Physical and Computational Considerations for the Use of GPS Occultation Observations in NWP

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1 Introduction

With the first launch of a small Low Earth Orbit (LEO) satellite, MicroLab-1, in April 1995, the GPS (Global Positioning System) Meteorology (GPS/MET) experiment demonstrated the capability of active remote sounding of the Earth's atmosphere by radio occultation techniques (Ware *et al.*, 1996;: Kursinski *et al.*, 1996). The GPS occultation measurements are not affected by clouds or precipitation and are of high vertical resolution. Instrument calibration is not required and observation errors are statistically independent of the other types of measurements. With these attractive features of GPS measurements, and the promising results of the preliminary GPS-retrieval products (Rocken *et al.*, 1997), several international projects included plans to launch many more LEO satellites equipped with GPS-receivers. How to make the best use of these new observations in numerical weather prediction? How will they affect global analyses and possibly change the need for other types of observations? Before one could answer these questions, a method that can extract useful information from these measurements needs to be developed and tested thoroughly.

From the basic measurements of the two Doppler-shifted radio frequencies and the orbital parameters of the GPS and the LEO satellites, a radio occultation bending angle can be derived assuming spherical symmetry of the atmospheric refractivity. The vertical profile of bending angle from each occultation event can either be inverted to obtain the refractivity profile using the Abel transform by invoking another time the spherical symmetry assumption, or be directly assimilated into numerical weather prediction model. Since atmospheric refractivity depends on pressure, temperature, and specific humidity in a neutral atmosphere, independent knowledge of one of the three quantities allows the other two variables to be retrieved from the GPS refractivity profile. For example, when water vapor contributions to the refractivity are small (e.g., stratosphere), a refractivity profile and the hydrostatic equation uniquely define pressure and temperature profiles.

The bending angle based on an inexact atmospheric state (analyzed, simulated, or predicted) is different from the observed one. Minimization of the differences between the simulated and observed bending angles are expected to improve the quality of the global and/or regional analysis of the atmospheric state, if the cost function measuring these differences is properly defined. Cares are needed in (i) formulating the forward model (observation operator) which derives simulated bending angle given a model refractivity field and the geometrical information of a given occultation event, (ii) estimating the mean and covariances of the observational and for-

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ward modeling errors, and (iii) deciding the required accuracy for the observation operator and affordable computational cost.

Over the past few years, efforts have been made to assimilate GPS/MET bending angles (Zou et al., 1999; Zou et al., 2000). Preliminary results from these studies were encouraging. In this study, we report several physical and computational considerations for the use of GPS bending angle observations in numerical weather prediction. Further refinement of the formulation of various components of GPS/MET bending angle assimilation will lead to a full understanding of the numerics and physics involved in the use of this new type of GPS occultation data, and eventually allow them to be properly incorporated into the global and regional analysis.

2 Specific issues

We discuss several issues associated with the use of GPS occultation measurements: computational cost, vertical resolution, bias removal, and observational weighting.

2.1 Computational cost

Numerical weather prediction models often tax the capability of the largest available computers. The GPS analysis and/or assimilation must conform to the operational requirement of the computational cost. The observation operator that calculates a simulated bending angle involves a numerical integration that solves the ray equation. The ray integration starts from a GPS transmitter in high orbit, passes the atmosphere, and ends at a GPS-receiver equipped on a low earth orbiting (LEO) satellite. The computational cost for the bending angle assimilation is therefore quite expensive. There are two kinds of methods to reduce the computational cost. One is to reduce the absolute CPU time, with some loss of accuracy in the calculated bending angle. This includes (i) using a more economic numerical scheme for the ray integration, (ii) reducing the vertical resolution of the simulated profile, and (iii) assimilating refractivity instead of bending angle. The other is to reduce the wall-clock time without loss of accuracy. This can be achieved by parallelizing the ray tracing procedure using message-passing interface. In summary, it is expected that a reasonable accuracy of analyses can be achieved while gaining a huge reduction in the computational cost.

Figure 1, for example, shows the fractional difference of bending angle using the two ray integration schemes: the fourth-order Runge-Kutta method (RK) and the second-order alternating direction implicit method (ADI, Zou et al., 1999). For a total of 380 simulated rays for a single occultation event that occurred at 12.22 UTC, October 11, 1995 (located at 57N, 83W), the CPU time used by RK and ADI is 983 and 381 seconds, respectively. In another word, the raytracing using ADI is 2.6 times cheaper than RK while the fractional difference in the calculated bending angle profile is less than 0.04%.

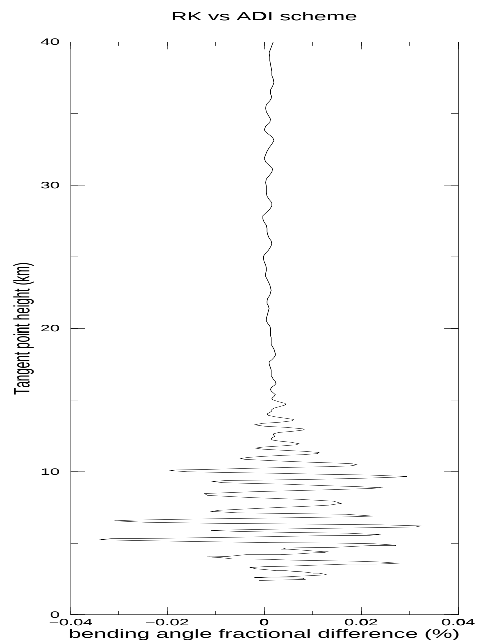

Figure 1: The fractional difference of the simulated bending angles using RK and ADI methods for a GPS/MET occultation event that occurred at 57N, 83W, 12.22 UTC, October 11, 1995.

2.2 Vertical resolution

The accuracy of the calculation of bending angle, if derived from phase delays of the simulated rays above and below the current ray path, is sensitive to the vertical resolution used in the observation operator. Figure 2 shows the fractional error of bending angle due to the use of coarse vertical resolutions. In this calculation, the Earth is assumed spherical, and a smooth vertically decaying refractivity profile, obtained by a horizontal average of the NCEP analysis of refractivity is used. The same occultation event as that in Fig. 1 is used. A 10 Hz vertical resolution can produce a much more accurate bending angle profile than those at 2 Hz and 5 Hz resolution.

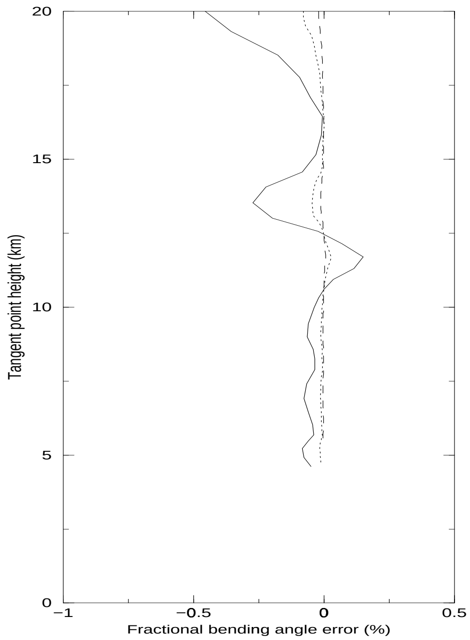

Figure 2: The fractional errors of bending angle calculation with vertical resolutions of 2 Hz (solid), 5 Hz (dotted), and 10 Hz (dashed). The same occultation event as in Fig. 1 is used.

2.3 Bias removal

The refractivity decreases exponentially with height. At high altitudes (e.g., above 40 km), the bending is negligible and the impact parameter is nearly constant along the ray path. The impact parameter at the tangent point height from the observation operator should be very close to the GPS derived impact parameter. The difference between the modeled and GPS/MET derived impact parameter at these higher levels, therefore, represents a (constant) measure of uncertainty in the impact parameter in the forward model. This uncertainty can be removed through a correction applied to the modeled bending angle vertical profile:

$$\alpha_{model}(a_t) = \alpha^0_{model}(a_t - \Delta a) \qquad (2.1)$$

where α_{model} is the adjusted value of model bending angle, α^0_{model} is the original (uncorrected) value of the model bending angle, and $\Delta a = a_t^{40\ km} - a_{GPS}^{40\ km}$ is the difference between the modeled and GPS/MET derived impact parameters at the tangent point at 40 km.

An example showing the significance of this bias correction is provided in Figure 3. Compared with radiosonde observations, the specific humidity profile after the bending angle assimilation without a bias correction contains large errors.

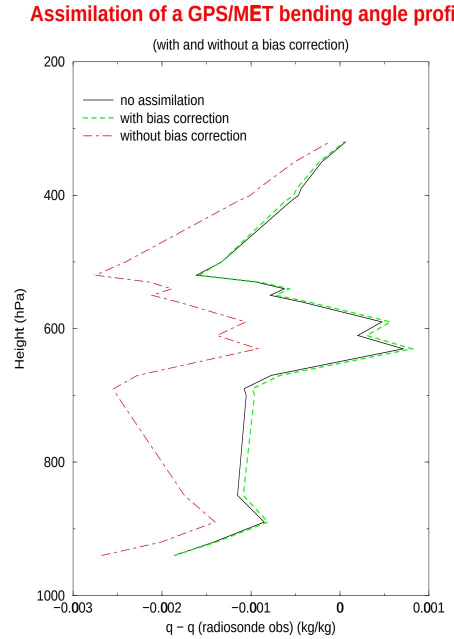

Figure 3: The vertical profiles of $q_{guess} - q_{radiosonde}$ (solid), $q_{assim,nobias} - q_{radiosonde}$ (dash-dotted), and $q_{assim} - q_{radiosonde}$ (dashed), where q_{guess} is from the NCEP analysis without GPS/MET data assimilation, $q_{radiosonde}$ is the radiosonde observations at (144.38W, 27.62S) at 00 UTC June 29, 1995, $q_{assim,nobias}$ is the results from GPS/MET bending angle assimilation without a bias correction, and q_{assim} is the results from GPS/MET bending angle assimilation with the bias correction. The GPS/MET occultation assimilated is located at (144W,27S), which was observed at 23.12 UTC June 28, 1995. The distance between the GPS/MET occultation and the radiosonde sounding is 178 km.

2.4 Observational weighting

The refraction angle α and possibly its error variance vary exponentially with height. The statistical information about bending angle observational errors are required for the assimilation of radio occultation bending angles. We test the sensitivity of the GPS/MET data assimilation results to the specification of the observation error covariance matrix of bending angle observations. Three covariance matrices are used: (i) A diagonal covariance matrix whose diagonal elements, the variances, are approximated by the mean square differences between the observed and the simulated bending angle based on the NCEP analysis. (ii) A diagonal covariance matrix whose diagonal elements, the variances, are estimated using an accurate 3-D ray-tracing model and include both the errors introduced by the spherical symmetry assumption and the observation operator. (iii) A full covariance matrix estimated similarly as in (ii).

The bending angle observations from the GPS/MET Level-3 data are used. These data are provided by the UCAR Payload Operations Control Center[1]. There were 837 GPS/MET occultation profiles observed during June 20-30, 1995. Of these 837 GPS/MET soundings, there are 52 for which there is at least one radiosonde profile that was observed within a ± 3 h time window, had more than 5-levels of data, and was less than 200 km from a GPS/MET sounding. The total number of these radiosonde profiles is 56. About half of the soundings (25) reached a height as low as 1 km.

A version of the National Centers for Environmental Prediction (NCEP) spectral statistical interpolation (SSI) analysis system is used for GPS data assimilation experiment. A description of the use of GPS/MET bending angle in the NCEP SSI analysis and assimilation system can be found in Zou et al. (2000).

The 56 temperature and specific humidity profiles from radiosonde are used as independent data sources for evaluating the results from the GPS/MET bending angle assimilation.

Table 1 provides the mean errors and the r.m.s. errors of the temperature and specific humidity fields before and after the GPS/MET bending angle assimilation using a diagonal covariance matrix whose diagonal elements are approximated by the mean square differences between the observed and the simulated bending angle based on the NCEP analysis. The radiosonde observations are used as the "truth".

Table 1: The mean errors and the r.m.s. errors of the temperature and specific humidity fields before and after the GPS/MET bending angle assimilation. Observations from the 56 radiosonde soundings are included in the calculations.

	mean (^{o}C)	rms (g kg^{-1})
	Temperature	
before	0.18 (1.54)	0.40
after	-0.01 (1.43)	0.36
	Specific humidity	
before	-1.19 (9.59)	3.25
after	-3.2 (8.92)	3.09

Figures 4-7 show the vertical profiles of the specific humidity and temperature errors before and after GPS/MET bending angle assimilation The GPS/MET occultation and the nearby radiosonde sounding for Figs. 4-5 are located at (14.4E, 49.9N) and (15.9E, 49.7N), and those of Figs. 6-7 are at (92.1E,58.5N) and (94.0E, 59.6N), respectively.

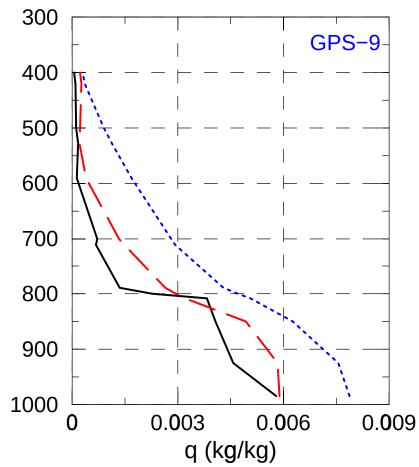

Figure 4: Specific humidity at (15.9E, 49.7N) from radiosonde (solid), before (dotted) and after (dashed) GPS/MET bending angle assimilation.

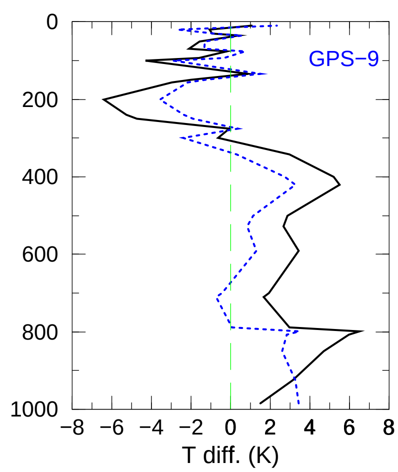

Figure 5: Differences between modeled and radiosonde observed temperature at (15.9, 49.7N). Solid: before the GPS/MET bending angle assimilation. Dotted line: after the GPS/MET bending angle assimilation.

Improvements in the temperature and specific humidity analysis due to the use of GPS/MET bending angle are obvious at these two nearby radiosonde stations.

[1](http://cosmic.cosmic.ucar.edu/gpsmet)

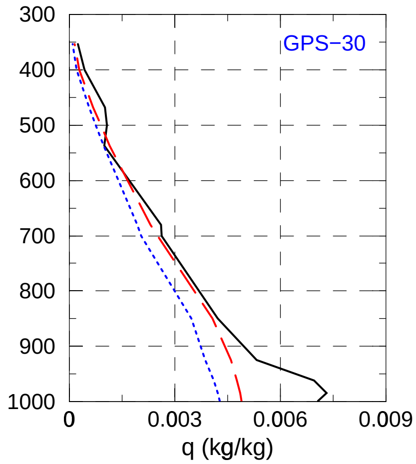

Figure 6: Same as Fig. 4 except at (94.0E, 59.6N).

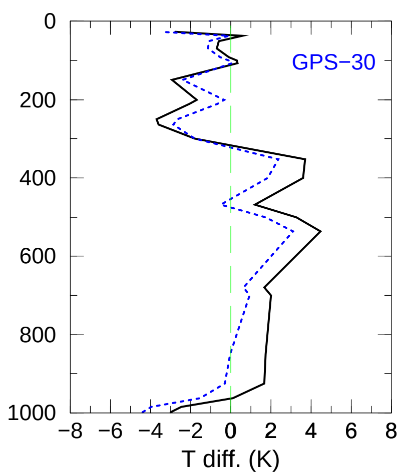

Figure 7: Same as Fig. 5 except at (94.0E, 59.6N).

3 Summary

The second-order ADI method provides more than 2.6 times CPU saving compared with the fourth-order RK method, while retaining a reasonable accuracy in the derived bending angle profile. The accuracy of bending angle derived from phase delays of the simulated rays depends on the vertical resolution used in the forward raytracing observation operator. A 10 Hz vertical resolution can produce a much more accurate bending angle profile than those at 2 Hz and 5 Hz resolutions. A bias correction is suggested to remove potential inconsistencies between forward observation operator and GPS/MET data processing procedure. The GPS/MET bending angle assimilation using an approximated diagonal observation error covariance matrix produced an overall improved analysis when compared with independent radiosonde observations. However, the impact of GPS/MET sounding judging from the results of GPS/MET bending angle assimilation varies from sounding to sounding. Further experiments testing the sensitivity of the GPS/MET bending angle assimilation results to the specification of observation error covariance matrix are being conducted. Results will be presented at the conference.

Acknowledgment

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