GRAS status and future European radio occultation missions

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ABSTRACT

The radio occultation instrument GRAS on-board of Metop-A has been measuring occultations since its activation on 27 October 2006 with only a few interruptions. On average, more than 600 occultations are collected during a day. Within this work, we briefly describe the GRAS instrument and processing, and then focus on validation of the bending angles by comparing them to co-located ECMWF and COSMIC profiles. We focus on a core impact height range from 8 km to 40 km, which is not affected by orbit approximations or limitations of the applied geometrical optics processing. Found agreement is generally good. We also briefly discuss future programs of EUMETSAT that could include a radio occultation mission.

1 Introduction

The Metop-A satellite belongs to the EPS (EUMETSAT Polar System), and is EUMETSAT's first LEO (Low-Earth-Orbit) satellite. In total, there will be 3 Metop satellites, each with an expected life-time of about 5 years. EPS is expected to provide data for at least 14 years (successive satellites will be flown with overlap times). All Metop satellites will fly in a sun-synchronous orbit, altitude about 820 km, equator crossing Local Solar Time at 9:30 in descending node. Each orbit of data (about 100 minutes) is down-linked over the Svalbard Archipelago at 78° N. For more information and a general introduction on EPS, please refer to [Klaes et al., 2007].

One of the instruments on-board of Metop-A is GRAS (GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding), a radio occultation instrument specifically designed for this task. It observes setting and rising occultations from the GPS (Global Positioning System) satellite constellation. Within this work, we validate recent GRAS measurements with co-located ECMWF (European Centre for Medium Range Weather Forecasts) profiles as well as with co-located observations from the COSMIC constellation. It is thus structured as follows: Section 2 gives a brief introduction on the GRAS instrument, processing, and dissemination; Section 3 outlines the used data for the validation; Section 4 presents the found results, Section 5 gives an outview to the coming upgrades in GRAS processing, and Section 6 concludes. A brief outlook on the future of radio occultation instruments from the EUMETSAT perspective is given in Section 7.

2 GRAS Instrument, Processing, and Dissemination

The GRAS radio occultation instrument is capable of tracking up to 8 GPS satellites on the zenith antenna, which is used for precise orbit determination. In addition, it has velocity and anti-velocity viewing antennas for occultation tracking, both are capable to track 2 occultations simultaneously. With the current GPS constellation of around 30 satellites, more than 600 occultations are tracked per day. GRAS is capable of tracking in closed-loop and in raw sampling mode (also called open-loop), where the former is at 50 Hz and the latter at 1000 Hz. Tracking is performed from the lowest part of the atmosphere up to about 80 km. Please refer to [Luntama et al., 2008] for more details on the instrument.

The GRAS PPF (Product Processing Facility) processes the data up to so-called level 1b, where the main products are bending angle over impact parameter, geo-location, time and type of measurement. The first processing step determines the Metop orbit, which is operating on 60 s of zenith data with the SRIF (Square-Root Information Filter). Additionally, precise GPS orbits and clocks are required, they are provided by the GSN (Ground Support Network) [Zandbergen and Dow, 2006]. The obtained Metop orbit is generally within the requirements of 0.1 mm/s in velocity and 1 ns in clock error at 1 Hz; for more information please refer to [Martinez et al., 2007, Montenbruck et al., 2008, Andres et al., 2008].

The bending angle processing of the currently operational PPF (version 2.11) uses only closed-loop data where both GPS frequencies are tracked, no raw sampling data is processed operationally. Bending angles are not optimized with a climatology, they are based on zero differencing and the geometrical optics assumption. Thus data below about 8 km to 10 km impact height is degraded, in particular at lower latitudes. At altitudes above about 40 km, approximations in occultation antenna position with respect to the orbit affect the data quality. These approximations still allow processing within the initial requirements for bending angles of an absolute accuracy of 1 μrad or 1 % (which ever is larger).

Dissemination of GRAS level 1b is performed through EUMETCast, providing the full data set in the EUMETSAT format [Luntama and Wilson, 2005], and in BUFR format (restricted to the core products needed for assimilation, for more information please refer to [Offiler, 2007]). A thinned version of the core products is also disseminated in BUFR on GTS (Global Telecommunication System) and EUMETCast, where profiles are currently thinned to a predefined set of 247 heights. All products are available latest within 2 h 15 min from observation time.

Processing from bending angles to level 2 is performed at the GRAS SAF (Satellite Application Facility). Level 2 products are e.g. refractivity, temperature, and water vapor profiles, available within 3 h from sensing time. Please refer to the GRAS SAF website for more information and availability [GRAS SAF, 2008].

In addition, all Metop data is available in offline mode from the U-MARF (Unified Meteorological Archive and Retrieval Facility) at EUMETSAT. Please refer to the EUMETSAT home page for further information [EUMETSAT, 2008].

3 Data

The GRAS data has been obtained from the operationally running PPF node on the EUMETSAT ground segment, version 2.11. It covers 16 days from the 29 of May to the 13 of June 2008. In total, there are 11102 occultations, out of which 343 are removed because they either provide no valid bending angles (e.g. because L2 tracking was not achieved), or they cover less than a 20 km impact height interval. The remaining 10759 provide more than 670 occultations on average per day.

The ECMWF co-located profiles are drawn from 12 h forecast fields, available at EUMETSAT at times 00 UT and 12 UT, with a resolution of 0.5 Degrees, on 91 vertical hybrid levels. They are forward modeled to bending angles using the freely available ROPP (Radio Occultation Processing Package) developed at the GRAS SAF [Offiler, 2008]. The COSMIC files are obtained offline from the CDAAC (COSMIC Data Analysis and Archive Center, Boulder, USA) archive [Kuo et al., 2004], where we use archived data from the Near-Real-Time stream.

All profiles are pre-processed to be available on 247 impact height levels, where impact heights are calculated from impact altitudes minus the local radius of curvature. The ECMWF profiles are up-sampled from the standard 91 model levels, the radio occultation data is thinned using a simple linear interpolation in log bending angle space provided by the ROPP tool.

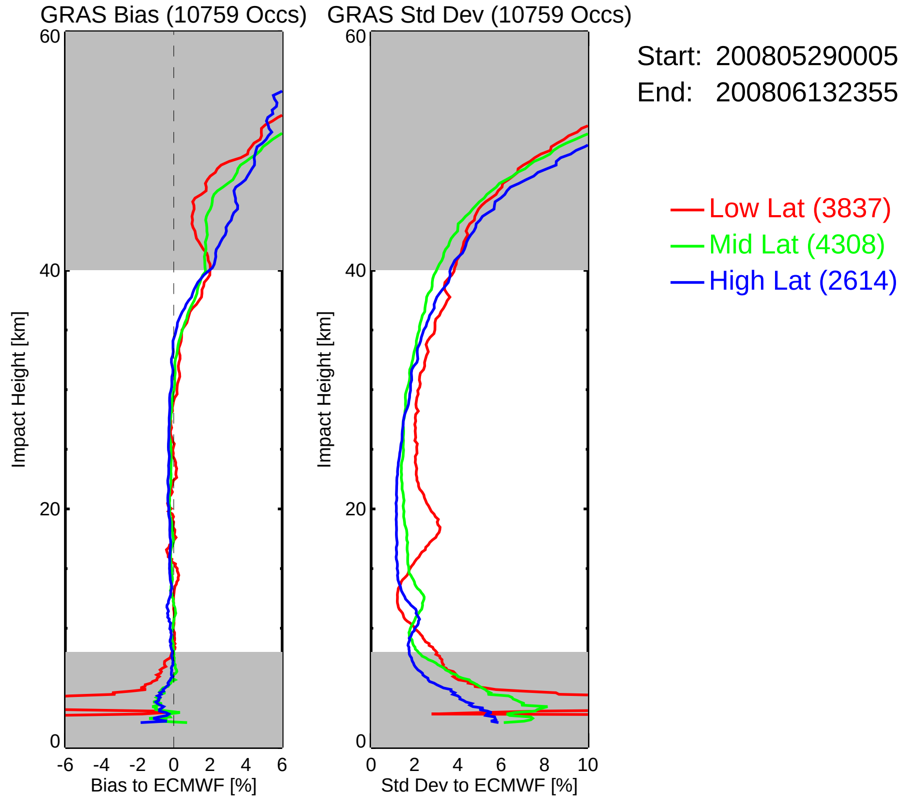

Figure 1: Operational GRAS PPF bending angles compared to co-located ECMWF profiles. 16 days in May, June 2008, PPF version 2.11. Bias (right), standard deviation (left) over impact height for 3 latitude bands separated in 30° steps. Grey shaded areas indicate regions affected by orbit (top) or by multi-path (bottom).

4 Results

Figure 1 shows so-called $(O-B)/B$ statistics, where O is the GRAS bending angle measurement, and B the forward propagated ECMWF background. These statistics are evaluated at each impact height level, using robust statistics. The robust statistic is an effective tool to deweight outliers from a noisy distribution, it returns the standard deviation and percentage of data points falling into the ± 2 sigma interval. This would be 95 % for an ideal Gaussian distribution. For the PPF 2.11 data, about 90 % fall into the ± 2 sigma interval, thus an additional 5 % of the data has been deweighted by the robust statistics.

The bias plot shows generally very good agreement for the core altitude range considered here, although the GRAS processing returns larger bending angles starting at about 35 km when compared to ECMWF fields. Deviations seen between 35 km and 40 km are likely caused by the resolution of the ECMWF fields, they tend to get smaller when moving to shorter forecast times and applying a linear interpolation in time on the ECMWF fields. Above 40 km, larger deviations from co-located ECMWF profiles occur that are caused by the above mentioned orbit approximations. Standard deviations clearly show the tropopause region, in particular at low latitudes. Here, gravity waves that are not fully represented in the ECMWF model are likely causing this observed increase.

Figure 2 shows the number of Near-Real-Time (NRT) GRAS bending angles profiles available over the investigated period, along with the number of NRT COSMIC profiles, as well as the number of matches. A match is assumed if the occultations are within ≤ 3 hours and ≤ 300 km. COSMIC shows a fair amount of variation over this period and provides on average about 2000 profiles a day. GRAS shows less variations, the slight dip on the 30. May 2008 is caused by a lost orbit dump. On average, about 700 profiles are obtained from GRAS, although these have not undergone any quality control, hence data available for assimilation tends to be around 650 profiles

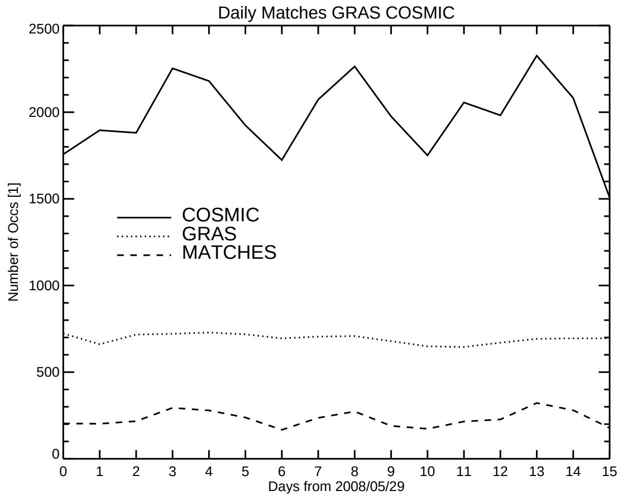

Figure 2: Near-Real-Time bending angles available from GRAS and COSMIC and number of co-located profiles. Period as in Figure 1.

per day. The number of matches is thus mainly affected by the available COSMIC profiles, generally around 200 are found per day. Not all matches are unique, on average about 35 profiles per day are matched more than once, where the main part are GRAS matched with more than one COSMIC.

Figure 3 shows the robust bias and standard deviation obtained with the matched data set. The bias agreement is very good for the core altitude range, the deviations seen around 35 km to 40 km against ECMWF (Figure 1) are not present here. Hence this feature is introduced by how ECMWF fields are used for co-location. The standard deviation plot shows increases around the tropopause for the different latitude bands. Similar results are also seen in refractivity comparisons of GRAS and COSMIC at the UK Met Office (M. Rennie, UK Met Office, personal communication, 2008). A reduction in the standard deviation increase near the tropopause level is observed when moving to closer matches.

5 Next Steps

For the near time future, we anticipate the following updates to the GRAS PPF: (1) better modeling of the antenna position in the occultation processing; (2) improved quality control, covering degraded orbit and degraded level 1b processing.

The first issue leads to the observed bias in bending angles at altitudes >40 km. Although formally the currently obtained bending angles are still within requirements, the processing to refractivity leads to a bias observed at much lower altitudes. Improved occultation antenna position modeling is expected to resolve this issue. The second issue will allow better selection of which data to assimilate at NWP centers. Quality control at the moment is based on a simple range check, more sophisticated methods such as the calculation of a cost function with respect to a climatological profile are being developed to identify severe outliers. In addition, degraded orbit quality will also be identified in one of the next PPF updates. Such degraded orbit quality could for example arise from a reinitialization of the SRIF orbit propagator.

The longer term development will focus on the upgrade of the PPF to deal with multi-path regions by wave optics calculation, and to improve quality control further through the use of variation assimilation [Marquardt et al., 2005]. Additionally, improved orbit processing to derive climate products from GRAS observations in offline mode are planned. Here, EUMETSAT will continue to provide level 1b data, while further processing is performed at the GRAS SAF.

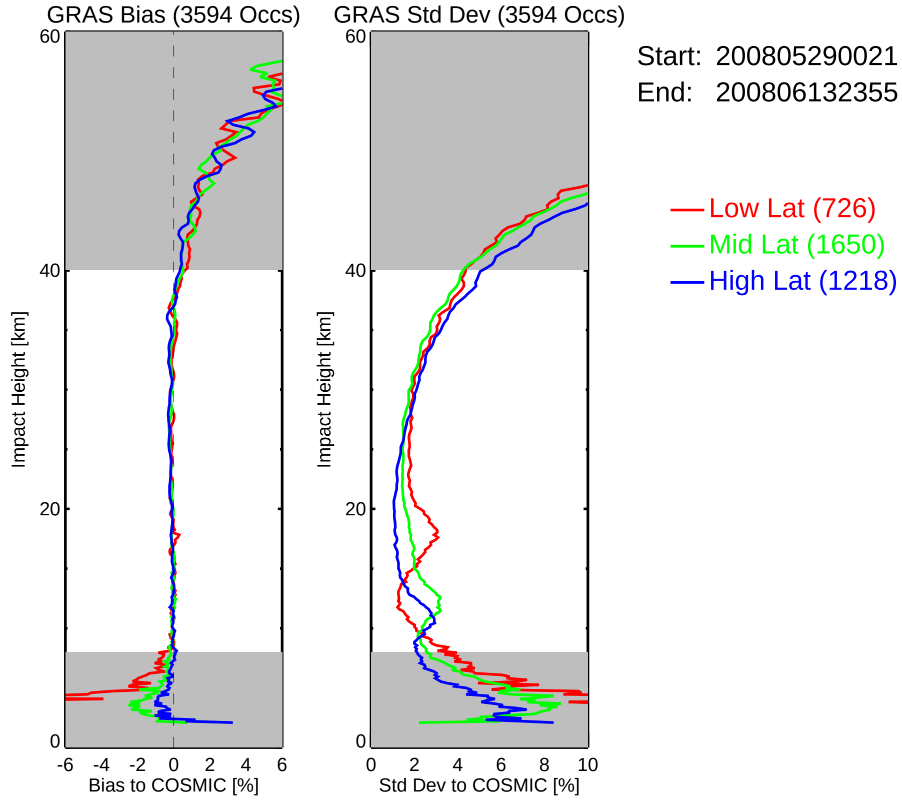

Figure 3: Operational GRAS PPF bending angles compared to co-located COSMIC profiles. Otherwise as Figure 1.

6 Conclusion

GRAS bending angle data is disseminated to world wide users since early 2008, and the processing achieved operational status in April 2008. Obtained bending angles agree very well with co-located ECMWF forward modeled data and also with COSMIC co-located profiles. The current processing does not include a wave optics algorithm to deal with multi-path regions, thus data validation has been restricted to altitudes ≥ 8 km. In addition, altitudes > 40 km are affected by approximations of the occultation antenna positions, showing up as a bias in bending angles. Future updates to the processor are expected to resolve these issues.

7 Future Radio Occultation Missions

As stated above, a GRAS instrument will be flying on 3 Metop satellites, up to at least 2019. Although all GRAS instruments are already build, there might arise a need to revisit requirements for the GRAS instrument on Metop-C since (1) the European constellation Galileo could provide further profiles a day; (2) the new GPS signal structure on L2 (so called L2C) could be further exploited; (3) updates to the GPS signal structures currently used on L1 and L2 that could endanger GRAS operations (mainly for times after 2020). But it also has to be kept in mind that changing an already build instrument will be costly.

Additionally, EUMETSAT is looking at the time scales beyond EPS with the future system Post-EPS; the above mentioned issues are relevant here. User needs for Post-EPS have been identified in so-called Position Papers, where each paper covers a specific areas. Radio occultation missions are taken into account in the relevant areas, e.g. atmospheric sounding. Please refer to [EUMETSAT, 2008] for updated information.

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