Assimilation of GPS radio occultation measurements at Météo-France

P. Poli [1], G. Beyerle [2], T. Schmidt [2], J. Wickert [2]

[1] Centre National de Recherches Météorologiques, CNRS-GAME,
42 avenue Coriolis, 31057 Toulouse Cedex 01, France
and
[2] GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany
Corresponding author email: paul.poli@meteo.fr

Abstract

The global and European limited-area operational data assimilation systems of Météo-France have been using GPS radio occultation (GPSRO) bending angle measurements from FORMOSAT-3/COSMIC (F3C) satellites 1—6, CHAMP, and GRACE-A since September 2007. The GPSRO assimilation relies on: a one-dimensional bending angle observation operator developed by the GRAS SAF, observation errors derived using Desroziers' [2005] triangle method, and specific quality control procedures. In this paper we assess the observation error estimates of four different GPSRO datasets: F3C near-real time (NRT), CHAMP and GRACE-A NRT, F3C post-processed, and CHAMP experimentally processed. For the first two datasets we find small differences in the observation error standard deviations in the stratosphere, in line with expectations. In the lower troposphere, CHAMP and GRACE-A seem to present smaller observation errors than F3C. This may reflect an under-sampling by CHAMP and GRACE-A of situations otherwise probed by F3C. The post-processed F3C data usually present smaller observation errors than the F3C NRT data. All first three datasets present observation errors that are vertically correlated with a full width at half maximum of about 600 m, and anti-correlations around +/-1500 m. The fourth dataset produced by GFZ-Potsdam using a different smoothing algorithm features much smaller correlations with a full-width at half maximum of only 90 m and anti-correlations that are much closer. It appears that the price paid for using wider filters is the existence of stronger negative anti-correlations further away from the measurements. This preliminary study confirms the presence of error correlations in all the current GPSRO soundings, and the influence of the processing method on the width of these correlations.

1. Introduction

The GPS radio occultation (GPSRO) technique was first demonstrated in 1995 with the GPS Meteorology (GPS/MET) experiment [Kursinski et al., 1995]. This technique allows to observe the Earth's atmosphere with a limb geometry using an artificial source of signal. Owing to the frequencies being sensed, the technique is virtually all-weather (note that does not mean that the performance is equal under all meteorological conditions). The GPS signals, whose wavelengths are the basic metric in such experiment, are periodically calibrated with atomic clocks on the ground. This provides the system with a regular absolute reference. This feature, unprecedented for meteorological measurements, makes the GPSRO observing system a good candidate to help benchmark and calibrate Earth atmospheric models with a view towards climate studies.

Due to the spatially varying atmospheric index of refraction, the signals sent by GPS satellites are bent (towards the surface under normal propagation conditions). With a GPS radio occultation receiver onboard a satellite in Low-Earth Orbit (LEO), it is possible to track the Doppler shift in the received signal as compared to the nominal GPS frequency when the GPS satellite (dis)appears behind the atmospheric limb, during so-called (setting) rising occultation events. With the precise knowledge of the event geometry (positions and velocities of transmitting and receiving receivers), a series of bending angles can be retrieved for each event, and further converted into a profile of refractivity assuming spherical symmetry. From then on, inversion algorithms such as one-dimensional variational (1DVAR) can be used to retrieve a profile of temperature and humidity, using a priori data [e.g. Healy and Eyre, 2000].

Since 2006, a total of eight satellites have been disseminating full GPSRO products in near-real time (NRT) to National Meteorological Services (NMSs), via the Global Telecommunications System (GTS): profiles of bending angles, of refractivity, and of retrieved temperature and water vapour. The satellites are FORMOSAT-3/COSMIC (F3C) Flight Models (FMs) 1—6 [Anthes et al., 2008], CHAMP [Wickert al., 2001], and GRACE-A [Beyerle et al., 2005].

The outline of the present paper is as follows. The section 2 details how GPSRO data are assimilated at Météo-France. The section 3 presents an investigation of the quality of four different GPSRO datasets, including NRT and post-processed data. The section 4 presents forecast impact study results. The section 5 presents a comparison of the first GRAS SAF data that we have received with our global forecasts. Finally, the section 6 gives out conclusions and perspectives for future work.

2. Status and methodology of GPS radio occultation assimilation at Météo-France

The data from the F3C, CHAMP, and GRACE-A satellites have been assimilated operationally at Météo-France since September 2007. Detailed accounts of the assimilation methodology are presented in the paper [Poli et al., 2008] (hereafter noted as [P+08]), and may be summarized as follows.

The GRAS SAF provided the bending angle one-dimensional observation operator, along with its tangent linear operator and adjoint operators. We further refined this operator to include proper account of the tangent point drift and to simulate all the levels of GPSRO data: refractivity and its lapse rate, temperature, humidity. The following quality controls (QCs) were derived after considering histograms of observation minus first-guess differences (first-guess departures, abbreviated as “f.g. dep.” hereafter). Besides the background check, we screen out for each profile all data located below the level (if there is one) where the refractivity lapse rate, either from the observation or the background, is below –50 km^{-1}. This is an attempt to screen out situations where super-refraction could have occurred. Note that we err on the safe side, given that the theoretical threshold for such phenomena is –79 km^{-1}. We also remove all data below levels where the absolute value of the derivative of the refractivity lapse rate exceeds 100 km^{-2}. Finally, we exclude occultation events which only start above 10 km altitude as we found that these were usually associated with rising occultations featuring abnormally large f.g. dep. in the lowest kilometres of acquisition. We further apply a horizontal thinning and a vertical thinning (one observation per background layer).

Figure 1 shows plots of monitoring of the standard deviation of the f.g. dep. for all satellites, for one month of data (December 2007). The plot includes results for NRT and post-processed data (this is discussed later on). The qualities of the data fit for all F3C satellites appear fairly similar, while that of CHAMP and GRACE-A are both different. In terms of f.g. dep. standard deviation, F3C5 is the only F3C that differs from the other five; this is visible above 35 km altitude, and may be related to a lower accuracy in the precise orbit determination (F3C5 operates with one POD antenna instead of two for the other F3Cs). Because CHAMP and GRACE-A operate at lower orbits (~350 km and ~470 km respectively) their ionospheric correction is not as accurate as that of the F3Cs. This results in f.g. dep. standard deviations that are larger than those of F3C in the stratosphere, starting as soon as 25-30 km altitude.

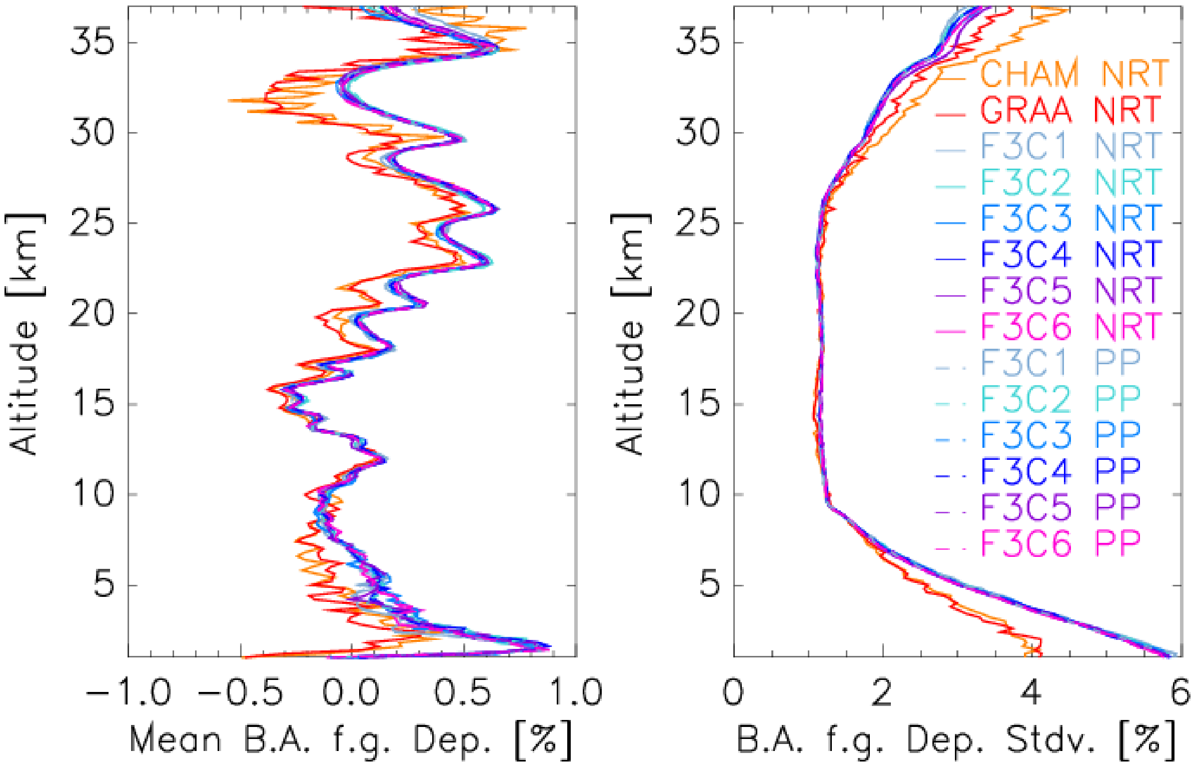

Figure 1: Statistics of first-guess departures of bending angle observations with respect to Météo-France short-term forecast, 1—31 December 2007. NRT refers to near-real time data and PP to post-processed data.

The f.g. dep. biases of CHAMP and GRACE-A are fairly different from those of the F3Cs, but, interestingly enough, are very similar to each other. Assuming that these differences do not originate from processing (this hypothesis is supported by detailed comparisons performed by the UCAR and GFZ-Potsdam teams, showing very little difference for collocated profiles), this points to differences in the actual atmospheric sampling achieved by the various F3Cs and the CHAMP and GRACE-A satellites. Although this is not a problem for data assimilation, it has to be kept in mind when considering statistics drawn from averages of profiles from each satellite.

For example, Figure 1 indicates that the f.g. dep. standard deviations for CHAMP and GRACE-A are up to 33% smaller than those of F3C for the lowest altitudes (4% instead of 6%). This does not necessarily reflect better quality measurements for CHAMP and GRACE-A but more likely indicates that CHAMP and GRACE-A provide data in regions for which the projection of the forecast into bending angle space gives results that are fairly consistent with the observations. This in turn suggests that, for the CHAMP and GRACE-A profiles, (1) the forecast itself is of better quality and/or (2) the forward modelling (which assumes normal radio propagation) is consistent with the actual measurement conditions. The conclusion (1) can be corroborated in simple terms given the lower penetration of CHAMP and GRACE-A data into the moist tropical troposphere, where forecasts have a limited ability to reproduce the strong water vapour variability. The conclusion (2) may be supported by considering that CHAMP and GRACE-A fail to probe the regions where most likely strong water vapour gradients are found, thus avoiding regions where abnormal radio propagation occurs (super-refraction, diffraction, or ducting). Both explanations appear reasonable but we cannot discriminate at this point which one is the more likely.

The strong wave-like pattern in biases above ~25 km altitude is explained by problems that arose with recent changes in our forecast model (increase in the number of levels from 46 to 60 and use of finite elements).

Although apparently problematic, these waves result from an inconsistent calculation of background quantities half levels versus at full levels. Given that the latter quantities are only used for model diagnostics and observation operators, this was not deemed to be a problem for the model dynamics itself. Indeed, the only practical consequence is that GPSRO assimilation must remain turned off above 25 km altitude in our assimilation system until this is fixed in the model, noting that an increased background vertical resolution could mitigate the problem.

3. Investigations of observation errors

The evaluation of GPSRO observation errors has been the topic of previous research, but with a focus usually on refractivity or derived products [Kuo et al., 2004], though recent studies have also investigated errors in bending angle space [Steiner and Kirchengast, 2005; Gorbunov et al., 2006]. We follow here the same estimation method as used in [P+08]. Briefly, the triangle method from Desroziers et al. [2005] assumes that errors in bending angle space and in observation space are uncorrelated, and makes use of analysis increments. We apply the method to various datasets, listed in the Table 1. Briefly, the method involves running a full assimilation and collecting the first-guess and analysis departures after assimilation. Note that in this assimilation we deactivate the vertical thinning and the QCs, except for the background check to remove outliers. Note that the method assumes no bias in all error sources. Consequently, the unaccounted biases may affect the error estimates.

Satellites	Processing type	Approx. sampling	Source	Dates
F3C 1—6	NRT oper. process.	200 m	UCAR via CDAAC	1-31 Dec 2007
CHAMP, GRACE-A	NRT oper. process.	200 m	GFZ via GTS	1-31 Dec 2007
F3C 1—6	Post-processed (PP)	200 m	UCAR via CDAAC	1-31 Dec 2007
CHAMP	Experimental proc. *	10 m	GFZ via FTP	1-31 Jan 2007

Table 1: List of the datasets considered in the present study.
** indicates smoothing of the phases with a polynomial filter order 3 before differentiation, no wave optics processing, and no statistical optimization.*

The first step in this approach is to verify that the background errors found for each satellite are similar for a given time period and vertical resolution, with the earlier remark that the UCAR and the GFZ datasets seem to observe different areas of the atmosphere (i.e. explore different variabilities). Figure 2 below shows the estimated background error. We verify that the error estimation algorithm correctly identified that the wave-like differences in the stratosphere were not the result of observation problems but a background error. In the troposphere, the background errors at the locations of NRT CHAMP and GRACE-A soundings appear to be lower than these at the locations of the F3C soundings. Note that the observation errors found in the lower troposphere are a bit lower than in [P+08]. We believe that this is because we applied here the background QC check before our error estimation analysis, thereby limiting the population studied to cases where the agreement between background and observation is fairly reasonable. The background errors at the time and vertical resolution of the CHAMP experimentally processed data are somewhat different from those of the other three datasets. Ideally one would have preferred to use datasets at the same vertical resolution and for the same time period; this could be the topic of future research.

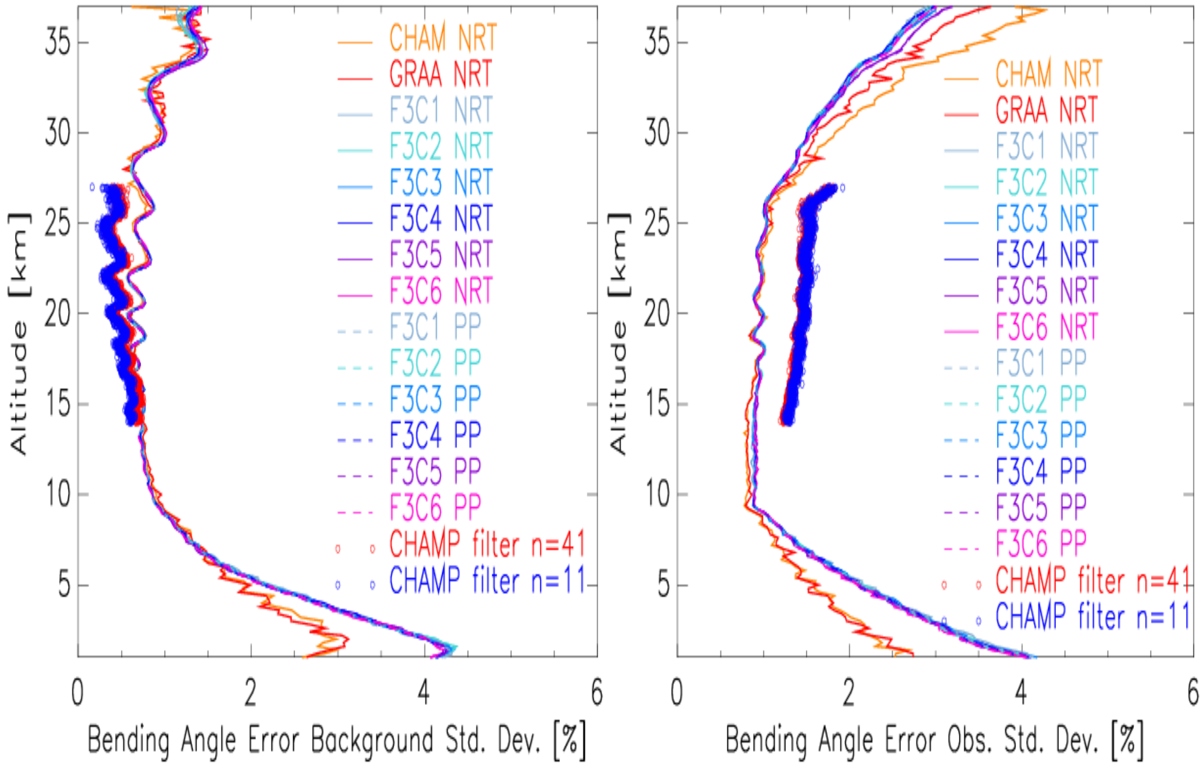

Figure 2: Left panel: estimate of the background error standard deviation, projected in bending angle space. Right panel: Estimate of the bending angle observation error standard deviation

Figure 2 above also shows the estimated observation error standard deviations. As expected, CHAMP and GRACE-A present a larger noise than the F3Cs in the stratosphere. In the troposphere, the opposite is observed. This may indicate that the phenomena observed by CHAMP and GRACE-A are better observed than those observed by F3C. One possible explanation is that (as mentioned earlier) the F3C soundings try to observe situations which are more difficult to resolve (moist lower troposphere).

The post-processed F3C data and the NRT F3C data present small differences (see Figure 3). We find that the improvement brought by post-processing is more important for the lower troposphere, with a relative reduction of about 2% as compared to the NRT products. For F3C6 we observe no significant difference between PP and NRT data.

The assimilation method at Météo France reverts to a vertical thinning in order to avoid the sub-optimal problem of assimilating data which present vertical correlations. Figure 4 shows an average of the observation error vertical correlations as estimated for levels between 16 and 27 km altitude. The average correlation is found to present a full width at half maximum (FWHM) of about 600 m, with negative correlations centred at 1.5 km distance above and below, going to zero at about +/- 3 km distance. We find that the various NRT datasets considered here present about the same correlations, which indicates that processing practices in that region of the atmosphere are consistent between the data producers.

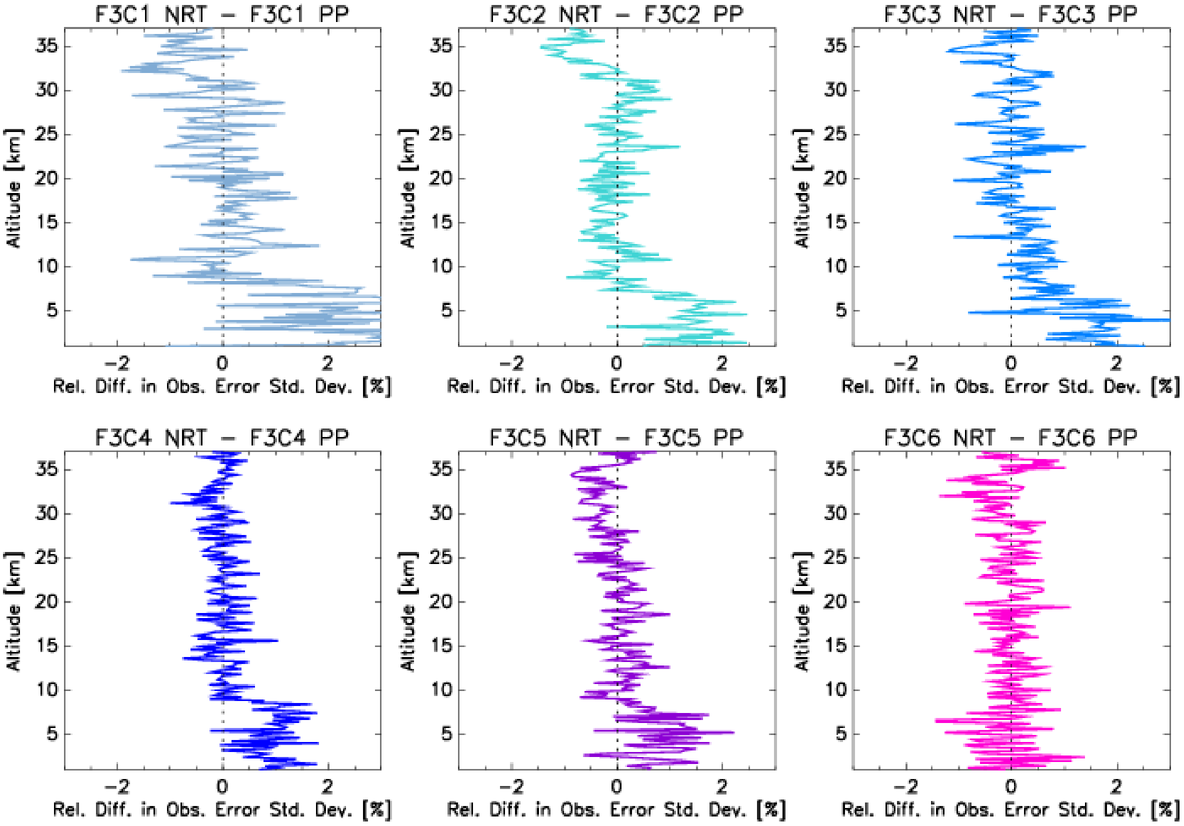

Figure 3: Estimate of the improvements [in %] between the post-processed (PP) products observation error and the near-real time (NRT) products observation error for each F3C satellite

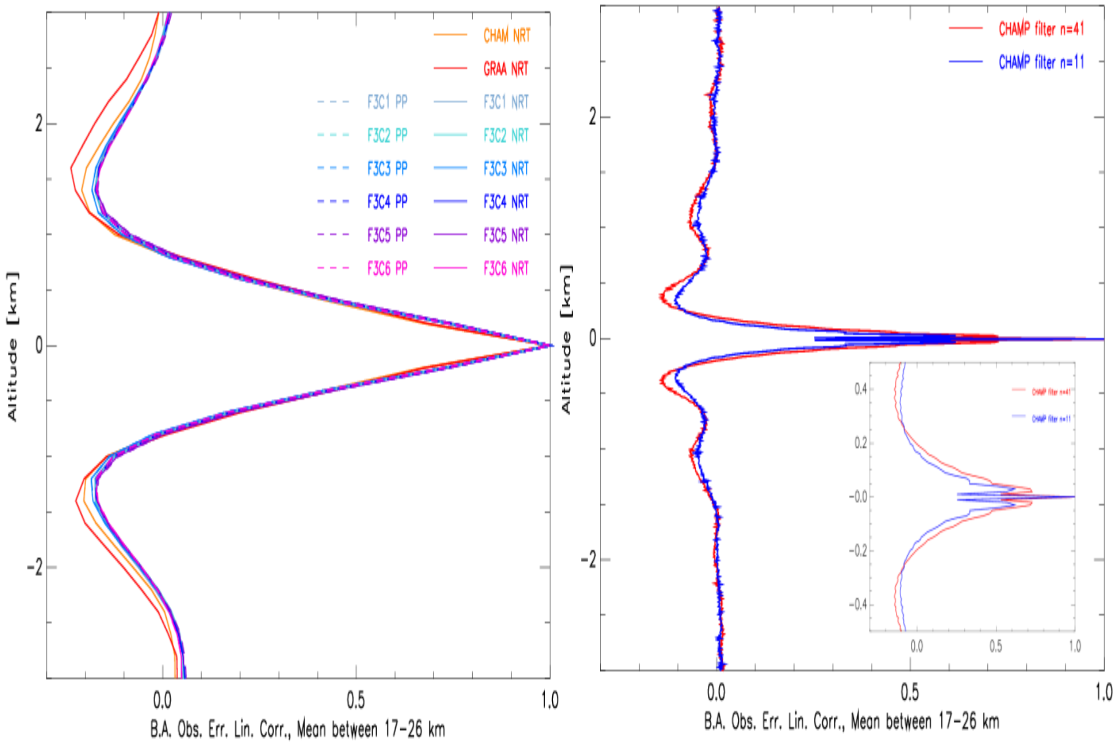

Figure 4: Left panel: Average of the vertical correlation of estimated observation errors, for all altitudes between 16-27 km [i.e. includes correlations of points between 13 km and 29 km]. Right panel: Same as Left panel but for the specially processed CHAMP dataset, with an inset showing a zoom for +/- 500 m

However, our thinning approach is neither the best solution nor satisfactory for the following two reasons. First, we thin the data based on their position relative to the background levels, and not on based on other, more relevant, criteria such as the intrinsic number of degrees of freedom of our analysis in the vertical as compared to that of the observations. Second, we throw out a lot of data which contain precious information content. Yet, we aim at finding a solution for GPSRO sounding that involves finding a proper processing so that the vertical correlations of error are mitigated or reduced. We feel that this could probably prove more efficient than trying to proper model the observation error correlations, which depend on the processing methods as shown here.

Following discussions at the 1st Colloquium on the Scientific and Fundamental Aspect of the GALILEO Programme held in Toulouse, 1—4 October 2007, the GPSRO processing team of the GFZ-Postdam generated a dataset of CHAMP data by an experimental processing method. That dataset does not result from the regular smoothing and processing applied in operational NRT processing, but uses instead a polynomial filter of order 3 which is then differentiated in order to calculate the derivative (Doppler shift). The sampling resolution of the data is about 10 m, while that of the other data considered here is about 200 m. Two datasets were provided using this method: the first dataset calculates the polynomial based on a sliding window of 41 points, while the second dataset considers only 11 points (sliding window more narrow). Because wave optics and statistical optimizations were turned off in this experimental processing, we focus here on the region located above the troposphere and below ~30 km altitude.

We note in Figure 2 above that the observation error estimates for these experimental CHAMP data are larger than those of the other datasets. This could be due to considering a different time period, but more likely higher data vertical resolution. Figure 4 above shows the average correlation in observation errors for these CHAMP experimental datasets. The correlations are much narrower than found for the other data; the FWHM is about 90 m, and the negative correlations are centred at a distance of about 350 m. Also, the special CHAMP dataset with a wider sliding window (41 points) is found to spread more the observation errors than the other dataset (11 points).

The inset in Figure 4 shows a zoom centred on +/- 500 m. We can observe a drop in correlations immediately next to the main auto-correlation feature. That drop is more important for the narrow filter (11 points). In fact, in the total absence of filter, we would observe only three features: the auto-correlation feature, and two strong negative correlations for the two neighbouring points above and below, with about zero correlation for all the other points. So the drop in correlation observed here simply results from the fact that the filter applied is not sufficiently wide. Note that the trade-off for a wider filter (i.e. smaller observation errors) is that the negative correlations further away from the auto-correlation peak are reinforced. Obviously, the investigations of the characteristics of what precise filter should be used for processing GPSRO data lie beyond this paper. It remains that this paper provides sound methodological grounds for investigating the quality of GPSRO datasets produced by different filtering/smoothing approaches.

4. Forecast impact studies

One recurrent question that is raised whenever advocates of GPSRO missions expose plans for future missions is “how many satellites are needed?” Several studies have already attempted to evaluate an ideal number by considering the number of soundings in a given time for a given surface area. In order to further feed the discussion, we present here results of an impact study aimed at assessing the forecast impact of an increase in the number of GPSRO soundings available to our global 4DVAR assimilation system. Three experiments were performed:

- The CONTROL experiment assimilates all the data assimilated in operations as of September-October 2007, except for GPSRO data which are absent from this run.
- The experiment GPSRO_FULL assimilates the same data as the CONTROL, with the addition of all the GPSRO profiles available. The QC procedures described above are applied and the data are assimilated below 25 km and down to 1 km at the poles (6 km in the tropics).
- The experiment GPSRO_HALF imitates the GPSRO_FULL experiment, except that it only sees half of the GPSRO profiles available. The other half of the profiles are removed by using a simple odd/even counter when extracting the occultations from the observation database, so that they do not even enter the assimilation.

Overall, this setup is intended to help determine, for our assimilation system, whether (a) a greater number of soundings results in a greater impact, or (b) a greater number of soundings results in a saturation in terms of impact. Note that data exclusion occurs independently of the satellite/data producer.

Figure 5 below shows the forecast root-mean square (RMS) error differences of GPSRO_HALF and CONTROL as compared to GPSRO_FULL. Positive (negative) values indicate forecast improvement (degradation) due to the assimilation of GPSRO data. The results obtained on this limited number of forecasts seems to indicate that there is so far no saturation in terms of forecast skill. As the number of GPSRO soundings is multiplied by two, the reduction in RMS error is also increased by a factor that seems in fact different than two, especially in the traditionally under-observed regions such as the southern latitudes. However, more cases are required in order to conclude definitively on such study.

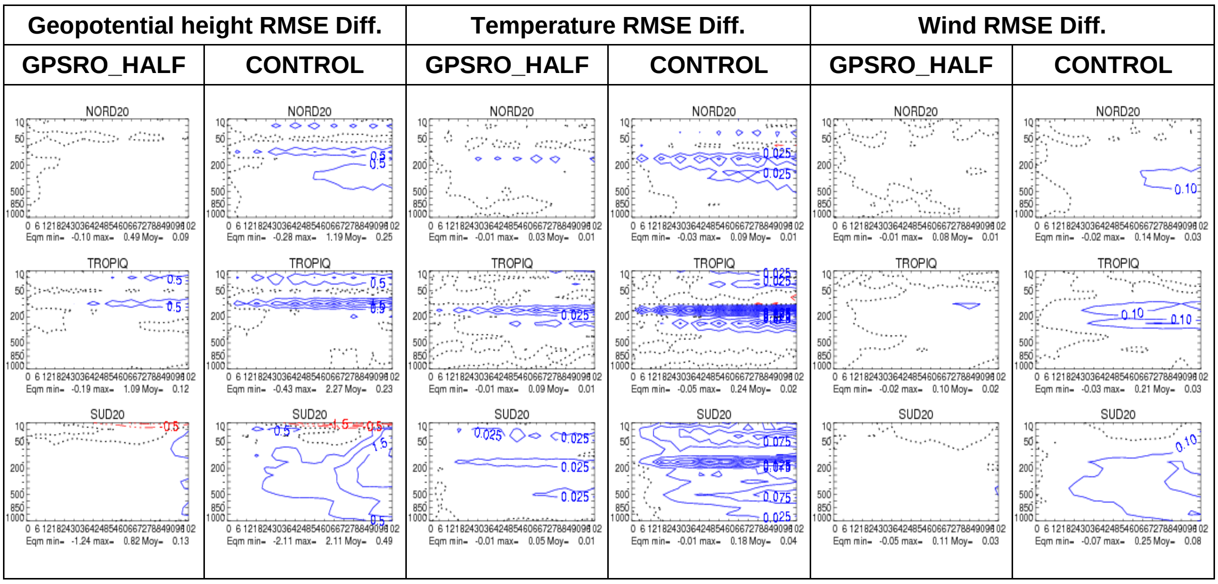

Figure 5: Impact of the assimilation of all or half GPSRO soundings on the forecast errors. 21 forecasts, 6-30 Sep 2007. Verification: analyses from each experiment. X-axis indicates forecast lead time (hours) and y-axis pressure (hPa). Positive blue (negative red) areas indicate improvement (degradation) of GPSRO_HALF or CONTROL as compared to GPSRO_FULL. NORD20 (TROPIQ, SUD20) refers to latitudes 20N-90N (resp., 20S-20N, 20S-90S)

5. A first look at GRAS data

Météo France started receiving three GRAS datasets in BUFR format in May 2008: level 1b (bending angle) data from Eumetsat in two datasets (one sampled at 30 m vertical resolution, the other thinned at 150—250 m vertical resolution), and, shortly after that, level 2 data from the GRAS SAF (containing bending angle and refractivity at 150—250 m vertical resolution). Given that our QCs derived from our experience with other satellites rely on refractivity, we made the choice to focus on GRAS SAF data for use in the near future.

We show here results for the first full day of data received: 5 June 2008. The number of occultations received (691) is superior to that of any other GPSRO satellite. The bending angle profiles received from the GRAS SAF without refractivity product present (very) large f.g. dep. Consequently, we discard such profiles (50 for that day). Figure 6 shows the statistics of f.g. dep. for the remaining 641 profiles, out of which 487 pass our QC. Overall, the bending angle data seem to feature a good quality between 10—37 km altitude.

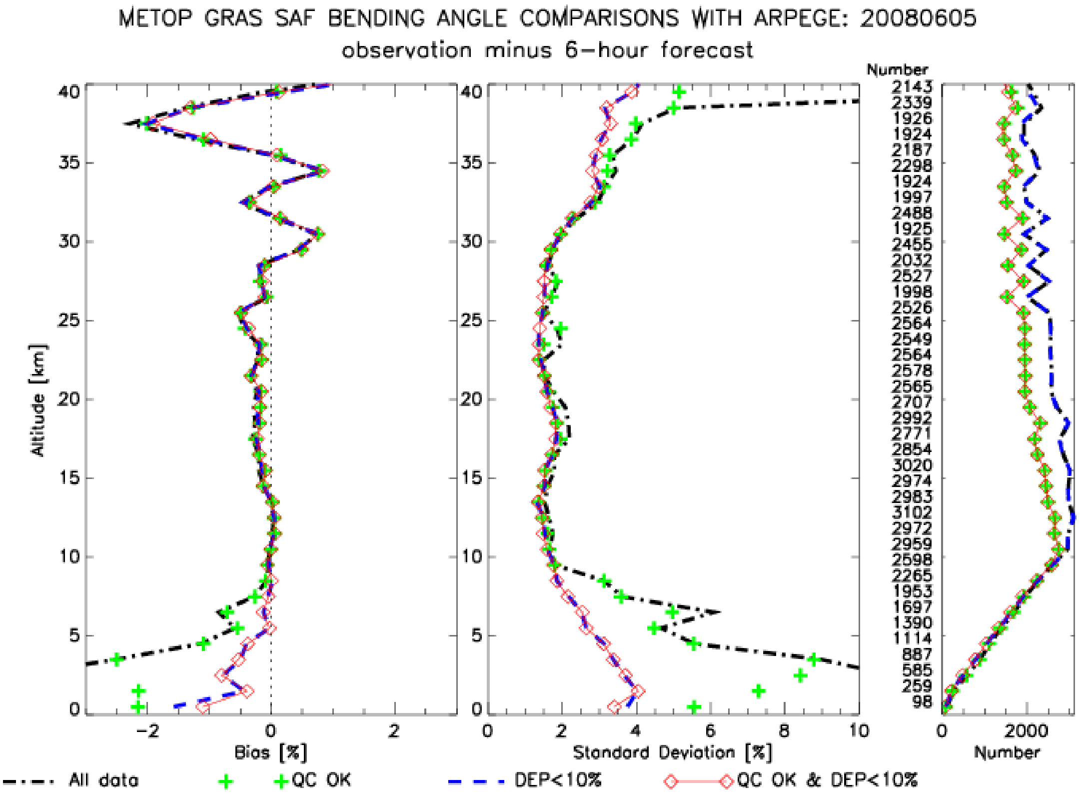

Figure 6: Bias and standard deviation of f.g. dep. for one day of METOP-A GRAS SAF bending angles. Profiles without GRAS SAF refractivity product are excluded from this plot

6. Conclusion

The 4DVAR global and 3DVAR limited-area assimilation systems of Météo France have been using GPSRO bending angle data since September 2007, thanks to an observation operator developed by the GRAS SAF.

In the present paper we investigated the error properties of various GPSRO datasets (NRT, post-processed, and CHAMP experimental processing) using Desroziers' [2005] triangle method. We found a noticeable improvement in the quality of post-processed F3C product versus the NRT products, of a few percents of the observation error. As expected, CHAMP and GRACE-A feature larger observation errors in the stratosphere. In the lower troposphere the less frequent penetration of CHAMP and GRACE-A soundings results in a different fit with respect to our forecasts, but the better fit observed as compared to F3C seems to point rather to a different sampling of the meteorological conditions (probably some 'difficult' situations in terms of radio propagation are not sensed as much by CHAMP and GRACE-A as they are by the F3C soundings). This is an important point when considering global average products from each satellite as they thus represent different climatologies. In terms of observation error vertical correlations, the results from F3C products are similar to CHAMP and GRACE-A NRT products, with a full-width at half maximum of about 600 m, and anti-correlations centred at +/-1500 m. Following the generation of a special dataset by the GFZ Potsdam with a different smoothing algorithm and a much higher resolution (10 m instead of 200 m), we observe that the spread in vertical error correlations and the strength of anti-correlations may be reduced, at the cost of higher observation error standard deviations.

We presented here an assessment of the first day of GRAS SAF data received, which are found to be of good quality between 10—37 km altitude.

Finally, we showed the results of an impact study designed to assess the increase in forecast skill benefit when the number of GPSRO soundings is increased. Preliminary results on 21 forecasts indicate (so far) that the forecast skill benefit scales at least as the number of available GPSRO soundings. Future work includes investigating further the quality of GRAS data and using them in our operational system.

7. References

Anthes, R.A., and Coauthors, The COSMIC/FORMOSAT-3 Mission: Early Results, *Bull. Am. Meteorol. Soc.*, **89** (3), 313—333, 2008.

Beyerle G, and Coauthors, GPS radio occultation with GRACE: Atmospheric profiling utilizing the zero difference technique, *Geophys. Res. Lett.*, **32** (13) L13806, 2005.

Desroziers, G. and Coauthors, Diagnosis of observation, background, and analysis error statistics in observation space, *Quart. J. Roy. Meteorol. Soc.*, 131, 3385-3396, 2005.

Healy, S.B., and J. Eyre, Retrieving temperature, water vapour and surface pressure information from refractive-index profiles derived by radio occultation: a simulation study, *Quart. J. Roy. Meteorol. Soc.*, **126**, 1661—1683, 2000.

Gorbunov, M.E., and Coauthors, Radio holographic filtering, error estimation, and quality control of radio occultation data, *J. Geophys. Res.*, **111**, D10105, doi:10.1029/2005JD006427, 2006.

Y.-H. Kuo, and Coauthors, Inversion and Error Estimation of GPS Radio Occultation Data, *J. Meteorol. Soc. Japan*, **82** (1B), 507—531, 2004.

Kursinski, E.R., G.A. Hajj, K.R. Hardy, and Coauthors, Observing Tropospheric Water Vapor by Radio Occultation Using the Global Positioning System, *Geophys. Res. Lett.*, **22**, 2365—2368, 1995.

Poli, P., and Coauthors, Quality control, error analysis, and impact assessment of FORMOSAT-3/COSMIC in Numerical Weather Prediction, *Terr. Atmos. Ocean. Sci.*, 2008, **in press**

Steiner, A.K., and G. Kirchengast, Error analysis for GNSS radio occultation data based on ensembles of profiles from end-to-end simulation, *J. Geophys. Res.*, **110**, D15307, doi:10.1029/2004JD005251, 2005.

Wickert, J., and Coauthors, Atmosphere sounding by GPS radio occultation: First results from CHAMP, *Geophys. Res. Lett.*, **28**, 3263—3266, 2001.