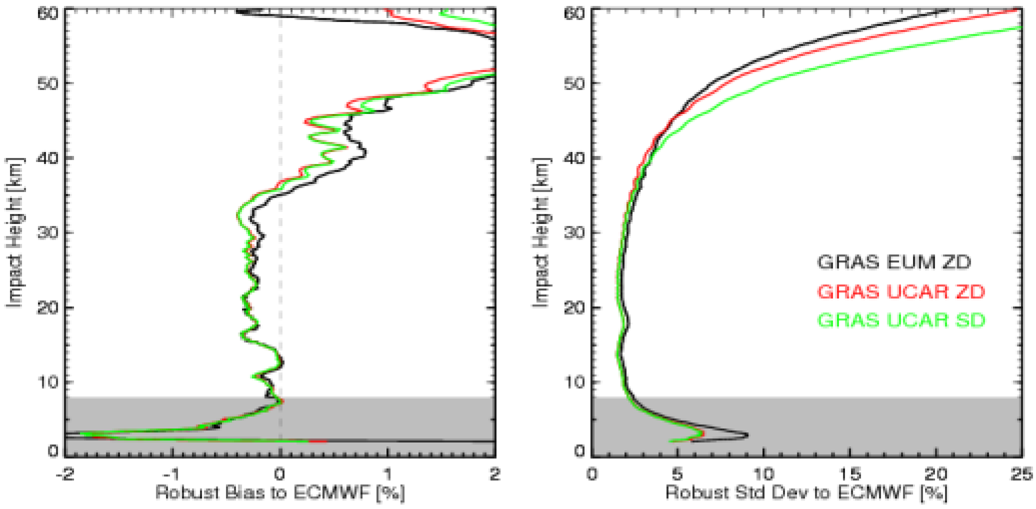

Figure 2 Bias (left) and standard deviation (right) over altitude for EUMETSAT and UCAR processing of GRAS occultations in October 2007. ZD: Zero differencing, SD: Single differencing. Grey shaded area indicates current GRAS operational processor limitation due to multi-path.

2.3 WO Results

The GRAS RS data reconstruction has been developed and a detailed validation of the required reconstruction algorithms for the RS data was performed within an ESA initiated study. EUMETSAT implemented the suitable algorithms and provided a reconstructed data set (essentially representing the level 1a product) to the participating centres.

WO processed RS data within the ESA study has been received from the University of Graz (UoG), GeoForschungsZentrum Potsdam (GFZ), Danish Meteorological Institute (DMI), in addition to two streams generated locally at EUMETSAT (GO and WO). The EUMETSAT

GO stream operates only on CL data, the WO stream uses the full 1kHz resolution available in RS mode and up-samples the CL data to the same resolution. All participants within this study have run their local WO implementation on the level 1a data as provided by EUMETSAT. Note that in the vertical altitude scale ("impact height") used here, Earth's surface corresponds to an altitude between 2 and 3 km.

Figure 3 shows the preliminary validation of bending angles against ECMWF forecast data for the different processing streams over altitude. DMI processes most of the available occultations (685), but has much increased noise at higher altitudes. The GFZ implementation provides fewer occultations; the algorithm requires external GPS Navigation Bits, which are missing in about 25% of cases. In addition it has problems with processing through data gaps and also shows increased noise at lower tropospheric altitudes. The EGOPS implementation suffers from some missing data in one of the early EUMETSAT provided reconstructed data set for rising occultations. These missing data caused no problems within the other algorithm implementations. Investigations are ongoing at the University of Graz why the processor did not at least provide all the setting occultations (around 340 on that day).

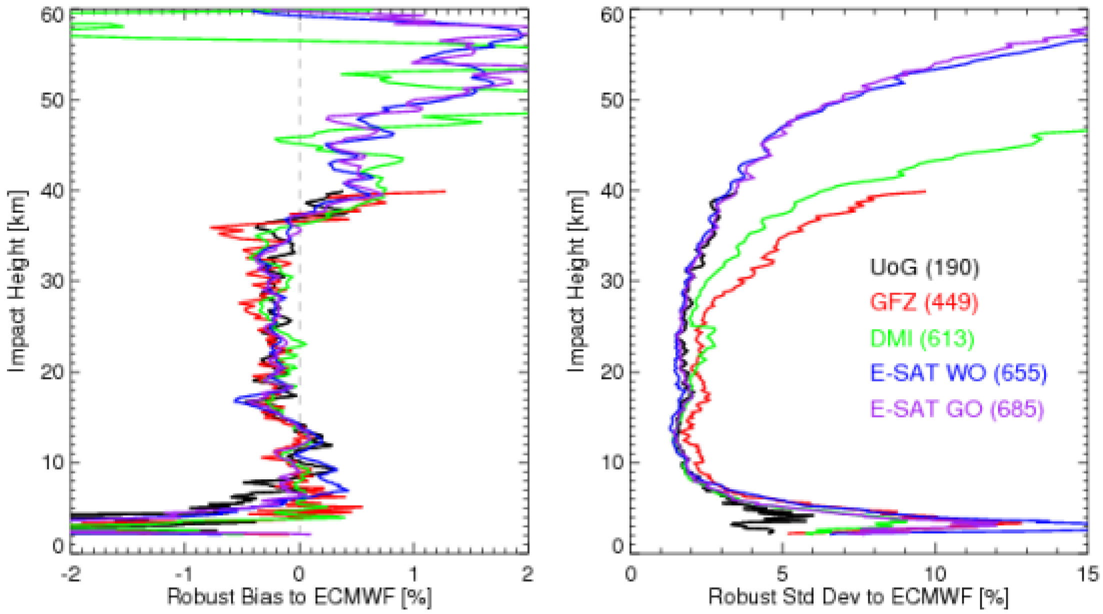

Figure 3 Bias (left) and standard deviation (right) over altitude with respect to ECMWF for different wave optics processing streams. All results based on EUMESAT reconstructed data for 30th of Sep. 2007. Number of occultations in brackets.

The EUMETSAT WO implementation processes most of the collected occultation on this day and is in good agreement with the other centres regarding the bias behaviour. But it shows much lower noise at higher altitudes - actually very similar to the GO calculation. It does however also show slightly higher noise in the lower troposphere, caused by the higher resolution / less filtering of WO data. Different filter options are currently evaluated.

The penetration depth of the different WO data streams is shown in Figure 4, normalized to the number of available occultations within that stream. At lower altitudes one clearly sees that the RS mode provides data into the lowest km. At higher altitude, one sees the deviation to a purely Gaussian distribution, thus lower numbers in the EUMETSAT WO processing around 10km indicate more outliers, very likely linked to the bias structure visible above.

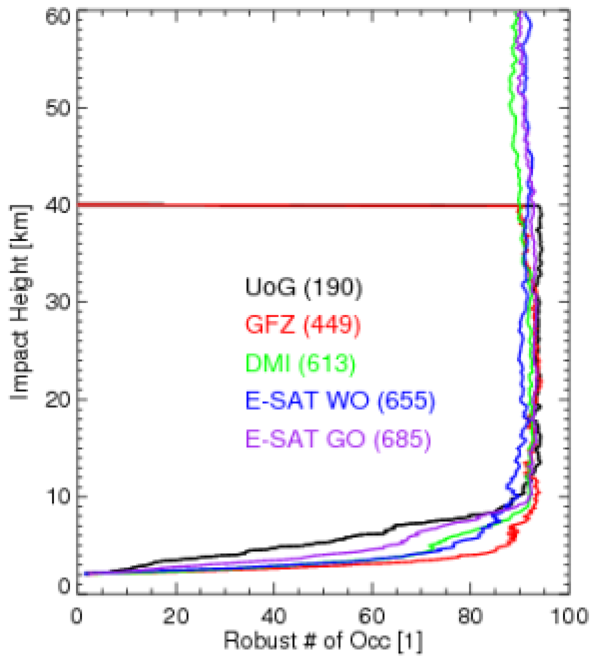

Figure 4 Pentration depth of different WO processing streams. All results based on EUMESAT reconstructed data for 30th of Sep. 2007. Number of occultations in brackets.

3 CONCLUSIONS

The operational GRAS processing has seen several upgrades improving the data quality. In particular the option to extrapolate the data paves the way for higher penetration depth and for possible instrument updates to avoid gaps in the mid troposphere. Also, less data is flagged degraded after an orbit convergence period (orbit reset).

The geometric and wave optics prototype processor has seen several major upgrades, allowing now to reconstruct data to level 1a and level 1b, inclusion of GPS navigation bits, and to process other than GRAS missions. First wave optics processed profiles from GRAS have been shown. A comparison with other wave optic implementations shows good agreement in terms of bias. Noise on the EUMETSAT provided wave optic data indicates that further smoothing might be required in the lower troposphere; at higher altitudes it shows excellent noise behaviour (similar to the GO processing). The data also confirms that GRAS penetrates into the lowest km with the raw sampling tracking. The comparison in addition highlights the need for further studies into processing options and how to optimize the use of any radio occultation instrument in the lower troposphere.

A provisional offline data stream of WO processed GRAS profiles on a best-effort basis is planned for October 2010. This would run in a quasi-routine mode in parallel to the operational processing and will allow data quality monitoring by several partner institutes in Near-Real-Time. Feedback from this monitoring will allow rapid updates of the prototype, and these will be fed into the operational processor development.