Atmos. Meas. Tech. Discuss., 4, 1061–1077, 2011
www.atmos-meas-tech-discuss.net/4/1061/2011/
doi:10.5194/amtd-4-1061-2011

Atmospheric Measurement Techniques Discussions

Processing of GRAS/METOP radio occultation data recorded in closed-loop and raw-sampling modes

M. E. Gorbunov[1,2], K. B. Lauritsen[2], H.-H. Benzon[2], G. B. Larsen[2], S. Syndergaard[2], and M. B. Sørensen[2]

[1]A. M. Obukhov Institute for Atmospheric Physics, Moscow, Russia
[2]Danish Meteorological Institute, Copenhagen, Denmark

Received: 3 February 2011 – Accepted: 7 February 2011 – Published: 15 February 2011

Correspondence to: M. E. Gorbunov (m_e_gorbunov@mail.ru)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Instrument GRAS (Global Navigation Satellite System Receiver for Atmospheric Sounding) on-board of the Metop-A satellite was activated on 27 October 2006. Currently, Metop-A is a fully operational satellite with GRAS providing from 650–700 measurements per day. We describe our processing of GRAS data based on our OCC software, which was modified to become capable of reading and processing GRAS data. We perform a statistical comparison of bending angles and refractivities derived from GRAS data with those derived from ECMWF analyses. We show that GRAS data have error characteristics close to those of COSMIC data. In the height range 10–30 km, the systematic refractivity difference GRAS-ECMWF is of the order of 0.1–0.2%, and the standard deviation is 0.3–0.6%. In the lower troposphere GRAS refractivity and bending angle indicate a negative bias, which reaches its maximum value in the tropics. In particular, the retrieved refractivity is biased by up to 2.5%. The negative bias pattern is similar to that found in the statistical validation of COSMIC data. This makes it probable that the bias should not be attributed to the instrument design or hardware.

1 Introduction

The instrument GRAS (Global Navigation Satellite System Receiver for Atmospheric Sounding) is a new generation instrument for the radio occultation (RO) sounding of the Earth's atmosphere. The instrument was launched by EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) on-board of the Metop-A satellite on 19 October 2006 and activated on 27 October 2006 (von Engeln et al., 2009; Bonnedal et al., 2010). GRAS was designed for observing setting and rising occultations from the GPS (Global Positioning System) satellite constellation. Measurements are performed in closed-loop (CL) and raw-sampling (RS) modes (Luntama et al., 2008; Bonnedal et al., 2010). From the processing view point, these modes

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are similar to phase-locked loop (PLL) and open-loop (OL) modes implemented in Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) (Rocken et al., 2000; Sokolovskiy et al., 2009).

Both in COSMIC and in GRAS, CL measurements are performed with 50 Hz sampling rate. CL mode is suitable for measurements with weak fluctuations of the phase. In processing of CHAMP and COSMIC data it was found that CL mode provides a good quality of measurements above 7–11 km in the tropics (Gorbunov and Kornblueh, 2003; Sokolovskiy et al., 2009). In the lower troposphere in the tropics the signal undergoes strong scintillations of both amplitude and phase, which degrades the quality of signal tracking and results in the increase of retrieval errors. This effect is weaker in middle latitudes. In polar latitudes, it is possible to perform retrievals using the CL mode down to the Earth's surface. In the CL mode, the receiver typically uses a two-quadrant detector, which is insensitive to the sign of the signal (or to the change of the phase by π radian) (Beyerle et al., 2003). This allows for automatically removing the signal modulation by the navigation bits, but results in the loss of half-cycles if the phase variations between samples exceed $\pi/2$ radian.

Measurements in the OL mode in COSMIC are also performed at a sampling rate of 50 Hz. In the OL mode, the signal frequency is down-converted by an oscillator numerically controlled by a phase model independent from the measured signal, i.e. without the feed-back. Because it is always possible to provide a phase model predicting the Doppler frequency of the signal with an accuracy of 10–15 Hz, the 50 Hz sampling rate is sufficient for the correct retrieval of the signal phase (Sokolovskiy et al., 2009). Measurements in the OL mode are performed by a four-quadrant detector, which can measure phase in the full range from 0 to 2π radian. However the removal of the navigation bits becomes a problem, which is resolved by collecting them from ground-based stations (Sokolovskiy et al., 2009). This is termed external demodulation. Another possibility is to use an internal demodulation algorithm, which is based on the identification of the phase jumps by π radian. The internal demodulation only works if the phase variation between the samples does not exceed $\pi/2$ radian. Otherwise it

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results in the loss of half-cycles and the degradation of the retrieval quality (Sokolovskiy et al., 2009).

Unlike the OL mode in COSMIC, the RS mode in GRAS employs a 1 kHz sampling rate. This makes the internal demodulation of the navigation bits easier, because the phase variation between signal samples is much smaller than for the 50 Hz sampling rate.

In this paper we describe our processing of offline GRAS data and present the statistical comparisons of bending angles and refractivities retrieved from GRAS observations with the ECMWF analyses. We show that GRAS data have a quality comparable to that of COSMIC data.

2 The data processing

For processing GRAS data we modified the OCC software (Gorbunov et al., 2011). We added modules for the automatic recognition and reading of GRAS data files. As the first step the following variables are obtained from the files: the GPS and Metop coordinates in the Earth's centered inertial frame, amplitudes and phase excesses for L1 and L2, and navigation bits. The satellite coordinates, amplitudes, and phase excesses are organized as two separate records: CL and RS. Navigation bits are only recorded for RS mode. The files contain two types of navigation bits: external, obtained from the ground-based stations, and internal, obtained from the phase by identifying the phase jumps by π radian between samples.

In most cases, CL and RS records overlap. When RS mode is active, both RS and CL records only contain L1 data. We implemented two modes of merging CL and RS data: (1) use CL data only and (2) use the complete RS record complemented with CL data where no RS data are present (RS + CL). Below we present a comparison of refractivity retrievals for both merging modes. The merged data are re-sampled with a uniform sampling rate, which can be specified by the user. For example, if in the

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RS + CL merging mode 1 kHz re-sampling is requested, then the RS data keep their full sampling rate, and the CL data are up-sampled at 1 kHz.

The data processing algorithm follows the guidelines described in (Gorbunov et al., 2006, 2011). The main steps include: (1) quality control and extrapolation of missing L2 where RS mode is active, (2) combination of bending (refraction) angle retrieval based on geometric optics (GO) above 25 km and wave optics below 25 km (using the CT2 algorithm introduced by Gorbunov and Lauritsen (2004)), (3) ionospheric correction combined with the statistical optimization (Gorbunov, 2002a), (4) standard refractivity retrieval by the Abel inversion, and 5) dry temperature retrieval.

3 Results

Figure 1 shows an example of the spectrogram of RO data (Hocke et al., 1999; Gorbunov, 2002b) indicating a reflection from the ocean surface combined with minor atmospheric multipath propagation effects. Reflected rays form the almost horizontal branch of the bending angle profile near the impact height of 2 km. The bending angle profile below 2 km is not related to the atmosphere, because it is obtained from the phase model used to fill in the area where the receiver was unable to track the signal. This part of the profile is discarded in the inversion. Multipath propagation results from a non-monotonic bending angle profile near the impact height of 2.7 km. Figure 2 shows a similar example where reflection is combined with stronger multipath effects. Figure 3 shows an example with very strong multipath effects resulting in a wide-band signal. These selected cases demonstrate the ability of the GRAS instrument to correctly measure RO signals in presence of multipath induced both by the atmospheric conditions and the Earth's surface reflections.

Figure 4 shows the statistical comparison of raw bending angles obtained from offline GRAS data using the RS + CL merging mode with the bending angles obtained by means of the GO forward modeling from the analyses of the European Center for Medium-Range Weather Forecast (ECMWF). Raw bending angles are defined as the

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linear combination of L1 and L2 bending angles (Vorob'ev and Krasil'nikova, 1994) without statistical optimization. Raw bending angles are independent from any background information. The comparison is based on 14250 RO events observed during 30 September and 1–27 October 2007. The systematic difference GRASECMWF does not exceed 0.3% in the height range 6–38 km in all latitude bands, with one exception: Around 16 km in the tropics it reaches 0.5%. This behavior is explained by the sharp tropopauses unresolved by the filter window of 2 km used in our data processing. Larger biases above 38–44 km are attributed to ECMWF analyses. Bending angles below 4–5 km are characterized by a negative bias (Sokolovskiy et al., 2010; Gorbunov et al., 2010, 2011; Marquardt et al., 2011) which has the highest magnitude of 6% in the tropics. The mid-latitudes indicate a moderate negative bias of 3%, in the polar region it almost disappears. Possible mechanisms responsible for the negative bias were discussed by Sokolovskiy et al. (2010) and Gorbunov et al. (2010).

Figure 5 shows the statistical comparison of refractivities retrieved from GRAS (RS + CL) data with the ECMWF analyses. The comparison is shown in the height range of 0–30 km. Above 35–45 km the residual error of the ionospheric correction becomes comparable with the weather variations of refractivity. The choice of the background atmospheric model used for the statistical optimization (Gorbunov, 2002a) is referred to as the initialization. In particular, in this study we were using bending angle profiles computed from the MSIS climatology and subjected to two-parameter fitting (Lohmann, 2007). Below about 30 km retrieved refractivities are almost insensitive to the initialization. The systematic differences and standard deviations GRASECMWF are very close to those of COSMIC data (Gorbunov et al., 2011; Marquardt et al., 2011). The results presented in Figs. 4 and 5 were obtained for the external navigation bits removal. Similar statistics computed with the internal navigation bits removal results in a negligible difference from these figures.

Figure 6 shows the statistical comparison of refractivities retrieved from GRAS CL data with the ECMWF analyses. The comparison is based on 506 RO events observed during 30 September 2007. The CL data have does not penetrate as deep as the RS data (Fig. 7). In the tropics, a negative bias is observed below 8 km, while RS data only indicate a negative bias below 2 km. In the mid-latitudes the bias is observed below a height of 4.5 km, and in the polar latitudes it is observed below 3 km. In the polar latitudes, the bias has a magnitude of 0.5%, which significantly exceeds the value of around 0.1% obtained for RS data.

4 Conclusions

GRAS is a modern instrument for RO measurements. For sounding the lower troposphere raw-sampling (RS) mode is implemented, which allows for accurate measurements of wave fields with strong multipath effects. The 1 kHz sampling rate activated in the RS mode allows for the accurate removal of the navigation message even in the absence of externally supplied navigation bits. The error characteristics of retrieved refractivity are similar to those of COSMIC measurements. The retrievals indicate the same pattern of a negative bias in the lower troposphere. Because two different instruments have similar negative bias, it is most probable that the bias should not be attributed to the instrument design or hardware. Further research should concentrate on the mechanisms resulting in the negative bias discussed by Sokolovskiy et al. (2010) and Gorbunov et al. (2010): the negative bias may result from the systematic loss of large bending angle peaks due to cut-off, contamination with noise and impact parameter variations along the ray path resulting from horizontal gradients of refractivity.

Metop-A is a fully operational satellite with GRAS providing from 650–700 measurements per day. COSMIC is another advanced, semi-operational system for RO sounding of the Earth's atmosphere. It has six LEO satellites implemented with receivers capable of performing measurements in open-loop mode with 50 Hz sampling rate. COSMIC also includes a network of ground stations providing navigation bits. Initially, COSMIC performed about 1500–2500 RO soundings per day. Currently, the number of soundings per day is decreasing, which is linked to the declining system health, and the COSMIC lifetime is expected to be a matter of one or two more years. Since the

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CHAMP mission does not exist any more, this indicates the importance of launching follow-up satellite missions that can provide RO measurements, which belong to important sources of information about the state of the Earth's atmosphere to be used in numerical weather prediction and climate monitoring. The GRAS instrument with its raw sampling mode meets the high standards defined by COSMIC.

Acknowledgements. The offline GRAS data used in this study was provided by EUMETSAT and the analysis fields by ECMWF. We appreciate the discussions with Magnus Bonnedal, Christian Marquardt, and the whole GRAS RO Performance Study team represented by RUAG Space, EUMETSAT, Wegener Center at University of Graz, and GFZ Potsdam. This work was performed under ESA contract no. 21995/08/NL/EL. M.E.G. was also supported by the Russian Foundation for Basic Research (grant No. 09-05-00180-a). K.B.L. and S.S. were also supported by the GRAS Satellite Application Facility under EUMETSAT.

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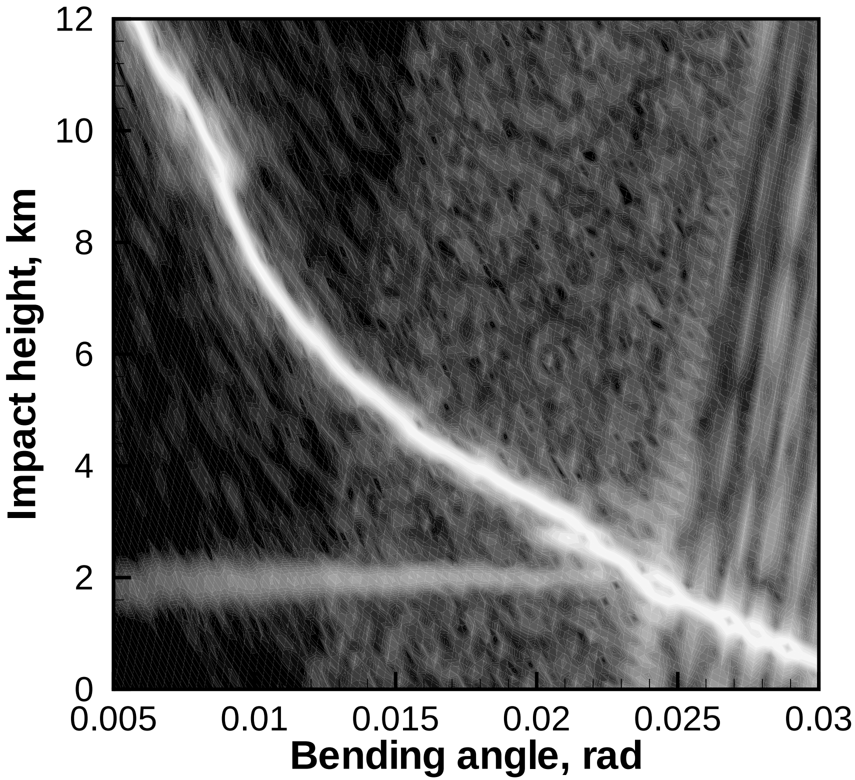

Fig. 1. Occultation event observed on 30 September 2007, 01:22 UTC, 56.72° S 3.53° E. Reflection and multipath over Atlantic Ocean.

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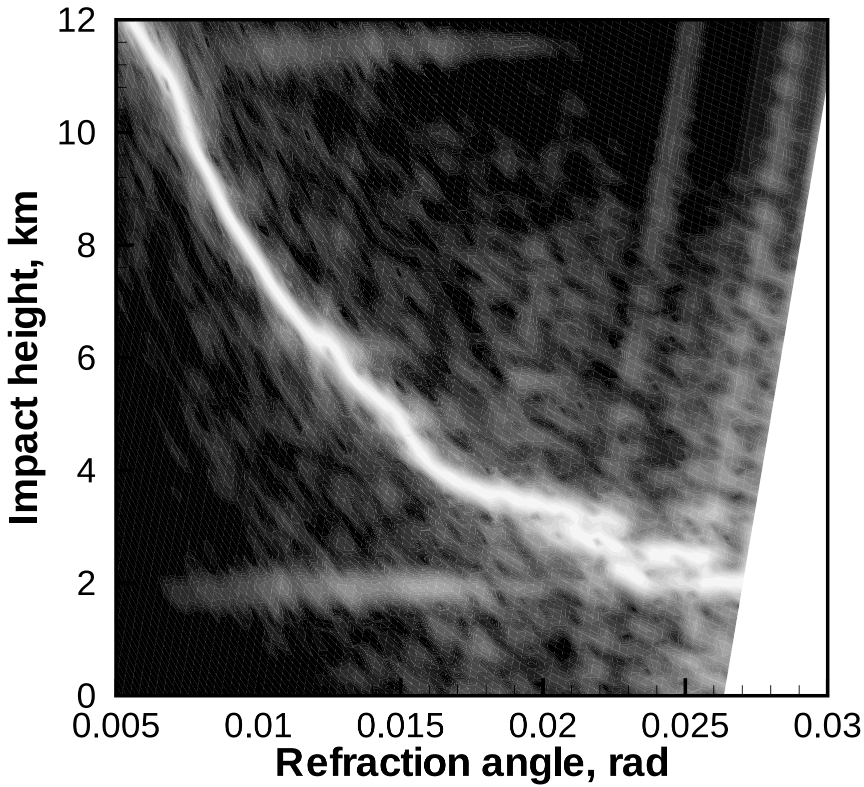

Fig. 2. Occultation event observed on 30 September 2007, 21:47 UTC, 65.93° S 87.20° E. Reflection and multipath near the Antarctic.

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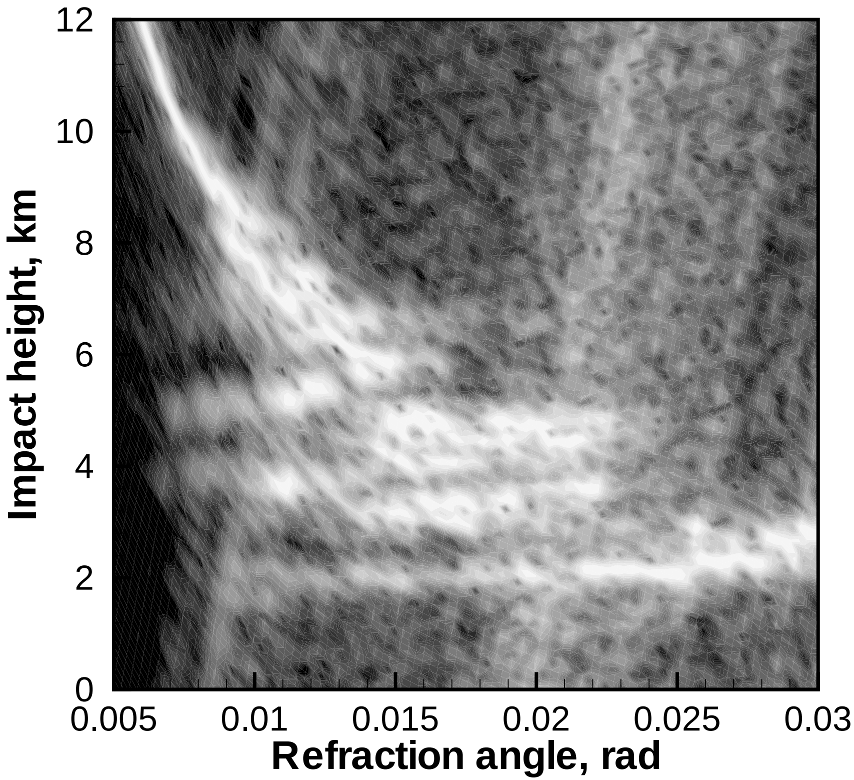

Fig. 3. Occultation event observed on 30 September 2007, 12:42 UTC, 45.37° N 29.34° W. Strong multipath over Atlantic Ocean.

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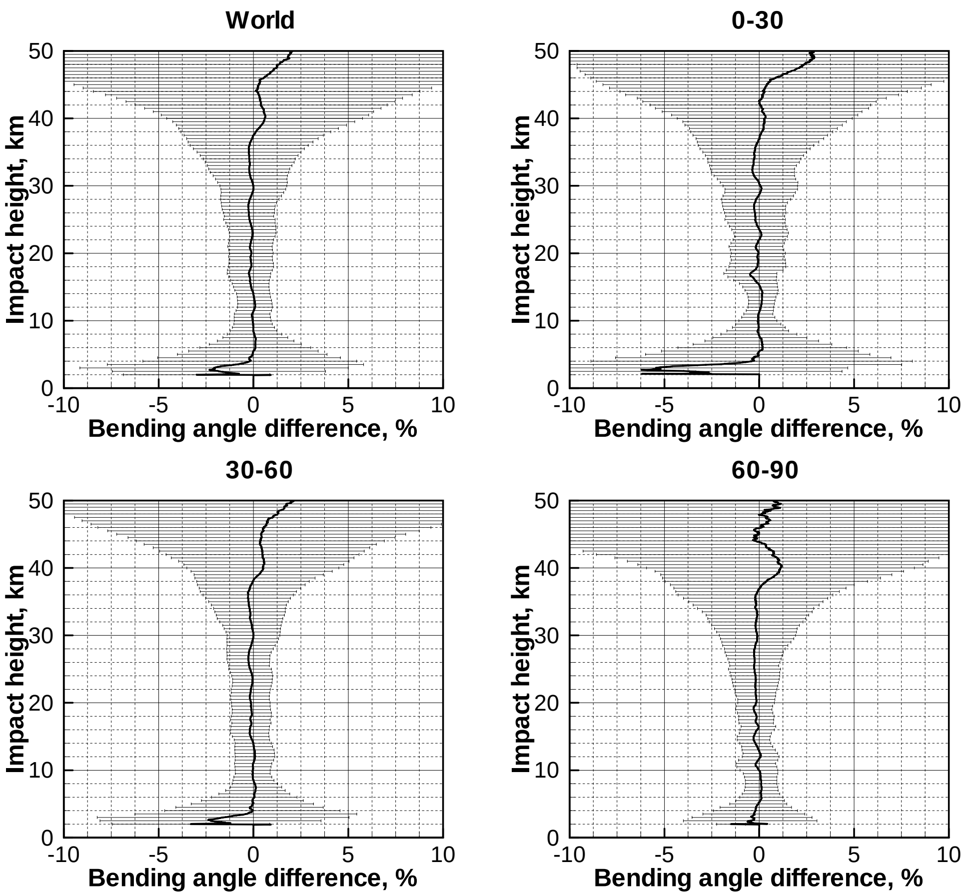

Fig. 4. Statistical comparison of GRAS RS + CL raw bending angles for October 2007 with bending angles obtained by the forward modeling from ECMWF analyses: the whole globe ("World"), tropics ("0–30"), mid-latitudes ("30–60"), and polar latitudes ("60–90").

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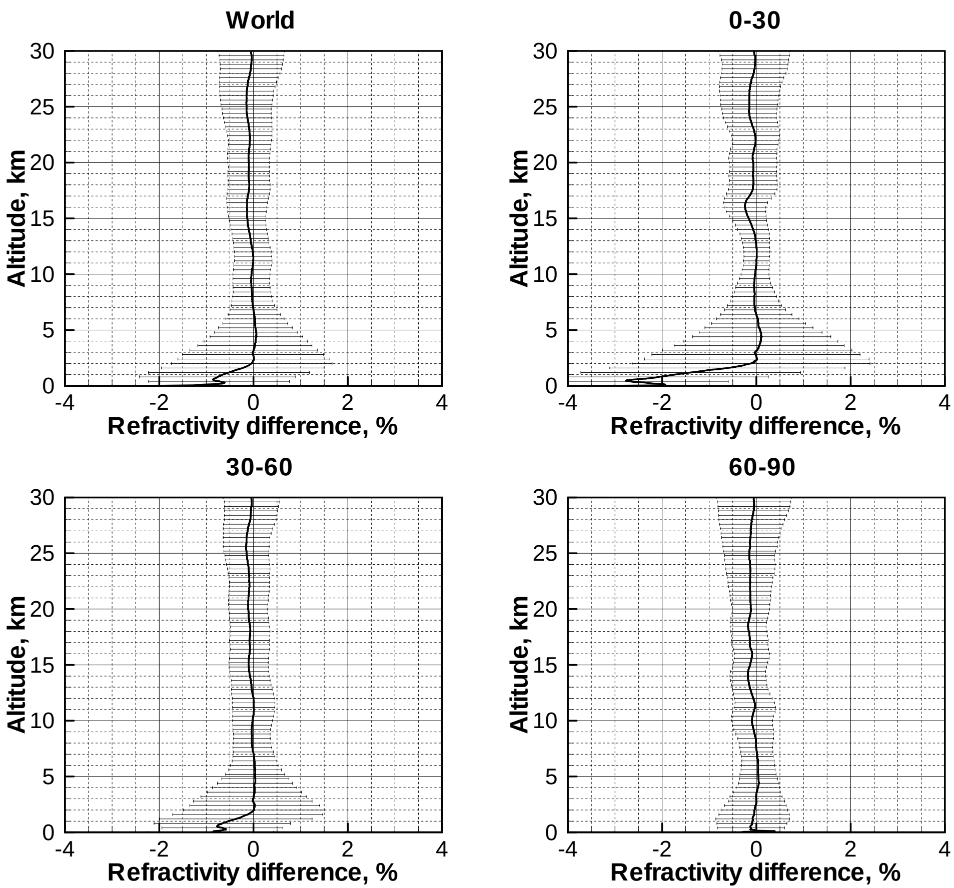

Fig. 5. tatistical comparison of GRAS RS + CL and ECMWF refractivities for October 2007: the whole globe ("World"), tropics ("0–30"), mid-latitudes ("30–60"), and polar latitudes ("60–90").

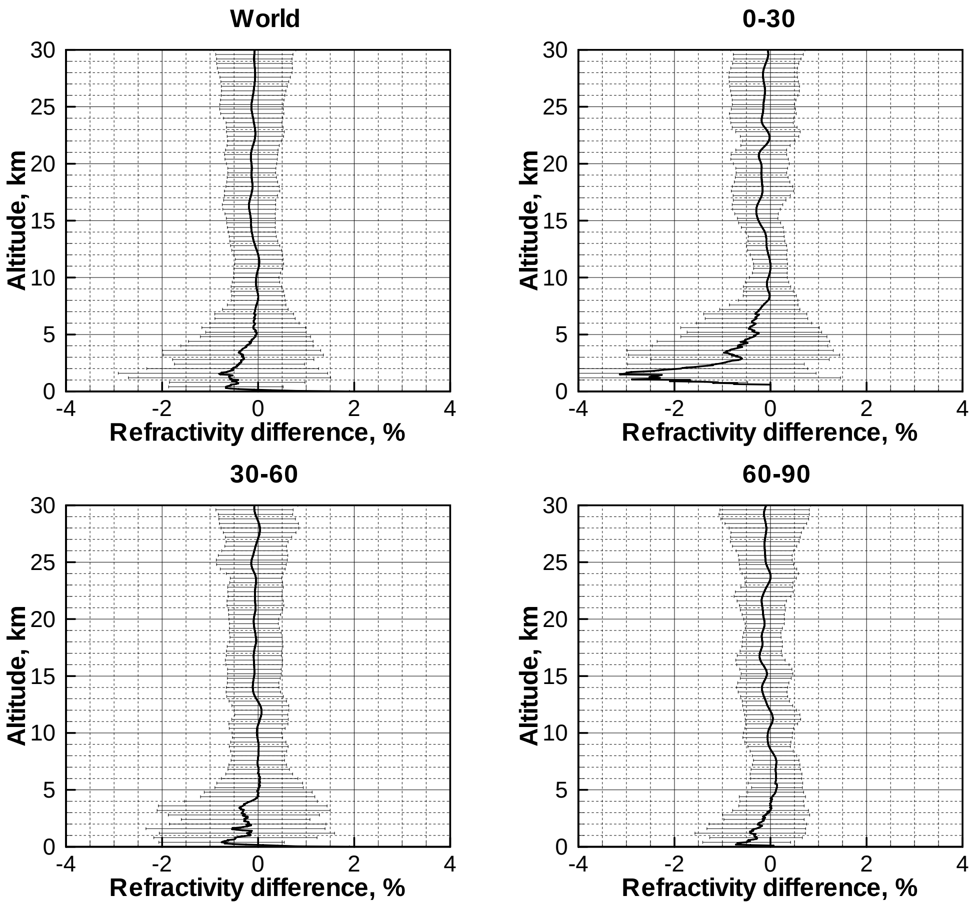

Fig. 6. Statistical comparison of GRAS CL and ECMWF refractivities for 30 September 2007: the whole globe ("World"), tropics ("0–30"), mid-latitudes ("30–60"), and polar latitudes ("60–90").

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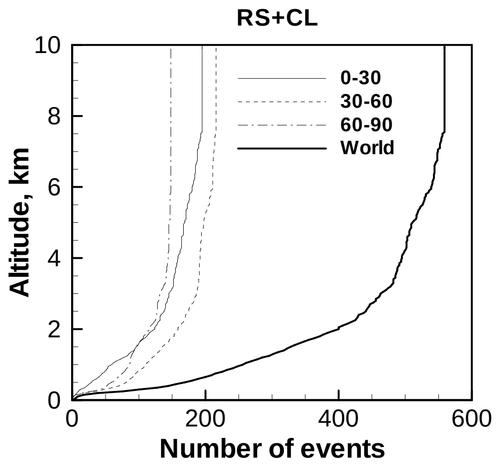

Fig. 7. Penetration depth for RO events observed on 30 September 2007 and processed in the RS + CL (left panel) and CL (right panel) merging modes: the whole globe ("World"), tropics ("0–30"), mid-latitudes ("30–60"), and polar latitudes ("60–90").

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