Validation of operational GRAS Radio Occultation Data

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GRAS RO (radio occultations) are validated against co-located ECMWF and COSMIC data and by ECMWF impact trials. We focus on closed-loop data at impact heights above 8 km. Results confirm the high GRAS quality and robustness, showing lower noise than COSMIC and more occultations per day/satellite. Mean differences to ECMWF and COSMIC from 18 km to 35 km show about 0.1 % smaller GRAS BAs (bending angles). Around 40 km, ECMWF shows on average about 1 % smaller BAs, which may be related to microwave radiances assimilation. Recent ECMWF updates, putting more weight on RO here, reduce this bias. COSMIC co-locations reveal smaller GRAS BAs up to about 50 km, probably partly caused by COSMIC smoothing; this is currently revised. ECMWF forecast trials show similar positive GRAS, COSMIC impacts for Southern latitudes standard deviations, although GRAS provides about 60 % fewer occultations. It also demonstrates that more RO instruments are beneficial, particularly for the tropics and Northern latitudes.

1. Introduction

The radio occultation (RO) instrument GRAS (GNSS (Global Navigation Satellite System) Receiver for Atmospheric Sounding) was launched on-board of the Metop-A satellite on 19. October 2006; GRAS was activated on 27. October 2006. Satellite and instrument are part of the EPS (EUMETSAT Polar System) [*Klaes et al.*, 2007]; it is EUMETSAT's (European Organisation for the Exploitation of Meteorological Satellites) first LEO (Low-Earth-Orbit) satellite. In total, there will be 3 Metop satellites, each with an expected life-time of 5 years. EPS should 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.

The EPS is designed for operational data provision, thus observations are rapidly made available to users. The requirement on timeliness is availability to users within 2.25 hours after sensing time. Each orbit of data (about 100 minutes) is down-linked over the Svalbard Archipelago (78° N), processed in the CGS (Core Ground Segment) at EUMETSAT, and disseminated to users. Users include e.g. NWP (Numerical Weather Prediction) centers worldwide. The data are also processed further at the SAFs (Satellite Application Facilities), these are specialized development and processing centers in EUMETSAT's member states. The timeliness requirement on operational SAF products is 3 hours.

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GRAS has been specifically designed for RO observations [*Kursinski et al.*, 1997; *Luntama et al.*, 2008], observing setting and rising occultations from the GPS (Global Positioning System) satellite constellation. Data are operationally assimilated into the ECMWF (European Centre for Medium Range Weather Forecasts) model since May 2008. Within this work, we validate recent GRAS measurements with co-located COSMIC (Constellation Observing System for Meteorology, Ionosphere & Climate) ROs [*Anthes et al.*, 2000], ECMWF profiles, and ECMWF forecast impact trials. 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, and Section 5 concludes and gives an outlook.

2. Instrument, Processing, Dissemination

The GRAS RO instrument can track up to 8 GPS satellites on the zenith antenna for precise orbit determination. For occultation measurements, velocity and anti-velocity antennas are each able to track 2 GPS satellites simultaneously. The current GPS constellation of around 30 satellites yields about 650 occultations per day. GRAS is capable of tracking in closed-loop (at 50 Hz) and in raw sampling / open-loop mode (at 1000 Hz). Tracking is performed from the lowest part of the atmosphere up to about 80 km.

The GRAS PPF (Product Processing Facility) processes the data up to so-called level 1b in the CGS, the main products are BA (bending angle) over impact parameter, geolocation, time, type of measurement. The first processing step, which is operating on 60 s of zenith data, determines the Metop orbit with the SRIF (Square-Root Information Filter). Additionally, precise GPS orbits and clock offset estimates are required (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 along track velocity at 1 Hz; for further information see *Martinez et al.* [2007]; *Montenbruck et al.* [2008].

The BA processing of the currently operational PPF uses only closed-loop data where both GPS frequencies are tracked, no raw sampling data are processed operationally. BAs are not optimized with a climatology, since refractivity processing, which requires a high altitude initialization, is performed at the GRAS SAF. BAs are based on zero differencing and the geometrical optics assumption, see e.g. *Kursinski et al.* [1997]. Thus data below about 8 km impact height is degraded since it requires advanced multi-path algorithms, in particular at lower latitudes with abundant water vapor. The operational BAs requirements are 1 μrad or 0.4 % (which ever is larger) RMS accuracy with no systematic biases [*Luntama et al.*, 2008].

Dissemination of GRAS data are performed through EUMETCast (EUMETSAT's Broadcast System for Environmental Data) and GTS (Global Telecommunication System) in BUFR (Binary Universal Form for the Representation of meteorological data) and in EUMETSAT format (providing the full data set). Data are generally processed within 1.85 hours and then disseminated, well in requirements. All EPS data are also available offline from the U-MARF (Unified Meteorological Archive and Retrieval Facility) at EUMETSAT. For more information see http://www.eumetsat.int.

Processing from BAs to level 2 products (e.g. refractivity, temperature, water vapor profiles) is performed at the GRAS SAF with a timeliness requirement of 3 hours [*Lauritsen et al.*, 2008]. Please see http://www.grassaf.org for more information.

3. Data

The GRAS data used here have generally been obtained from the operationally running PPF node on the CGS. It covers more then 250 days from November 2008 to July 2009. The ECMWF co-located profiles are extracted from 12 h forecast fields, available in-house at times 00 UT and 12 UT, with a resolution of 0.5°, on 91 vertical hybrid levels. Vertical profiles at the nearest time are forward modeled to BAs using the freely available ROPP (RO Processing Package) developed at the GRAS SAF [*Offiler*, 2008]. The COSMIC files are obtained from the CDAAC (COSMIC Data Analysis and Archive Center, Boulder, USA) [*Kuo et al.*, 2004]; we use archived data from the NRT (Near-Real-Time) stream.

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

Forecast experiments comparing the impact of GRAS and COSMIC measurements have been performed with the ECMWF NWP system. The RO measurements have been assimilated into the four-dimensional variational assimilation system using a one-dimensional BA forward model [*Healy and Thépaut*, 2006], for the period June 1 to July 31, 2008. The assimilation experiments use all the non RO measurements used operationally during this period. Three configurations have been tested, assimilating 1) no RO data; 2) COSMIC only; 3) GRAS only. COSMIC measurements are assimilated from the surface to 50 km, whereas GRAS measurements are from 8 km to 50 km in the Northern (NL, 20N - 90N) and Southern latitudes (SL, 20S - 90S) and between 10 km and 50 km in the tropics (TR, 20S - 20N). Note that operational GRAS data from this period was processed with an earlier PPF version, but this update did not change the data quality in the upper-troposphere, lower/mid stratosphere, so it does not change the main forecast impact results given here.

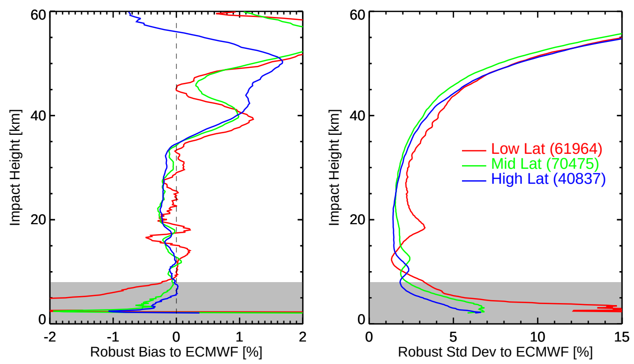

Figure 1. Bias (left) and standard deviation (right) of GRAS bending angles compared to co-located ECMWF profiles for different latitude bands. Brackets show number of occultations. Grey shaded area indicate region affected by multi-path.

4. Results

Figure 1 shows $(O-B)/B$ statistics, where O is the GRAS BA measurement and B the forward propagated ECMWF forecast. Deviations are shown in percent, although note this can be mis-leading at higher altitudes, e.g., average BAs at 60 km are about 5 μrad, thus the GRAS requirement of 1 μrad translates into an accuracy requirement of about 20 % at these impact heights. Data are separated into 30° latitude bands and evaluated at each impact height altitude, using a robust estimator (Tukey's biweight [*Hoaglin et al.*, 1983]). This estimator is an effective tool to deweight outliers from noisy distributions, returning standard deviation and percentage of data points falling into the $\pm 2\,\sigma$ interval. This would be 95 % for an ideal Gauss curve, for GRAS it is about 92 %. Thus 3 % of the data have been deweighted by the robust statistics. In addition, about 2.5 % of all occultations did not provide a valid BA and are thus excluded.

The bias plot shows generally very good agreement for altitudes above 8 km, although the GRAS processing returns larger BAs starting at about 35 km when compared to ECMWF fields. Deviations seen between 35 km and 45 km are likely the result of an ECMWF bias, probably related to the bias correction applied to satellite radiance observations. Recent ECMWF data (from 10. March 2009) shows a reduction in this bias, because RO data up to 50 km is assimilated

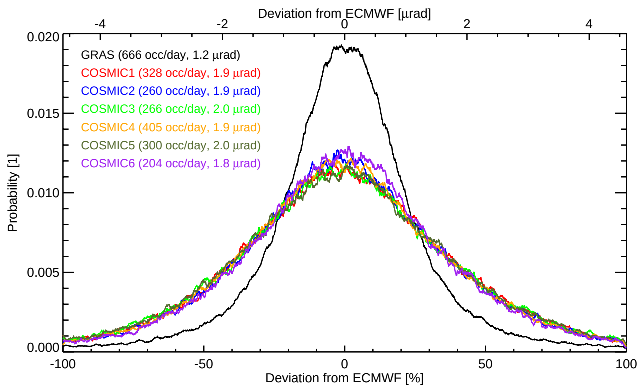

Figure 2. Probability density with respect to ECMWF model for GRAS and COSMIC satellites, average number of occultations / day and standard deviation given in brackets.

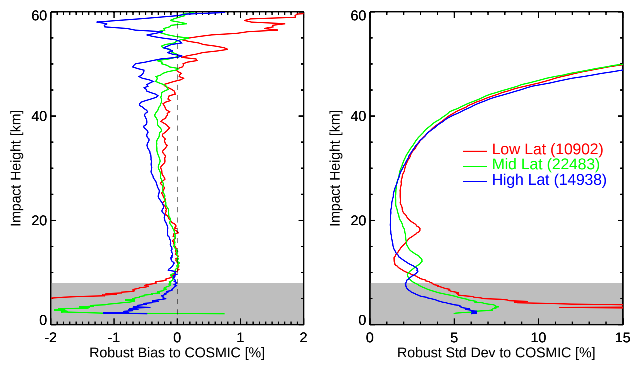

Figure 3. Bias (left) and standard deviation (right) of GRAS bending angles compared to co-located COSMIC profiles. Otherwise as Figure 1.

and BA errors are halved for data above about 30 km (prior to the update, a maximum in bias of about 1.4 % at 40 km is observed, which is reduced to about 0.7 %). Small negative biases from about 18 km to 35 km are currently under investigation at ECMWF. COSMIC data also show a systematic difference to GRAS data in this altitude range (see Figure 3), but even GRAS only assimilation trials show this bias, hence it is not caused by COSMIC data assimilation. Also visible is the impact of water vapor / multi-path on the processed data, where low latitudes show a larger deviation from ECMWF at altitudes below about 8 km. Standard deviations clearly show the tropopause region, in particular at low latitudes. Here, gravity waves that are not fully represented in the ECMWF model could cause this observed increase.

For the investigated period, almost 1800 COSMIC occultations are available on average per day. Although this shows a fair amount of variation, with a standard deviation of more than 20 % (GRAS has 3.5 %). Matching these occultations within ≤ 3 hours and ≤ 300 km provides on average almost 190 occultations per day (standard deviation of 22 %). Not all matches are unique, on average about 30 GRAS profiles per day are matched with more than 1 COSMIC profile.

Figure 2 compares the GRAS, COSMIC noise levels around 60 km altitude directly by visualizing the probability density of the deviation to the ECMWF model. It clearly shows the superior GRAS noise characteristics, caused by e.g. zero differencing (COSMIC uses single differencing) and the high gain occultation antennas. GRAS requirements are expressed in RMS accuracy which translates into a standard deviation of about 0.7 μrad. The shown one is 1.2 μrad, although this includes ECMWF contributions. These are difficult to remove since mesospheric temperature errors are hard to estimate. The average number of occultations per day shows fairly large variability among COSMIC spacecrafts from about 200 to 400, although they should all be able to track similar numbers, on average GRAS yields about as many as 2 COSMICs.

Figure 3 shows the robust bias and standard deviation of the matched data set. The bias agreement is good for altitudes above 8 km, the deviations seen around 35 km to 40 km against ECMWF (Figure 1) are not present here, confirming that this is an ECMWF bias. Nevertheless, an average bias of about 0.1 % to 0.2 % is found for altitudes from about 20 km to 50 km, although at high latitudes it can reach about 0.5 %. Further investigations by the GRAS and the COSMIC teams identified the COSMIC phase smoothing as a likely cause. GRAS processing uses a Savitzky-Golay filter while COSMIC uses a Gaussian filter (S. Sokolovskiy, COSMIC team, personal communication, 2009). Processing of COSMIC data at EUMETSAT has shown that the Gaussian filter introduces similar biases. The COSMIC team is currently in the process of updating their operational setup, which should bring the two RO instruments into even better agreement. Closer matches (≤ 1 hours, ≤ 100 km - on average, about 14 matches / day) do not change this bias, although standard deviations are reduced by more than 20 % at lower altitudes. This found reduction in particular around the tropopause could indicate that closer matches are observing similar gravity wave structures. The increase in standard deviation around the tropopause is not introduced by the processing, as verified by processing COSMIC data at EUMETSAT.

Forecast impact trial results, verified against radiosonde observations, are shown in Figure 4 for different latitude bands. Note that data are separated here into NL, SL, TR in order to allow evaluation of the impact in data rich areas (NL, where a lot of radiosonde data are available), and areas where most information is provided by satellite data

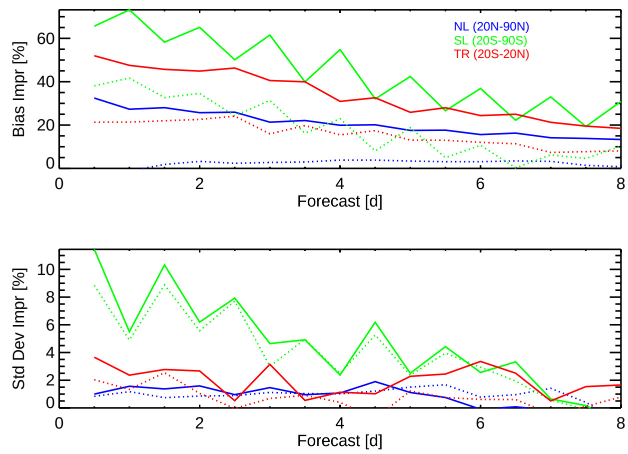

Figure 4. Forecast temperature bias (top) and standard deviation (bottom) improvement at 100 hPa of COSMIC only (solid) and GRAS only (dotted) over an assimilation run with no RO measurements, separated into different latitude bands.

(SL, TR). The main temperature improvement in bias and standard deviation is found at SL for COSMIC only as well as GRAS only. Regarding the SL standard deviation, COSMIC only and GRAS only results are very similar, although COSMIC provides about 3 times as many occultation. For SL and TR bias, the larger number of COSMIC observations roughly doubles the improvement, while in the NL more observations are needed; the GRAS only trial does not show an improvement. In NL and TR standard deviation, small improvements are visible.

One of the main RO characteristics is that they can be assimilated without bias correction, and they anchor the bias correction of satellite radiance measurements. In general, the stratospheric temperature biases against radiosonde measurements are largest in the "no RO" experiment and smallest in the COSMIC only experiment. GRAS is clearly improving the biases, however these results indicate that more than one instrument is beneficial.

5. Conclusion and Outlook

GRAS BA data are disseminated operationally since April 2008, it is generally available within less than 2 hours from sensing time. Obtained BAs agree very well with co-located ECMWF and COSMIC profiles for altitudes ≥ 8 km. Currently, ECMWF and COSMIC data show a bias of about 0.2 % in the altitude range from about 18 km up to about 35 km (for ECMWF) and 50 km (for COSMIC). COSMIC data processing using a phase filter as also used on GRAS data reduces the bias against COSMIC. An updated processing algorithm is under development at the COSMIC team. Around 40 km, an average bias of about 1 % is observed in validation against ECMWF data, probably caused by insufficient instrument information for the bias correction of radiance observations at ECMWF. Noise evaluations of GRAS and COSMIC around 60 km show about 40 % lower noise in GRAS measurements.

Forecast impact trials show improvements in a GRAS only setup, in particular for Southern latitudes. But it also shows that more RO instruments are beneficial, in particular for Northern latitudes and the tropics.

For the near future, an update to the available GPS satellites provided by GSN is under way, this should increase the number of occultations by about 3 %. The longer term development will focus on PPF upgrades to deal with raw sampling data and multi-path regions by using wave optics calculation, first results are expected by mid-2009. Improvements to quality control through the use of variational assimilation [*Marquardt et al.*, 2005] are also planned. Additionally, improved orbit processing is under investigation. The currently used SRIF setup can lead to a drifting Metop clock solution, which appears as a bias with opposite sign for setting and rising occultations. On average, this is 2.3 % at 60 km altitude and about 0.25 % at 40 km. It is still within the GRAS requirements, nevertheless, such a bias will affect the quality of climate products derived offline. More stable orbit processing setups are currently being developed, these use larger data segments. This setup will be used for climate processing and is also being considered for the NRT setup.

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References

Anthes, R., C. Rocken, and Y. Kuo, Applications of COSMIC to meteorology and climate, *Terr. Atmos. Oceanic Sci.*, *11*(1), 115–156, 2000.

Healy, S., and J.-N. Thépaut, Assimilation experiments with CHAMP GPS radio occultation measurements, *Quart. J. Roy. Meteor. Soc.*, *132*(615), 605–623, 2006.

Hoaglin, D., F. Mosteller, and J. Tukey, *Understanding Robust and Exploratory Data Analysis*, John Wiley & Sons, 1983.

Klaes, K., et al., An introduction to the EUMETSAT polar system, *Bull. Amer. Meteor. Soc.*, *88*(7), 1085–1096, doi: 10.1175/BAMS-88-7-1085, 2007.

Kuo, Y.-H., T. Wee, S. Sokolovskiy, C. Rocken, W. Schreiner, D. Hunt, and R. Anthes, Inversion and error estimation of GPS radio occultation data, *J. Met. Soc. Japan*, *82*(1B), 507–531, 2004.

Kursinski, E., G. Hajj, J. Schofield, R. Linfield, and K. Hardy, Observing Earth's atmosphere with radio occultation measurements using GPS, *J. Geophys. Res.*, *102*(D25), 23,429–23,465, 1997.

Lauritsen, K., H. Gleisner, M. Gorbunov, F. Rubek, S. Syndergaard, and M. Sorensen, GRAS SAF project and products, in *ECMWF GRAS SAF Workshop on Applications of GPS Radio Occultation Measurements, 16 - 18 June 2008*, ECMWF, Reading, UK, 2008.

Luntama, J.-P., G. Kirchengast, M. Borsche, U. Foelsche, A. Steiner, S. Healy, A. von Engeln, E. O'Clerigh, and C. Marquardt, Prospects of the EPS GRAS mission for operational atmospheric applications, *Bull. Amer. Meteor. Soc.*, *89*(12), 1863–1875, 2008.

Marquardt, C., S. Healy, J.-P. Luntama, and E. McKernan, GRAS level 1b product validation with 1D-Var retrieval, *Tech. rep.*, EUMETSAT, technical Memorandum No.12, 2005.

Martinez, F., A. Agueda, and F. Sancho, GRAS NRT precise orbit determination: Operational experience, in *Proceedings of the 20th International Symposium on Space Flight Dynamics*, NASA/CP-2007-214158, NASA, USA, 2007.

Montenbruck, O., et al., Tracking and orbit determination performance of the GRAS instrument on MetOp-A, *GPS Solutions*, doi:10.1007/s10291-008-0091-2, 2008.

Offiler, D., The radio occultation processing package (ROPP) an overview, *Tech. rep.*, GRAS SAF, Document-No: SAF/GRAS/METO/UG/ROPP/001, 2008.

Zandbergen, R., and J. Dow, Sounding the atmosphere - ground support for GNSS radio-occultation processing, *ESA Bulletin*, *126*, 48–53, 2006.

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