Evaluation of a non-local observation operator in assimilation of
CHAMP radio occultation refractivity with WRF

Hui Liu, Jeffrey Anderson, Ying-Hwa Kuo, Chris Snyder, and Alain Caya

National Center for Atmospheric Research
Boulder, CO 80307

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Corresponding author: Hui Liu
Email: hliu@ucar.edu
Address: 1850, Table Mesa DR.
Boulder, CO 80305
Phone: (303) 497-1304
Abstract

A non-local RO observation operator (Sokolovskiy et al., 2005a) is evaluated in the assimilation of CHAMP (CHAllenging Minisatellite Payload) RO refractivity using a WRF ensemble data assimilation system at 50km resolution. The assimilation is done in two different situations: in conjunction with dense, high quality radiosonde observations; with only satellite cloud drift wind observations. Analyses of temperature and moisture with the RO refractivity assimilated using a local and the non-local operator are verified against nearby withheld radiosonde observations. The performance of the non-local operator is evaluated over North America during January, 2003. Analyses using the non-local operator are significantly better than those using the local operator in the troposphere when the only additional observations are satellite cloud drift winds. The impact of the non-local operator remains positive, but with reduced magnitude, when radiosonde observations are also assimilated.
1. Introduction

When there are strong horizontal gradients of atmospheric assimilation of GPS radio occultation (RO) refractivity/bending angle as local values at the estimated tangent points of the radio rays may result in significant errors. Assimilation of the RO refractivity/bending angle using non-local operators may significantly reduce the errors (see e.g., Sokolovskiy et al., 2005a, 2005b, Syndergaard et al., 2005a, 2005b, Poli, 2004, etc.). A number of non-local and local refractivity/bending angle operators have been tested in assimilation of GPS radio occultation data with global and regional data assimilation systems (Healy and Thepaut, 2006a, 2006b, Zou et al., 1999, Kuo et al., 2000, Liu et al., 2003, etc). The benefit of using non-local operators compared with local operators, however, has not been demonstrated in the middle and lower troposphere with high horizontal resolution data assimilation systems (< 100km). As shown in Sokolovskiy et al. (2005a) and Foelsche and Kirchengast (2004), the positive impact of using non-local operators may be most significant in the middle and lower troposphere at resolutions of 100km or higher. In this study, the impact of using non-local operators in assimilation of RO data with a relatively high horizontal resolution (50km) version of the Weather Research and Forecasting (WRF) model is examined.

In this study, the excess phase operator developed by Sokolovskiy et al. (2005a), is evaluated in the assimilation of CHAMP RO refractivity with the WRF ensemble data assimilation system being developed at NCAR. One feature of the non-local operator is that it uses a predefined ray-path which is independent of refractivity so the operator is a
linear one. In their evaluation of the operator with simulated RO data and CHAMP data (using WRF forecasts only), use of the non-local operator significantly reduced forward modeling errors compared with use of a local operator (see Sokolovskiy et al., 2005a, 2005b). Here, these operators will be evaluated in realistic assimilation of CHAMP refractivity together with other observations using the WRF ensemble data assimilation system.

In regions where conventional high quality data (e.g., radiosonde) are sparse, like over oceans, the impact of GPS RO data is expected to be larger than for conventional data dense regions. This may be especially true in the presence of deep clouds over the oceans as in the case of winter storms and hurricanes. In the presence of clouds, satellite radiances are not yet routinely assimilated and satellite cloud drift winds are the major data resource. However, these have much larger observational errors than radiosondes and do not measure temperature or moisture. In this study, we evaluate the non-local operator in two different situations: in conjunction with dense radiosondes with only satellite cloud drift wind observations. This is done for a North American domain due to existence of dense radiosondes there.

In Section 2, the WRF ensemble data assimilation system is briefly introduced. The implementation of the non-local RO operator with the WRF ensemble data assimilation system is described in Section 3. The details of the experimental design for examining the performance of the non-local operator are given in Section 4. The CHAMP RO refractivity and satellite cloud drift wind data are described in Section 5 and the
latitudinal distribution of the horizontal variations of atmospheric refractivity in
the troposphere of the WRF model are briefly discussed in Section 6. Detailed evaluation of
the non-local operator is presented in Sections 7 and 8. Finally, conclusion and
discussion are given in Section 9.

2. WRF ensemble data assimilation system

The WRF ensemble data assimilation system is based on the NCAR’s Data
Assimilation Research Test-bed. The Ensemble Adjustment Filter (Anderson, 2001,
2003) is used to assimilate observations with WRF short-range forecasts. The system can
assimilate radiosonde observations, aircraft reports, satellite winds, retrieved temperature
and moisture profiles from satellite radiances, and many kinds of surface observations.
GPS RO refractivity can also be assimilated using both local and non-local observation
operators. In this study, 50 km horizontal resolution with 28 vertical levels is used in the
assimilation of CHAMP refractivity. The model top is at 50 hPa (~20km).

One advantage of using the ensemble data assimilation system is that various non-local
and local RO observation operators can be implemented and evaluated easily without the
development of tangent linear and adjoint models of the operators. Another important
advantage is that time-varying multivariate forecast error covariances of temperature with
moisture are included in the assimilation of RO data. The forecast error of moisture is
expected to be correlated with that of temperature due to the dynamical and physical
processes involved as well as the deficiencies of physical parameterizations in the
forecast model (see e.g., Liu et al., 2006). The forecast error covariances involving
moisture may also be highly time- and space-dependent, especially at the mesoscale. Using the information from the flow dependent multivariate forecast error ‘covariance’ for temperature and moisture should improve the retrieval of temperature and moisture from the RO data. Our previous study shows that inclusion of these forecast error correlations in the ensemble data assimilation system significantly improves the analyses of temperature and moisture in the assimilation of idealized RO measurements (Liu et al., 2006).

3. Implementation of the non-local operator

The non-local RO operator (Sokolovskiy et al., 2005a) integrates observed and model RO refractivity along prescribed ray paths (straight lines here),

\[ S_{\text{obs}} = \int_{\text{ray}} N_{\text{RO}}(r) dl \]
\[ S_{\text{mod}} = \int_{\text{ray}} N_{\text{mod}}(x, y, z) dl \]

where \( r \) is \( r_c + z \). \( r_c \) is the local curvature radius of the earth, and \( z \) is the height above the earth’s surface. This gives a new observable, excess phase, \( S_{\text{obs}} \) and a corresponding model counterpart \( S_{\text{mod}} \). The ray paths do not depend on the refractivity and so the operator is linear.

For \( S_{\text{obs}} \), the operator integrates observed 1D RO refractivity along the prescribed rays which are tangent to the observed RO ray directions. The integration stops at a given height, \( H_{\text{top}} \). In this study, \( H_{\text{top}} \) is set to 15km, a bit below the model top (50hPa, ~20km above earth surface), so that only the atmosphere below 15km is used in the calculation.
of the excess phase. This reduces the impact of the artificial upper boundary of the model on the forward observation operator. A step-size of 5km is used in the integration. The 1D CHAMP RO refractivity (see next section for more details) is used in the integration. For calculation of refractivity at an arbitrary height along the rays, a linear interpolation is used.

For $S_{mod}$, the WRF 3D grid refractivity field is projected onto the sphere with the local curvature radius $r_c$ of the RO observations. The model refractivity is integrated along the same rays as the $S_{obs}$. For calculation of refractivity at an arbitrary point along the rays, linear interpolations in both vertical and horizontal directions are applied. Using identical discretizations and calculations of the excess phase in both the model and observations ensures that the modeling errors of the operator are minimized.

For comparison, a local RO refractivity operator is also evaluated. With this local operator, WRF 3D model grid refractivity is interpolated linearly to the RO observation’s location.

4. Experimental design

The assimilation experiments are done over a North American domain where radiosondes are dense and many nearby radiosondes are available for verification of the analyses of temperature and moisture from the RO assimilation experiments. We examine the impact of the CHAMP RO refractivity on analyses using WRF at 50km horizontal resolution during January, 2003. Since the impacts of using the non-local operator may
be significant only in the troposphere (see e.g., Sokolovskiy et al. 2005b), we focus on that region here.

Two sets of experiments are done to evaluate the performance of the non-local operator in the presence of only satellite cloud derived wind observations or in the presence of dense radiosonde observations. The first set includes:

Experiment I: Assimilate only satellite cloud drift wind observations.

Experiment II: Assimilate the same set of satellite wind observations as in Experiment I plus RO refractivity using the non-local RO operator.

Experiment III: Same as Experiment II, but assimilate the RO refractivity using the local refractivity operator.

The second set includes:

Experiment IV: Assimilate the radiosonde observations including wind, temperature, and specific humidity. Radiosonde observations within 200km and +/- 3-hours of an RO observation are withheld for verification.

Experiment V: Assimilate the same set of radiosonde observations as in Experiment IV plus RO refractivity using the non-local RO operator.

Experiment VI: Same as Experiment V but assimilate the RO refractivity using the local refractivity operator.

5. The observations
In January 2003, there are 536 CHAMP RO profiles available over the North American domain (see Fig. 1). Only the RO observations that passed the COSMIC Data Analysis and Archive Center (CDAAC) quality control (Kuo et al., 2004, Rocken et al., 2000) are used; no additional quality control is applied to the RO observations. The few RO refractivity observations below 2km are excluded to avoid possible large measurement errors.

To reduce possible errors associated with aliasing of small-scale structures of RO refractivity onto larger scale vertical structures of WRF model refractivity, the high vertical resolution raw RO data is smoothed to the domain-averaged WRF model vertical levels. These smoothed RO observations are then assimilated using the non-local and local operators.

Observational error estimates for the CHAMP RO refractivity and excess phase are shown in Fig. 2. The estimates were obtained for August 2003 using a 45km resolution version of WRF 24 hour forecasts and the CHAMP RO data using the Hollingsworth and Lonnberg method (1986). The estimates include measurement and forward modeling error for WRF at 45 km resolution.

The satellite cloud drift wind observations are obtained from the National Environmental Satellite, Data, and Information Service (NESDIS) and are thinned by using only one of every 20 raw observations. After thinning, there are ~3,500 satellite wind observations available within the domain daily. The observation error estimates for

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the satellite cloud drift winds used in the NCAR/NCEP re-analyses is used here; these errors are much larger than those for the radiosonde winds.

In all experiments, the RO refractivity and satellite wind observations are assimilated at 00Z, 06Z, 12Z, and 18Z and the radiosonde observations at 00Z and 12Z. The initial and boundary ensemble mean conditions are obtained from the 1x1 degree AVN analysis, produced routinely by NOAA’s National Centers for Environmental Prediction (NCEP) as part of the operational weather prediction enterprise. A total of 20 ensemble members are used in this study. The initial (1 January, 2003) and boundary ensembles are generated randomly according to the forecast error covariance statistics of the WRF 3D-Var data assimilation system. An alternative way to generate the initial and boundary ensembles would be to use global ensemble forecasts but that is not done here. A localization of the impact of the observations on nearby model state variables is used to reduce the sampling errors due to the limited ensemble size. The cutoff distance is set to 1300km; when the distance between the observation and a state variable is larger than 1300km, the impact of the observations on the state variables is set to zero. For separations less than 1300km, the impact of the observation is reduced by a compactly supported Gaussian-like function with a half-width of 650km (Gaspari and Cohn, 1999).

The locations and times of the withheld radiosondes within 200km and +/- 3 hours of the RO observations are shown in Fig. 3. A total of 104 co-located radiosonde soundings are available during the period and these are distributed across the North American
domain. Since we excluded the few RO measurements below 2km, we only examine the impact of the RO refractivity on the analyses above 800 hPa.

6. Latitudinal distribution of refractivity gradient of the forecasts

To examine the importance of assimilation of the RO refractivity using the non-local operator, we first examine the refractivity gradient of the WRF 6-hour forecasts at 50 km resolution. We calculate the horizontal variation of refractivity at the RO locations (perigees) as the average of the absolute values of the differences between the refractivity at the perigees and the points which are 50km away from the perigees (along the direction of the ray) on either side of the perigees. This variation gives a measurement of the refractivity gradient of the WRF forecasts at the perigees. Figure 4 shows the latitudinal and height distribution of the horizontal variations of the refractivity of the forecast (ensemble mean) of Experiment I calculated at the perigee points of the RO refractivity locations and averaged for all of the RO refractivity locations over the domain during January, 2003. The major feature is that the horizontal variation of refractivity is much larger in the lower and middle troposphere, and the variation is much larger at the low and middle latitudes than the high latitudes. For example, a maximum variation of 2 N-units/50km is located at 25N near 2km. The variation is, however, much weaker at 60N near 2km, only ~ 0.6 N-unit/50km.

A similar latitudinal distribution of the horizontal variation of the refractivity can also be found in the WRF 6-hour forecasts of Experiment IV (Fig. 5). These distributions of the refractivity variations suggest that the use of the non-local operator in the assimilation
of RO data may be most important in the middle and lower troposphere and at the low and middle latitudes. Therefore, in the following, we will evaluate the performance of the non-local operator in two separate latitude belts from 15-45N and 45-75N.

7. Impact of the non-local operator in the presence of only satellite winds

Figure 6 shows the vertical distribution of the mean and RMS fit of the analysis of temperature to the co-located radiosondes in Exps. I, II, and III, averaged for the latitudes of 15-45N. A cold bias of ~-1.1K exists at ~700 hPa and 400 hPa in the analysis using satellite winds only. When the RO refractivity observations are assimilated using the non-local operator (Exp. II), the cold bias is reduced to -0.75K and -0.85K respectively. When the RO refractivity is assimilated using the local operator, the reduction of the cold bias is not seen. The RMS error for the analysis assimilating only satellite winds has a minimum of ~2.1K in the middle troposphere. The RO refractivity assimilated using the non-local operator reduces the error to ~1.5K, a significant reduction of ~0.6K. When the local refractivity operator is used (Exp. III), however, the reduction is only ~0.25K, less than half of that for the non-local operator.

The vertical distribution of the mean and RMS fit of the analysis of specific humidity is shown in Fig. 7. The specific humidity analysis from assimilating only satellite winds has a wet bias in the lower troposphere. The RO refractivity assimilated using either the non-local or local operators is able to reduce the wet bias by almost a half. The difference between using the non-local and local operator is generally small. The impact of RO data on the analysis of specific humidity is expected to be less than on the temperature
analysis since moisture only contributes a small part of the RO refractivity in January over the domain. Note that the radiosonde observations, especially for moisture, may have larger “representativeness” error in the lower troposphere which may mask the impact of assimilating RO observations.

For the high latitudes of 45-75N, the vertical distributions of the mean and RMS fit of the analysis of temperature are shown in Fig. 8. The relative benefits of using the non-local operator are less evident because the horizontal variations of the refractivity of the forecast are much weaker than in the lower latitudes (see Figs. 4 and 5). The analysis of temperature using satellite winds has a cold bias of 0.5K at 600 hPa. The assimilation of the RO refractivity using both the non-local and local operators reduces the bias by half, but there is no obvious difference between the performances of the two operators. The assimilation of the RO refractivity in concert with satellite winds also reduces slightly the RMS error of the analysis of temperature in the upper and middle troposphere. Again, there is no significant difference in the performance of the two operators.

Near 800 hPa, the assimilation of the RO refractivity using the non-local operator degrades slightly the analysis of temperature. In the presence of radiosonde observations (discussed shortly), however, we do not see such degradations. Therefore, the degradation might be related to the less satisfactory analyses and forecasts from using only the satellite wind observations at this height level. Assimilation of additional observation types, such as QuikScat ocean surface wind observations and/or satellite microwave/infrared radiance products, might help to ameliorate this problem.
For specific humidity (Fig. 9), the analysis from assimilating only satellite winds has a wet bias of 0.3 g/kg at 600 hPa. The RO refractivity assimilated using both the non-local and local operators is able to reduce the wet bias by ~0.1 g/kg. The RO refractivity assimilated using the two operators also reduces the RMS error in the lower troposphere from 0.9 g/kg to 0.8 g/kg. However, there are no significant differences in the performance of the non-local and local operators.

8. Impact of the non-local operator in the presence of radiosondes

Assimilations of the radiosonde observations produce mean and RMS fits of the analysis of temperature that are significantly smaller than those from assimilating only satellite wind observations. As a result, the impact of the RO data on further improving the analyses of temperature and specific humidity is reduced in the presence of the radiosonde observations. For the latitudes of 15-45N, the temperature analysis assimilating radiosonde observations has a bias of only -0.5K at 700 hPa (Fig. 10). The RO refractivity assimilated using the non-local operator reduces the bias to -0.3K. The non-local operator performs slightly better than the local operator in the lower troposphere. In addition, the RO refractivity assimilated using the non-local operator slightly reduces the RMS error of the analysis in the lower troposphere. It can be seen that use of the non-local operator slightly improves the analysis compared to the use of the local operator.
For specific humidity (Fig. 11), the RO refractivity assimilated using both non-local and local operators is able to reduce the RMS error of the analysis in the lower troposphere but the performance of the non-local operator does not differ from that of the local operator. For the bias of the analysis, the RO refractivity assimilated using the local operator has no impact on reducing the small bias in the middle and lower troposphere. The RO refractivity assimilated using the non_local operator has mixed impact on the bias of the analysis in the middle and lower troposphere.

For the high latitudes of 45-75N, the assimilation of the RO refractivity using both the non-local and local operator has no impact on reducing the bias of the analysis of temperature (Fig. 12, compare to Fig. 8). The assimilation of the RO refractivity using the non-local operator slightly reduces the RMS error of the analysis in the upper troposphere. The assimilation of the RO refractivity using the local operator does not have any noticeable impact on the RMS error of the analysis.

For specific humidity, the RO data modestly improves the analysis in the lower troposphere (Fig. 13). The analysis from assimilating radiosonde observations has a wet bias of 0.35 g/kg in the lower troposphere. The RO refractivity assimilated using both the non-local and local operators reduces the wet bias by ~0.15 to 0.2 g/kg. In addition, the RO refractivity assimilated using the two operators reduces the RMS error in the lower troposphere from 0.95 g/kg to 0.85 g/kg. There are no significant differences in the performance of the non-local and local operators.
9. Conclusion and discussion

For the North America domain of January 2003, the CHAMP RO refractivity assimilated using the non-local operator significantly improved analyses of temperature and moisture in the troposphere in the presence of only satellite cloud drift wind observations. Compared with the local operator, use of the non-local operator significantly improves the analyses of temperature and moisture, especially in the middle and lower troposphere at the low and middle latitudes. In the presence of dense and high quality radiosonde observations, however, the positive impacts of RO data are diminished and differences between using the local and non-local operators reduced.

It may be concluded that use of the non-local RO operator can significantly improve the assimilation of RO data in the middle and lower troposphere in regions where conventional high quality observations are sparse and satellite could drift winds are the major data resource. Such regions would include most of the tropical oceans and much of the extra-tropical oceans.

Over tropical oceans, NCEP and ECMWF analyses of temperature and moisture rely heavily on satellite radiances and winds. Significant areas of cloud-cover may exist, especially in the vicinity of tropical storms. Cloudy radiances are not yet used in the operational analyses systems on a regular basis, so satellite cloud drift and scatterometer winds are the major data resources. These observations, however, have much larger observational errors than radiosondes and do not measure temperature and moisture. The analyses of temperature and moisture may therefore have large uncertainty. As a result,
initialization of hurricane forecasts from such analyses may also have large uncertainty. In addition, study of the weather and climate over oceans (e.g., ITCZ and MJO) also needs more reliable analyses of temperature and moisture. The results obtained in this study suggest that GPS RO data may significantly improve the analyses of temperature and moisture over the tropical oceans in cloudy situations. As a result, GPS RO data may have the potential to improve the tropical storms and provide better analyses of temperature and moisture for the study of climate and weather in the tropics.

We plan to further evaluate the non-local operator for assimilating RO data over tropical oceans. In these regions, the gradient of refractivity is expected to be much larger than for the middle latitudes due to the existence of abundant moisture and convection. WRF at a higher horizontal resolution (~30km) will be used in the evaluation of the non-local operator. It is expected that the non-local operator may have larger advantages compared to the local operator at these resolutions.

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**Figure captions:**

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Figure 4. Latitudinal and height distribution of the refractivity variation of the 6-hour forecasts (ensemble mean) of Experiment I at the perigee points of the CHAMP RO locations, averaged over the North American domain for January, 2003. Unit: N-nits/50km.

Figure 5. Same as Fig. 4 but for Experiment IV.

Figure 6. Vertical distribution of temperature analysis (a) Mean error, and (b) RMS fit to the collocated radiosonde temperatures, and (c) the number of verifying radiosonde temperature observations for the assimilation experiments in the presence of satellite cloud drift wind observations during January, 2003. Values are averaged for the 15-45N. Solid line is for assimilation of only satellite wind observations, dashed line is for the satellite wind observations plus the CHAMP RO refractivity using the non-local operator, dotted line is for the satellite wind observations and the RO refractivity using the local operator.

Figure 7. Same as Fig. 6 but for specific humidity.
Figure 8. Same as Fig. 6, but for the 45-75N.

Figure 9. The same as Figure 8 but for specific humidity.

Figure 10. Vertical distribution of temperature analysis (a) Mean error and (b) RMS fit to the withheld nearby radiosonde temperature observations, and (c) the number of the withheld radiosonde temperature observations for the assimilation experiments in the presence of radiosonde temperature, wind, and moisture observations during January, 2003. Results are averaged over 15-45N. Solid line is for assimilation of only radiosonde observations, dashed line is for radiosonde observations plus the CHAMP RO refractivity using the non-local operator, dotted line is for the radiosonde observations and the RO refractivity using the local operator.

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