Forecast impact experiment with GPS radio occultation measurements

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[1] Refractivity profiles from CHAMP GPS radio occultation measurements have been assimilated into the Met Office numerical weather prediction (NWP) system. A forecast impact experiment was run using 16 days of CHAMP data from May/June 2001, in addition to conventional and satellite observations which are used in operational forecasts. Although typically only 160 CHAMP profiles are assimilated daily, it is demonstrated that they reduce NWP temperature analysis and forecast mean and root mean square (RMS) differences against radiosondes in the upper troposphere and lower stratosphere. A significant impact is found in the Southern Hemisphere where 24 to 96 hour forecast 250 hPa temperature RMS differences are reduced by ~0.1 K. No improvement in humidity forecasts is found because refractivity values below 4 km are not used in the experiment. These results are encouraging and would support the case for using CHAMP measurements in NWP if they were available in near real time. Citation: Healy, S. B., A. M. Jupp, and C. Marquardt (2005), Forecast impact experiment with GPS radio occultation measurements, Geophys. Res. Lett., 32, L03804, doi:10.1029/2004GL020806.

1. Introduction

[2] The GPS/MET [Rocken et al., 1997] and CHAMP [Wickert et al., 2001] missions have demonstrated that GPS radio occultation (RO) measurements contain potentially useful atmospheric state information. The measurements have an all-weather capability and good vertical resolution [Kursinski et al., 1997], and consequently numerical weather prediction (NWP) has been suggested as a possible application. However, although the GPS/MET and CHAMP validation exercises (cited above) have suggested sub-Kelvin temperature accuracy between ~7 km to 20 km, it does not necessarily follow that RO measurements will significantly improve NWP forecasts. This is because the information provided by RO may already be available from existing measurements. In NWP, a wide variety (and large number) of conventional and satellite observations are passed through a “data assimilation system” [e.g., Lorenc, 1986] in order to correct forecast errors and determine the “analysis”. The analysis is a statistically optimal, simultaneous fit to both a short range NWP forecast and observations which provides the initial conditions for the next numerical forecast. The potential utility of RO can only be assessed on the basis of whether assimilating the new data—in addition to those that would be used ordinarily—improves the analyses and the subsequent NWP forecasts. Previously, Liu et al. [2001] investigated how assimilating 837 GPS/MET bending angle profiles over a 10 day period modified analyses produced with the National Centers for Environmental Prediction (NCEP) spectral statistical analysis system, but their findings were limited because other satellite measurements available at that time were not assimilated. Poli and Joiner [2003] have looked at the impact of GPS/MET measurements on short- to medium-range NWP forecasts, but could not see any significant improvement in the forecast quality. Zou et al. [2004] reported some improvement in the southern hemisphere 500 hPa height forecasts as a result of assimilating CHAMP bending angle profiles. However, the improvements are not realistic because the 24 hour forecast errors in their “NO-GPS” control was close to 30 m, around a factor of 2 larger than would be obtained with an operational NWP system (G. Kelly, ECMWF, personal communication, 2004).

[3] The Met Office has developed the capability to assimilate RO measurements into its global NWP forecast system in order to perform forecast impact (or “observing system”) experiments. The RO measurements are assimilated as refractivity profiles, which is straightforward and not computationally expensive. We present results with 16 days of refractivity profiles from May/June 2001, derived from CHAMP RO measurements by GeoForschungZentrum (GFZ) Potsdam. In section 2, we describe the forecast impact experiment. The results are presented in section 3, followed by the conclusions in section 4.

2. Forecast Impact Experiment

[4] The forecast impact experiment uses the Met Office nonhydrostatic, global circulation model [Cullen et al., 1997] and three-dimensional variational (3D-Var) assimilation system [Lorenc et al., 2000]. The forecast model produces a global, three-dimensional estimate of the atmospheric state on a 0.55° by 0.833° latitude-longitude grid and 39 height levels between the surface and ~42 km. The 3D-Var system produces 4 analyses per day, at 00, 06, 12 and 18Z which are subsequently used to generate forecasts.

[5] The RO observations are assimilated as refractivity (N) profiles. The forward model maps the NWP forecast information to refractivity space, evaluating

\[ N = \frac{aP}{T} + \frac{bP_w}{T^2} \]  

where \( P \) is the total pressure, \( P_w \) is the water vapor pressure and \( T \) is the temperature; \( a = 77.6 \) K/hPa and \( b = 3.73 \times 10^5 \) K²/hPa are empirically derived constants [Bean and Dutton, 1968]. The model evaluates \( N \) on the NWP model height levels and then interpolates to the observation
heights, assuming that $N$ varies exponentially between the NWP model height levels. In the 3D-Var calculation, the NWP pressure and relative humidity values on the fixed height levels are adjusted to fit the observed refractivity profiles and minimize the 3D-Var cost (or penalty) function [e.g., Lorenc, 1986].

Refractivity profiles are provided by GFZ-Potsdam [Wickert et al., 2001] and are derived with the geometrical optics approximation. CHAMP produces $\sim 160$ profiles per day and each profile contains $N$ values on a 200 m height grid. The 3D-Var calculation requires an observation error covariance matrix for each refractivity profile assimilated. We assume that the fractional refractivity errors vary with height [Kursinski et al., 1997]. The percentage error in observed $N$ is assumed to be 1.1% at 4 km above the surface, falling linearly with observation height to 0.25% at 10 km. Above 10 km, we use a constant percentage error of 0.25%, until this reaches an absolute lower limit of 0.02 N units. This lower limit value was derived by propagating $3 \times 10^{-6}$ radian bending angle noise through an Abel transform routine. The vertical error correlations introduced by the Abel transform are modeled with an exponential decay with observation height separation, assuming a scale length of 3 km [Healy and Eyre, 2000]. To ensure that the actual refractivity errors are reasonably consistent with the error covariance matrices used in the 3D-Var, we preprocess each refractivity profile with a one-dimensional variational (1D-Var) retrieval, using the same observation error specifications. If the absolute difference between an observed refractivity value and the value simulated from the 1D-Var solution vector exceeds 5 times the expected observation error, the observed refractivity value is not used in the 3D-Var. In addition, the entire measurement profile is rejected if the 1D-Var cost function value is 10 times greater than the expected value [Healy and Eyre, 2000]. Note that we only assimilate observed refractivity values at heights between 4 km and 30 km above the surface. The 4 km lower limit clearly restricts the humidity information that can be derived from the measurement, but it is imposed because CHAMP refractivity profiles, like GPS/MET [Rocken et al., 1997], are biased low near the surface, particularly in the tropics [Marquardt et al., 2003]. This problem is an area of active research [Ao et al., 2003], but we do not currently have a good understanding of the statistical characteristics of the errors and correlations near the surface. The 30 km upper limit is used because the measurement information content falls rapidly above this height because of measurement noise. The assimilated profiles typically contain $\sim 120$ refractivity values between 4 and 30 km.

3. Results

The numerical experiment uses 16 days of CHAMP measurements, beginning on 26th May, 2001 and ending on 10th June 2001. The total number of CHAMP profiles is 2213, of which 2% are removed by the 1D-Var quality control (QC). We have performed two runs of the NWP system for this period—with and without CHAMP refractivity profiles being assimilated. The “control” run assimilates surface observations, radiosondes, ATOVS radiances, SSMI sea surface winds, satellite atmospheric motion vector winds and aircraft observations. For example, after thinning and QC the typical number of ATOVS radiances assimilated at 12Z is $\sim 12500$. The “GPSRO trial” is identical, except that the CHAMP profiles are also assimilated. Note that the number of GPS profiles is only around 40 per assimilation cycle, meaning that around $\sim 4800$ refractivity values are assimilated.

The improvement in forecast quality as a result of assimilating the CHAMP refractivity profiles is investigated by “objective verification” against observations. We compare how well the control and the GPSRO trial NWP forecasts are able to predict (or fit) conventional measurements—such as radiosonde temperature values—at the time and location of the observations. Note that assimilating RO measurements does not lead to significant degradation of any meteorological fields investigated in the experiment, but we will only outline the most significant improvements here. The largest differences between control and trial analyses and forecasts are found in the upper tropospheric and lower stratospheric temperatures between 7 km–22 km, which is consistent with theoretical “information content” studies [e.g., Healy and Eyre, 2000; Collard and Healy, 2003]. Figure 1 shows a global plot of the root mean square (RMS) differences in the control and GPSRO analyses at 250 hPa and 50 hPa over the trial period. As expected, differences are smallest in data-rich (in terms of radiosondes) regions of North America and Western Europe. The largest differences are apparent in the Southern Hemisphere (SH). Figures 1 shows the mean (a) and RMS (b) fit of the NWP forecasts to radiosonde temperature observations at 250 hPa.
for radiosonde locations in the SH (latitude ≤ −20°). The forecast range is from 0 hours, corresponding to the analysis, up to 96 hours. The statistics are based on ~45 radiosonde observations per day and the error bars are the one sigma, 68% interval. The control analyses (“0” hour forecast) are biased warm against the radiosondes by over 0.2 K. The control 24 hour forecasts are also biased warm by around 0.5 K, with the bias then tending to increase slightly for longer range forecasts. Assimilating the CHAMP observations improves the analysis fit to radiosondes by 0.07 K. The results indicate that the RO and radiosonde measurements—which are independent and not generally colocated—are providing consistent information in the 3D-Var assimilation. We emphasize that these results are achieved without any bias correction of the CHAMP refractivity profiles, which is a particularly attractive characteristic of the RO observations.

Furthermore, the CHAMP data subsequently improves the fit to the radiosondes values for most of the forecast range. For example, the bias at 24 hours is reduced by ~0.15 K when the RO measurements are assimilated. At the Met Office, a reduction in the RMS fit of 2% is usually considered significant in forecast impact experiments. The reduction in RMS fit is 7.2%, 7.6%, 4% and 4.2% for the 24, 48, 72 and 96 hour forecast ranges respectively, which are all greater than 0.1 K in absolute terms. Consequently, this is considered to be a very clear signal. We also find that the heights of the 250 hPa surface are improved in the SH. The reduction in the RMS fit to radiosonde measurements are 2.9%, 2.6% and 2.4% at 24, 48 and 72 hour forecast ranges respectively. Despite this we do not see any significant improvements in the winds at 250 hPa, which could arise through modifying the gradient of 250 hPa height field. This is slightly disappointing because the 250 hPa winds are important in aviation.

[10] It is more difficult to see improvements in the NWP forecasts for the northern hemisphere (NH) extratropics (≥20°) because NH analyses are already well constrained by radiosonde and ATOVS measurements. RMS height differences with radiosondes at 100 hPa are reduced by 1.8% and 2.0% at 24 and 48 hours, respectively, but we are only able to see a clear (≥2%) reduction in the RMS fit to radiosondes at 50 hPa. Although Figure 1 shows that the 50 hPa analysis differences are smallest over North America and Western Europe, the differences are found to be significant, as illustrated in Figure 3, which shows the mean (a) and RMS (b) fit to the radiosonde observations at 50 hPa. The statistics are based on around 280 radiosonde observations per day. It is noticeable that the control analyses are biased cold by ~0.85 K, and the bias reduces as the forecast range increases, resulting in the RMS difference falling with forecast range. In fact, this bias is found globally and is a known problem in the Met Office operational NWP forecasts. It is associated with the assimilation of ATOVS radiances and is thought to be caused by the radiances bias correction scheme for the upper stratospheric channels (S. J. English, Met Office, personal communication, 2003). A similar temperature bias of ~1 K around 50 hPa is also found in the 1D-Var retrieval increments, produced during the QC of the measurements. The RO should provide accurate temperature information around 50 hPa and consequently the measurements are given a lot of weight in the 3D-Var assimilation. Therefore, it is encouraging that assimilating CHAMP measurements seems to partially correct this systematic sub-Kelvin NWP error, improving both the analysis and forecast fit to the radiosonde observations; the reduction in RMS fit is 3%, 2.4%, and 2.5% for the 24, 48 and 72 hours forecasts respectively. The results at 50 hPa also suggest that assimilating RO measurements may indirectly improve ATOVS assimilation through better

![Figure 2](image2.png)

Figure 2. Mean (a) and RMS (b) fit to radiosonde temperature observations at 250 hPa in SH (latitude ≤ −20°) as a function of forecast range for control (red) and GPSRO (blue-dashed) experiments.

![Figure 3](image3.png)

Figure 3. Mean (a) and RMS (b) fit to radiosonde temperature observations at 50 hPa in NH (latitude ≥ 20°) as a function of forecast range for control (red) and GPSRO (blue-dashed) experiments.
bias correction of the radiances. English et al. [2000] note that the current bias correction scheme assumes that the NWP output is unbiased because the assimilation of radiosonde measurements prevents the analyses “drifting”. RO measurements in the upper troposphere and lower stratosphere may potentially prevent such drift.

[11] Improvements in the NH 50 hPa height are also found, indicating that the RO measurements are adjusting temperature values below 50 hPa, but it only becomes apparent when the effects are integrated. We obtain similar improvements for the temperature and height of the 50 hPa in both the tropics and SH. The temperature results are particularly impressive in the tropics, where the reduction in the RMS fit to the radiosonde values is 6.9%, 5.0% and 3.9% at 24, 48 and 72 hours respectively.

[12] We do not see any significant improvement in the water vapor fields in any geographical region or forecast range. This is not surprising because the 4 km lower limit used for the observed refraction profile removes the measurements that potentially contain the most humidity information. Whilst it could be argued that we are currently rejecting useful humidity information, in practice it is extremely difficult to make use of any observations when their error characteristics are poorly understood.

### 4. Conclusions

[13] The forecast impact experiment has demonstrated that RO measurements can improve NWP analyses and forecasts in the upper troposphere and lower stratosphere when verified against radiosonde measurements. The results have been obtained by assimilating refractivity profiles, which do not require any bias correction in the upper troposphere and lower stratosphere. The assimilation approach is simple, computationally inexpensive and suitable for an operational NWP system.

[14] We did not observe any significant improvement in the humidity fields because refractivity values below 4 km were not assimilated. Recent work [Poli et al., 2003] has suggested refractivity profiles derived with the canonical transform [Gorbunov, 2002] rather than geometrical optics have smaller errors near the surface. Therefore, it may be possible to relax the 4 km lower limit; this will be investigated in future work.

[15] Overall, these results would support the case for assimilating CHAMP RO measurements into the operational NWP system if they were routinely available, but it must be emphasized that more forecast impact experiments are required before the measurements can be assimilated operationally at a NWP center. Nevertheless, the results from our first forecast impact trial with CHAMP RO measurements are encouraging. Given that an impact is apparent with a total of ~19200 refractivity values per day from 160 CHAMP profiles, obtaining an order of magnitude more observations from a constellation of satellites, such as COSMIC [Anthes et al., 2000], is an interesting prospect.

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