Impact of an Atmospheric Profiling Mission on NWP

Luis Kornblueh and Lennart Bengtsson
Max-Planck-Institute for Meteorology
Bundesstr. 55, D-20146 Hamburg, Germany

Gottfried Kirchengast
Institute for Meteorology and Geophysics
University of Graz
Halbärthgasse 1, A-8010 Graz, Austria

Xiang-Yu Huang, Per Høeg, and Georg Bergeton Larsen
Danish Meteorological Institute
Lyngbyvey 100, DK-2100 Copenhagen, Denmark

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Executive Summary

Study
of Potential Utility of GNSS Occultation Signals
for an
Atmospheric Profiling Earth Watch Mission

by
Luis Kornblueh, Gottfried Kirchengast, and Xiang-Yu Huang

1 Introduction

Because radio occultation measurements have been playing a very important role in the exploration of the atmospheres of the planets in the solar system (Kliore et al., 1965; Fjeldbo and Eshleman, 1968; Lindal et al., 1990; Lindal, 1992), the application of this technique to the atmosphere of the earth has been investigated as well. But in difference to the atmospheres of the other planets, where almost any new information was important, the exploration of the Earth's atmosphere raised significantly the accuracy requirements on the radio occultation measurements. The first radio occultation soundings of the Earth's atmosphere (Rangaswamy, 1976; Yakovlev et al., 1995) were not able to satisfy these requirements.

The situation changed significantly with the introduction of the US Global Positioning System (GPS). The use of the GPS system for the radio occultation measurements was suggested first by Gurvich and Krasil'nikova (in Russian 1987, in English 1990) and Melbourne et al. (1988). The GPS system consists of 24 operational satellites equipped with high-precision radio transmitters. It is able to provide high accuracy measurements of the atmospheric refraction and a good coverage of the Earth's surface (TERMA Elektronik AS, 1998). This allow the GPS measurements to compete with other data sources for operational meteorology. The biggest advantage of the radio occultation technique is the weather independence. A general review on the radio occultation techniques can be found in Kursinski et al. (1997).

The results of the first proof-of-concept experiment with the satellite Microlab-1 with a GPS-receiver on board (launched on April 3, 1995) were very promising, even if the receiver was not perfect for this purpose (Ware et al., 1996). This experiment also gave an insight into the difficulties arising in processing and utilization of the radio refractometric data.

The basic method of processing radio refractometric data till recently has been the Abel inversion (Phinney and Anderson, 1968; Fjeldbo and Eshleman, 1968) with the approximation of local spherical symmetry, neglecting the horizontal gradients of the atmospheric refractivity in the vicinity of the ray perigees (Ware et al., 1996; Kursinski et al., 1996; Hocke, 1997; Anthes et al., 1997; Kuo et al., 1997; Rocken et al., 1997). In the stage of a proof-of-concept experiment this approximation was sufficient. Theoretical investigations of the potential accuracy and horizontal resolution of the Abelian inversion (Gorbunov and Sokolovskiy, 1993; Gorbunov et al., 1996a) indicated that its errors become significant in the lower troposphere due to the complicated structure of the humidity field. Another new development is the replacement of the Abelian by a Fresnel inversion (Mortensen and Høeg, 1998).

The information content of radio occultation data for data assimilation in general was explored as part of a ESA study (TERMA Elektronik AS, 1998). Due to the fact that the simulation of a full data assimilation cycle for radio occultation data is impossible with the current available measurements a very general approach has been used. Assuming that the radio occultation receiver provides temperature data with global coverage a series of twin experiments were carried out assuming a homogenous distribution of simulated occultation measurements in both space and time. In this experiments it was assumed that observations were available from the top of a model atmosphere (e.g. 10 hPa) down to 300 hPa and further down to selected model levels until 850 hPa as lowest assimilation level, respectively. Real global model analysis data from the ECMWF reanalysis project where used. In the twin experiments this real analysis data have been assimilated into the model with a forcing dominating the model. This is representing the true atmosphere. In the other runs the data have only been assimilated in assumed instrument observation regions between the top and the specific lowest level. A comparison between this different model runs shows the potential influence of later measured data on the state of the atmosphere. The results are showing remarkable improvements (about 75 %) in the reduction of error amplitudes and slightly better results in error phase. This results encourage the next step in the development of a data assimilation system. One important point to mention on this experiments are nevertheless the perfect global data coverage which can hardly be provided by real observations.

Numerical simulations of the tomographic reconstruction of the global atmospheric fields from the refractometric measurements performed by a multi- Low Earth Orbiting (LEO) satellite system (Gorbunov and Sokolovskiy, 1993) indicated that the number of the LEO satellites necessary for accurate reconstruction of the horizontal structure in the lower troposphere at a resolution of a Global Atmospheric Circulation Model is estimated to a few hundred. Such a big amount of LEO satellites is, however, extremely unlikely to become available in the future. In case of effective data-assimilation this amount can be, this is a first order estimation, significantly reduced to minimum of 12 – 16 LEO satellites and 46 Global Navigation Satellite System (GNSS) satellites with an reasonable coverage.

The logical next step in investigating the impact of radio occultation data is the simulation of the impact of real data on numerical weather prediction (NWP) models considering previous established satellite setups. This is the main task to be explored in this study.

The optimal way of utilizing refractometric data is a data assimilation framework such as Optimal Interpolation (OI) or 4d variational assimilation (4DVAR) into a global atmospheric circulation model (Eyre, 1994; Zou et al., 1995). This approach has very strong advantages compared with the tomographic reconstruction of the global atmospheric fields. It is capable of assimilating any amount of the data without resulting in high-frequency artifacts due to insufficient resolution, usual in the standard tomography. This advantage makes data-assimilation especially valuable in the situation when only one LEO satellite is available, and it is impossible to arrange a tomographic high-resolution scanning of the atmosphere. This method is also capable of assimilating any kind of measured data in an unique way. The problem of separation of the humidity and temperature influence on the refractivity, is also solved with this method automatically (Zou et al., 1995). As can be shown in the first attempt to assimilate radio occultation data (Zou et al., 1998a,b) this is in general possible. Unfortunately there are not enough data available to perform real experiments which show an improvement due to the additional radio occultation data. In the framework of an ESA study at MPI a 4DVAR operator has been developed (TERMA Elektronik AS, 1998). This can be used only in an operational 4DVAR environment which is presently available in Europe at ECMWF only. Work is ongoing in the CHAMP project of the Geoforschungszentrum Potsdam (GFZ-Potsdam) for the implementation of this operator in a data assimilation setup with the climate model ECHAM5 until 2002.

Due to the complexity of 4DVAR experiments in the expected size of this study and unpredictable problems as well as missing information on the error-covariance matrix essential for such a data assimilation setup, we suggest a more suitable system based on an Optimal Interpolation (OI) data assimilation scheme for the global case. This can be used together with the MPI climate model ECHAM4 in forecast mode for the global coverage experiments.

The exploration of the NWP impact is split in four steps. First the setup of different satellite constellations is evaluated and the most promising in terms of spatial and time coverage are selected. The decision rules used are explained. Next step is the generation of the required observations out of predefined atmospheric states to accomplish the available standard and satellite observations for data assimilation usage. Third step is the data assimilation cycle itself. Finally conclusions have to be made up on the information gained.

2 Satellite mission scenario

Exploring the impact of GNSS Radio Occultation (RO) data on modern NWP systems requires the base information related to spatial and temporal sampling requirements. This requirements are given by the Report of the GRAS-SAG[1]. They are reviewed concerning their suitability briefly.

The basic requirements include horizontal and vertical sampling, both of which are associated (by the nature of the satellite-to-satellite sounding technique) with characteristic temporal sampling requirements for a given GNSS/LEO satellite constellation. Horizontal sampling expressed (to zeroth order) by the average sampling distance between individual occultation profiles depends strongly on the time interval allowed for a single sampling cycle based on the required time resolution. Vertical sampling, expressed by the average vertical distance of individual occultation rays sampled within a suitable height interval depends strongly on the sampling rate of the GNSS receiver(s) on board a LEO.

These interdependencies have to be kept in mind when focusing on reviewing the constellation-relevant requirements in the GRAS-SAG report. One implication is that the vertical sampling requirement only weakly depends on a given constellation. Thus it can be considered an off-line topic with respect to a constellation study. The mission scenario study therefore concentrates on the sampling of the geographical (horizontal) space.

It is also very important to take into account typical natural constraints on GNSS/LEO constellations. The GNSS side is very strongly constrained by prescribed layout of the existing GPS and GLONASS (Russian Global Navigation Satellite System) space segments so that these can be used, favorably, as firm-fixed reference constellations.

The LEO side, however, has much more degrees of freedom. Without assuming some basic constraints for this side, the investigation of optimal constellations is prohibitive due to the very large space of options. Sensible a priori constraints as introduced below help to greatly reduce the space of scenario options. This allows for a tractable number of scenarios to be studied.

The final decision has been taken to include one satellite mission which is dedicated to METOP-1 as well as one constellation consisting of 6, 12, and 24 satellites respectively. The decision have been based on the following set of parameters:

- (1) Sampling Requirements Penalty J_d
- (2) Mission Cost Penalty J_c
- (3) Event Number Penalty J_N

[1]Global navigation satellite system Receiver for Atmospheric Sounding - Science Advisory Group

- (4) Unequal Coverage Penalty J_{σ_N}
- (5) Geographic Irregularity Penalty J_{σ_d}
- (6) Time Separation Penalty J_t
- (7) Time Irregularity Penalty J_{σ_t}

Furthermore, we defined a Total Penalty, J_{tot}, which shall be a (user-)weighted and normalized sum of the 7 specific penalties (1) – (7).

3 Assimilation Procedure

To describe the assimilation cycle in detail a flow chart of the system is given in figure 1. It describes top down the sequence of processing.

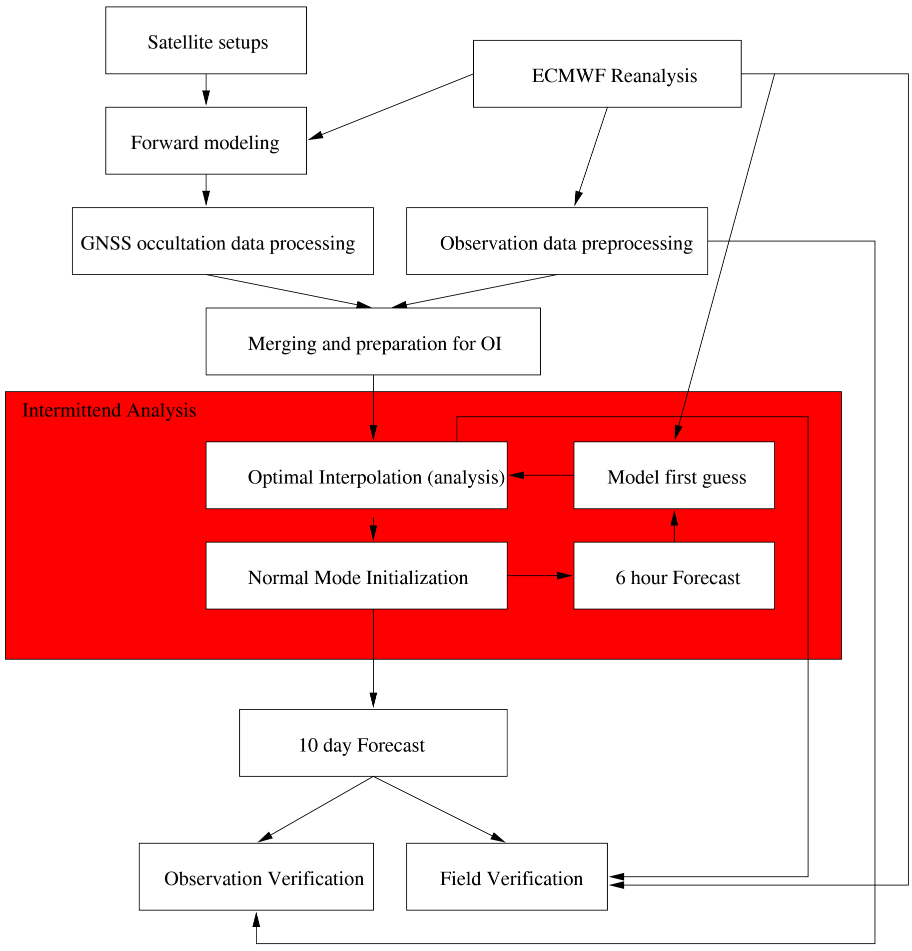

Figure 1: General experiment setup.

The first set is already done. The satellite setup is eplained and the forward modeling is performed based on the ECMWF Reanalysis first guess fields. Missing is the modeling of the receiver system. This is done using EGOPS. To put ECHAM into an balanced state concerning the start date of the assimilation cycle, the nudging technique has been used.

At this stage of processing we have available the data as they are expected to be delivered by future satellite system. As well available are all observations originaly used by the ECMWF Reanalysis; quality controled and blacklisted. This allows for running the full assimilation cycle and derive the final results.

4 Results and Conclusions

The most important fact on the comparision is the possibility to compare to the performance of other NWP models and a relatively simple measure for representing the results. This is after carefully evaluating the given possibilities, the anomaly correlation. We will present the standard anomaly correlation of the 500 hPa geopotential field and additionally the 100 hPa geopotential field.

The results of the standard case shows a difference in the results on the northern and southern hemisphere. The gain in crossing the persistence level of 60 % is about one day better on the northern hemisphere (see figures 2 and 3). This difference vanishs on the 100 hPa level (figures not shown here). The amount of observation data in the Northern hemisphere is much larger than in the Southern which results in the usual forecast performance gap between the hemispheres - major responsible influence is the poor knowledge of water vapour in the Southern hemisphere. In the upper part the GNSS RO derived data dominate and equalize the state - here the influence of water vapour can be neglected. Differences in the 100 hPa level are only marginal any more.

Another important aspect is the convergence of the cases with 12 and 24 satellites. This can be seen in all results. This seems to show a saturation of the information content of additional observations. The defined horizontal area measured by the GNSS RO is given by the GRAS SAG to be around 300 km. So most information is getting redundant, explaining the results.

Beside the explained saturation effect remarkable is the improved forecast performance by approximatelly one day. This is a remarkable result for a single new instrument. But we would like to warn on taking this result as absolut measure. An OSSE is always overestimating the influence of the results due to the fact that the generated observations fit very well the models state.

A comparison with the forecast performance of several well known NWP centers shows that the results of this experiment fit very well in the standard range of forecast skills as can be seen in figure 4.

Concluding all information given by our experiments the following points are the most important:

- GNSS RO data improve forecasts - in the experiments by a very good additional 1 day.
- There is a saturation effect somewhere between 12 and 24 satellites. This has to taken very carefully: rising and setting LEOs have been taken into account and a full set of GPS and GLONASS satellites. Currently GPS only is working and most likely

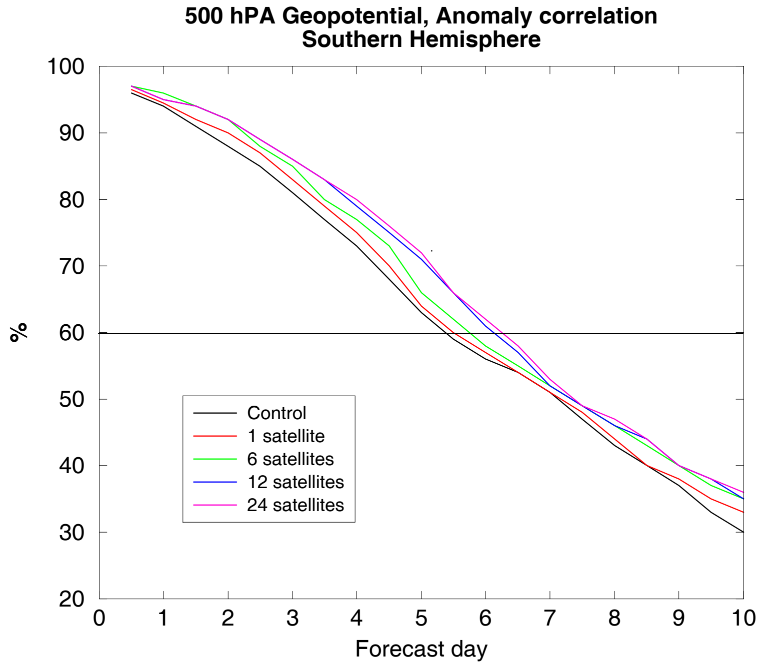

Figure 2: Anomaly corellation, 500 hPa Sourthern hemisphere

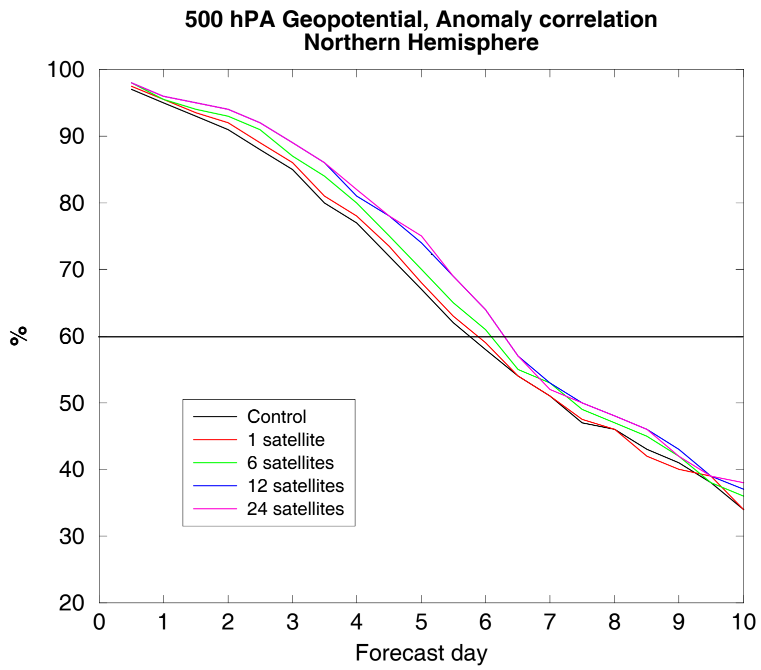

Figure 3: Anomaly corellation, 500 hPa Northern hemisphere

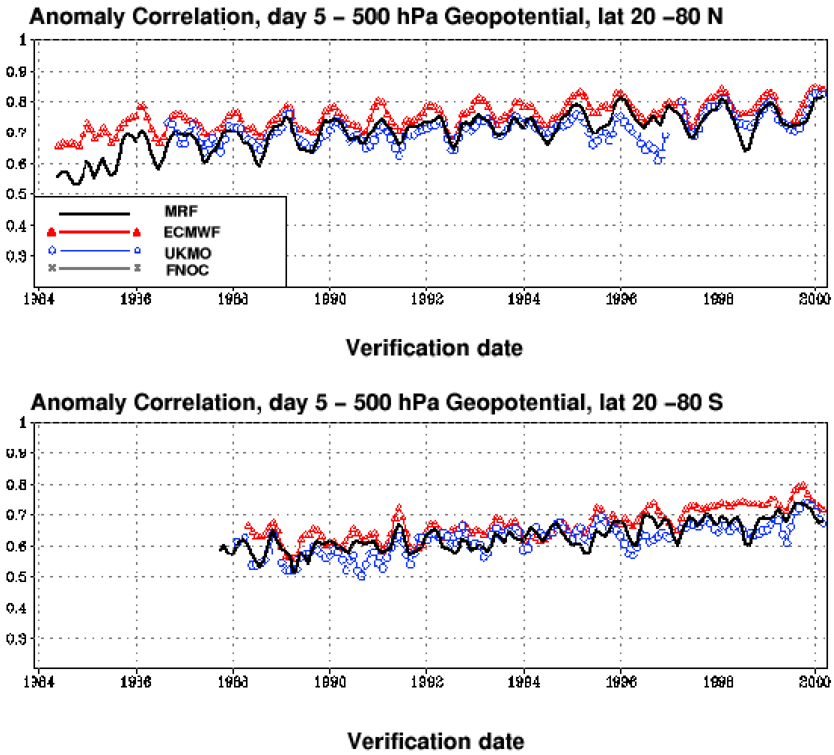

Figure 4: NCEP anomaly correlation comparison of selected NWP models.

GLONASS will never work. Which means that only half of the occultations might be available in the real world, doubling the necessary number of LEO satellites and requiring a new orbit setup - different to the one proposed in this study. On the other hand the setup of an European system, GALILEO, is on the way. In case this is available, we will get the simulated environment of this study.

- The technique used to process the GNSS RO data is not optimal in using the information content. Improvements may be possible with advanced techniques in the near future (assimilation of bending angles based on ray tracing for 3/4DVAR).

- The handling of error covarince matrices have been taken very carefully, but nevertheless only a long term monitoring of an actual flying instrument can give really reasonable numbers.

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