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Evaluation of Stratospheric Radio Occultation Retrieval Using Data from CHAMP, MIPAS, GOMOS, and ECMWF Analysis Fields

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Abstract. Two radio occultation (RO) retrieval schemes designed at IGAM to enhance the performance at high altitudes are presented, applied to CHAMP RO data, and validated against ECMWF analyses, GFZ operational retrieval, ENVSAT/MIPAS-, and ENVIAT/GOMOS-derived temperature profiles. IGAM proposes to include background information into the RO retrieval only at one point at bending angle level in order to be able to track error characteristics of the retrieved product. The results show very good agreement with GFZ retrieval and ECMWF analysis below 15 km and, depending on the background information used, either a significant warm bias or essentially no bias up to 30 km. Compared to MIPAS, the only independent data source, the IGAM/ECMWF retrieval is unbiased up to 40 km.

Key words: CHAMP, MIPAS, GOMOS, ECMWF, radio occultation, retrieval, statistical optimization, validation

1 Introduction

Current Global Navigation Satellite System (GNSS) radio occultation (RO) retrieval techniques yield excellent results on refractivity, geopotential height (or pressure), and temperature in the upper troposphere and lower stratosphere. Above 30 km, throughout the upper stratosphere, the errors of the retrieved parameters increase significantly. There are two prominent pathways to enhance retrieval quality in the stratosphere: to increase the signal-to-noise ratio by building better GNSS receivers and developing better ionospheric correction algorithms (ionospheric noise is the major error source at high altitudes) and to utilize statistical optimization techniques invoking background information. This paper describes how background information is used at IGAM to improve RO retrieval algorithms in the stratosphere (Sect. 2), presents results retrieved from CHAMP RO data and evaluates these results in comparison with various other data sources (Sect. 3). The interpretation of results is given in Sect. 4.

2 IGAM Retrieval Schemes

The basic idea of including background information into RO retrieval is to stabilize two integrals involved: The inverse Abel transform (Eq. 1, n: refractive index, α: bending angle, a: impact parameter) to derive refractivity N (N=10^6(n-1)) and the hydrostatic integral (Eq. 2, p_d: dry pressure, g: acceleration of gravity, k_1 = 77.60 K hPa^{-1}, R = 8.3145 kJ K^{-1} kg^{-1}, M_d = 28.964 kg kmol^{-1}) to derive pressure from refractivity. Dry temperature is proportional to p_d/N. Both equations are responsible for downward propagation of errors during the RO retrieval. To keep these errors minimal the concept of statistical optimization was introduced into the field of RO retrieval [1]. It derives the best linear unbiased estimator (BLUE, Eq. 3), $\boldsymbol{\alpha}_{opt}$, from an observed ($\boldsymbol{\alpha}_o$) and a background ($\boldsymbol{\alpha}_b$) bending angle profile under the assumption of unbiased Gaussian errors. **O** and **B** are the observation and background error covariance matrices, respectively.

$$n(a) = \exp\left[\frac{1}{\pi}\int_a^\infty \frac{\alpha(a')}{\sqrt{a'^2 - a^2}}\mathrm{d}a'\right] \quad (1)$$

$$p_d(r) = \frac{M_d}{k_1 R}\int_r^\infty g(r')N(r')\mathrm{d}r' \quad (2)$$

$$\boldsymbol{\alpha}_{opt} = \boldsymbol{\alpha}_b + \mathbf{B}(\mathbf{B}+\mathbf{O})^{-1}(\boldsymbol{\alpha}_o - \boldsymbol{\alpha}_b) \quad (3)$$

$\boldsymbol{\alpha}_{opt}$ is a fused bending angle profile dominated by background information in the upper part and by the observation in the lower part. Though most recent retrieval schemes initialize the hydrostatic integral with a pressure value derived from a temperature guess at 40 – 50 km, this is not necessary if the refractivity profile derived from Eq. 1 reaches high enough (~120 km). The IGAM retrieval schemes integrate background information only at one point of the retrieval (at bending angle level), so that the results have well defined error characteristics. We implemented statistical optimization in two different ways, both relying on Eq. 3, but using different sources of background information and different ways of pre-processing of this information: IGAM/MSIS uses bending angle profiles extracted from the MSISE-90 climatology [2] and applies best-fit-profile library search and bias correction procedures [3] in order to diminish know biases in the climatology [4]. IGAM/ECMWF uses bending angle profiles derived from operational analyses of the European Center for Medium-Range Weather Forecasts (ECMWF). More details can be found in Tab. 1. Both schemes are geometric optics dry air retrievals. For moist retrieval (not used in this study), IGAM applies the 1D-Var approach [5] below 10 to 15 km.

Table 1: Technical overview of the IGAM RO retrieval schemes.

	IGAM/MSIS	IGAM/ECMWF
Outlier Rejection and Smoothing	"3σ" outlier rejection on phase delays and smoothing using regularization.	Like IGAM/MSIS
Ionospheric Correction	Linear combination of bending angles [6]. L2 bending angles < 15 km derived via L1-L2 extrapolation.	Like IGAM/MSIS
Bending Angle Initialization	Statistical optimization of bending angles 30–120 km. Vert. correlated background (corr. length L=6 km) and observation (L=1 km) errors. Obs. error estimated from obs. profile >60 km. Backg. error: 15%. Backg. information: MSISE-90 best fit-profile, bias corrected [3].	Like IGAM/MSIS, but co-located bending angle profile derived from ECMWF operational analysis (above ~60 km: MSISE-90) as backg. information. No further pre-processing.
Hydrostat. Integral Init.	At 120 km pressure = p(MSISE-90).	Like IGAM/MSIS
Quality Control	Refractivity 5–35 km: $\Delta N/N$ <10%; Temperature 8–25 km: ΔT <25 K. Reference: ECMWF analysis.	Like IGAM/MSIS

3 Validation

Data from ECMWF analyses, the GFZ operational RO retrieval, MIPAS and GOMOS were used to validate the IGAM retrieval schemes using (dry) temperature profiles as retrieval performance indicator. The validation covers 11 days (~1750 profiles) in 2002 (20.9.-27.9., 11.10.-13.10.) and was performed by calculating error statistics profiles showing the bias and standard deviation between 5 and 40 km.

Comparisons with operational ECMWF analyses (Fig. 1) are a validation for the IGAM/MSIS scheme, but not for the IGAM/ECMWF (background information same as reference). In this case it still helps to interpret the retrieval performance. Wave-like bias patterns of both retrieval schemes between ~10 and 18 km reflect the better vertical resolution of the CHAMP profiles in the tropopause region. Both schemes feature 1-3 K standard deviation up to 25 km. IGAM/MSIS shows a significant warm bias from below 20 km upwards which is due to biases in the background information that could not be accounted for properly in that case and propagate downwards predominately via the hydrostatic integral. This warm bias could be observed in comparisons with GFZ operational retrieval, MIPAS, and GOMOS data as well (not shown) and shows how strong biased background information can influence the retrieved temperatures. However, validation studies at refractivity level (e.g., [7]) show that IGAM/MSIS- and RO-derived refractivity profiles in general are virtually independent from statistical optimization or high altitude initialization up to 30 – 35 km (no hydrostatic integration needed in this case).

The IGAM/ECMWF retrieved dry temperatures are virtually bias-free up to ~29 km, but warm biased by up to 2 K above which shows that they are not entirely dominated by background information up to above 40 km (Fig. 1b). The transition altitude from observation dominated to background dominated is around 50 km for the CHAMP RO data (not shown).

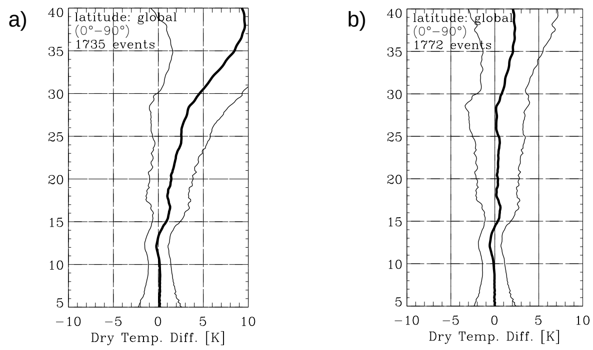

Figure 1: Bias (bold) and standard deviation (thin) of CHAMP dry temperatures compared to ECMWF operational analyses. a) IGAM/MSIS minus ECMWF, b) IGAM/ECMWF minus ECMWF.

Error statistics for the GFZ (operational retrieval version 4) and IGAM/ECMWF comparison are shown in Fig. 2a. Below 15 km, the agreement is excellent, the bias and standard deviation is smaller than 0.1 and 0.5 K, respectively. Above 15 km the bias stays below 0.3 K up to 26 km and below 1 K below 29 km, while the standard deviation increases to near 3 K. Above ~29 km, a warm bias qualitatively similar to the bias against ECMWF analyses can be observed, i.e., the GFZ retrieval follows ECMWF more closely than the IGAM/ECMWF retrieval. Both schemes use ECMWF analyses as background information, but in a different way: IGAM/ECMWF to generate the BLUE bending angle profile (GFZ uses MSISE-90-derived bending angle) and GFZ to initialize the hydrostatic integral at 43 km with ECMWF values.

The MIPAS instrument on ESA's ENVISAT is an independent data source for CHAMP retrieval validation. In Fig. 2b, the comparisons of coinciding MIPAS observations (retrieved by IMK) with IGAM/ECMWF is shown. Coincidences were defined to be less than 300 km and 3 h apart. The standard deviation amounts to ~5 K over the entire height range and is basically due to variance in the MIPAS data set. The most salient result is that no significant bias can be observed from 20 to 40 km, though the IGAM/ECMWF and the MIPAS retrieval are entirely independent and both not in agreement with ECMWF analyses above 30 km. From the GOMOS instrument on ENVISAT, temperature profiles are derived using time-delay signals from two fast photometers (retrieval by CNRS). This method is under development and yields only preliminary results so far. In Fig. 2c, IGAM/ECMWF-GOMOS comparison for 26 coinciding occultation events are shown. Roughly, the bias above 30 km shows a similar behavior as in Fig. 1b, which might be due the ECMWF analyses being used for upper-boundary initialization of the GOMOS retrieval.

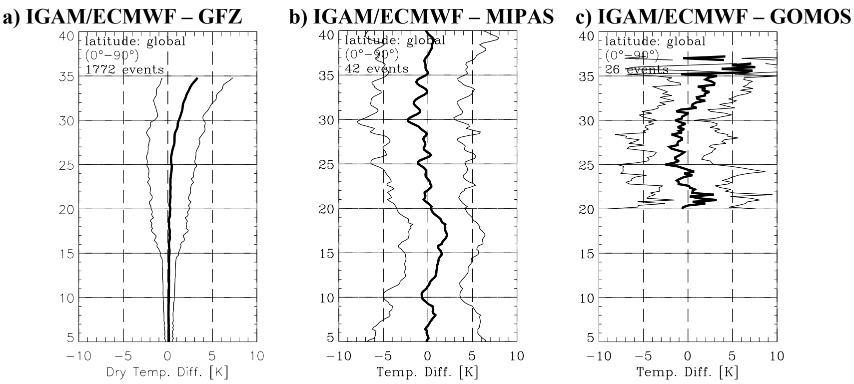

Figure 2: Bias (bold) and standard deviation (thin) of CHAMP dry temperatures (IGAM/ECMWF retrieval) compared to a) GFZ operational CHAMP retrieval, b) coinciding MIPAS measurements, and c) coinciding GOMOS measurements.

4 Conclusions

The IGAM stratospheric RO retrieval schemes apply statistical optimization based on the best linear unbiased estimator of observed and background bending angle profiles. In order not to give the background information too much weight and to maintain well defined error characteristics, no further background information is involved. Background information is either derived from the MSISE-90 best-fit-profile (bias corrected) or from ECMWF analyses.

Below 15 km, both IGAM retrieval schemes are in very good agreement with ECMWF analyses and strongly conform with the operational GFZ retrieval results (< 0.1 K bias, < 0.5 K std. dev.). Though on refractivity-level no high-altitude bias occurs up to ~35 km [7], the IGAM/MSIS temperatures are warm biased above 15–20 km, which shows that the background bias correction algorithm involved is not fully effective when applied to CHAMP data.

The IGAM/MSIS scheme was successfully evaluated in simulation studies using METOP-GRAS receiver specifications [3], the lacking performance applied to CHAMP data is due to worse data quality at high altitudes (higher receiver-noise level, outliers, residual ionospheric noise stemming from small-scale structures in the ionosphere that were not modeled in the simulation study). Since RO retrievals independent from NWP analyses are desirable, this scheme will be further developed to become more robust against noisy data, and better profile-search libraries than the MSISE-90 climatology are envisaged.

The IGAM/ECMWF results show excellent agreement with the GFZ retrieval up to ~26 km (<0.3 K bias, <3 K std. dev.) and a warm bias up to 2 K above that height. Compared to MIPAS, this bias does not occur up to 40 km, which shows that the IGAM/ECMWF retrieval scheme is less dominated by background information in the stratosphere and still yields excellent results.

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