Assimilation of GPS radio occultation measurements at NCEP

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The Joint Center for Satellite Data Assimilation (JCSDA) was established in 2001 to accelerate and improve the quantitative use of research and operational satellite data in weather and climate prediction models. The partners of the JCSDA are: (1) NOAA/NWS/NCEP Environmental Modeling Center, (2) NOAA/NESDIS Office of Research and Applications, (3) US Navy, (4) NASA/GSFC Global Modeling and Assimilation Office, (5) NOAA/OAR Office of Weather and Air Quality, and (6) US Air Force. One of the priority projects at the JCSDA has been to develop the infrastructure (codes, scripts, etc) necessary to operationally monitor and assimilate COSMIC GPS radio-occultation (RO) observations at NOAA.

In April 2006, the COSMIC mission (a joint project between the US and Taiwan) launched six Low-Earth Orbit (LEO) satellites into a circular polar orbit from Vandenberg Air Force Base, California (Anthes at al. 2008). Each of the LEO satellites carries a GPS RO receiver to measure time delays of the GPS signals traveling from the GPS to the LEO satellites. As a GPS satellite occults behind the Earth's atmosphere, one can retrieve accurate information (sub-Kelvin temperature accuracy between ~5-30 km) on the thermodynamic state of the atmosphere traversed by the ray path (Kursinski et al.1997, Rocken et al. 1997).

Over the past few years, the NCEP Environmental Modeling Center (EMC) has developed a new Global Data Assimilation System. This system includes the capability to assimilate two different forms of GPS RO retrieved-observations. The first type of data is the bending angle, the change in the ray-path direction accumulated along the ray-path. The second type of derived-observation is the refractivity, which in the neutral atmosphere at the GPS frequencies is a function of temperature, water vapor pressure and pressure. Soundings of refractivity are derived from soundings of bending angle after several assumptions and processing steps (Kursinski et al. 1997).

With the implementation of the new NCEP's Global Data Assimilation System on 1 May 2007 into operations, the assimilation of GPS RO observations from the COSMIC mission became operational at NOAA/NCEP. Observations from both rising and setting occultations are assimilated and there is no rejection of the low-level observations from the assimilation system, provided they pass the quality control checks.

The assimilation of the GPS RO data required the development of an appropriate forward model, the adjoint of the forward model, appropriate observational and representativeness error estimates, quality control procedures, data handling routines and data monitoring software. In preparation for the use of COSMIC data, the NCEP Environmental Modeling Center (EMC) developed the capability to assimilate soundings of bending angle and derived refractivity profiles.

The forward operator used to simulate observations of refractivity as a function of the geometric height (z) is composed of the following steps:

- Compute model geopotential heights at the location of the observations

- Convert geometric height of the observation (*z*) to geopotential height in order to locate the observation within the model's vertical grid.
- Interpolate model profiles of pressure, temperature and water vapor pressure to the location of the observation.
- Get model refractivity N ,

$$N = 77.6\left(\frac{P}{T}\right) + 3.73\times 10^5\left(\frac{P_v}{T^2}\right),$$

where P is the total atmospheric pressure (in hPa), T is the atmospheric temperature (in Kelvin), and P_v is the partial pressure of water vapor (in hPa). The quality control implemented in the code is based on a month-long comparison between observations and forecasts of N. In the assimilation system, observations are rejected if they deviate from the forecast more than three standard deviations or if an observation above it in the same profile is rejected.

Forecasts of bending angle (α) as a function of the asymptote miss distance a are computed by evaluating the following integral:

$$\alpha(a) = -2a\int_a^\infty \frac{d\ln n / dx}{(x^2 - a^2)^{1/2}}\,dx$$

$$(x = nr)$$

where n is the index of refraction and r is the radius of a point on the trajectory of the ray. The magnitude x is the refractional radius. The impact parameter remains constant along the trajectory of a ray for a spherically symmetric atmosphere. The singularity in the integrand at $x = a$ can be overcome by evaluating the integral on a new grid s, where

$$x = \sqrt{a^2 + s^2}$$

The integral is then evaluated in an equally spaced grid in s, so the trapezoidal rule can be easily and accurately applied. In order to simulate bending angles from model variables the following steps are applied:

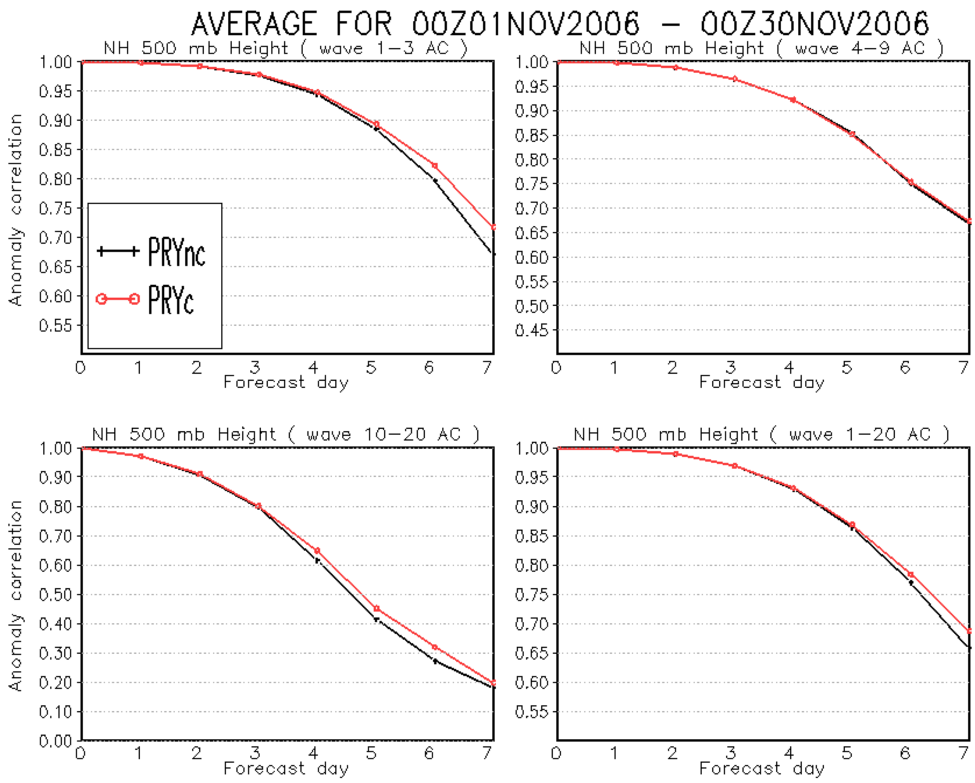
- Model profiles of geopotential heights and N are computed at the location of the observation. Geopotential heights are then converted to geometric heights z.
- The radius r is obtained by adding z to the radius of curvature of the local spherical fit to the ellipsoid.
- Profiles of N are converted to refractive index profiles, n=1+$10^{-6}N$
- Model profiles of refractional radius x=nr are calculated.
- n and x are extrapolated above the model top by assuming an exponential decay for N within the two uppermost layers.
- Model profiles of n and x are interpolated to the new grid s.
- The integrand is computed on the new grid s.
- The integral is evaluated in an equally spaced grid.

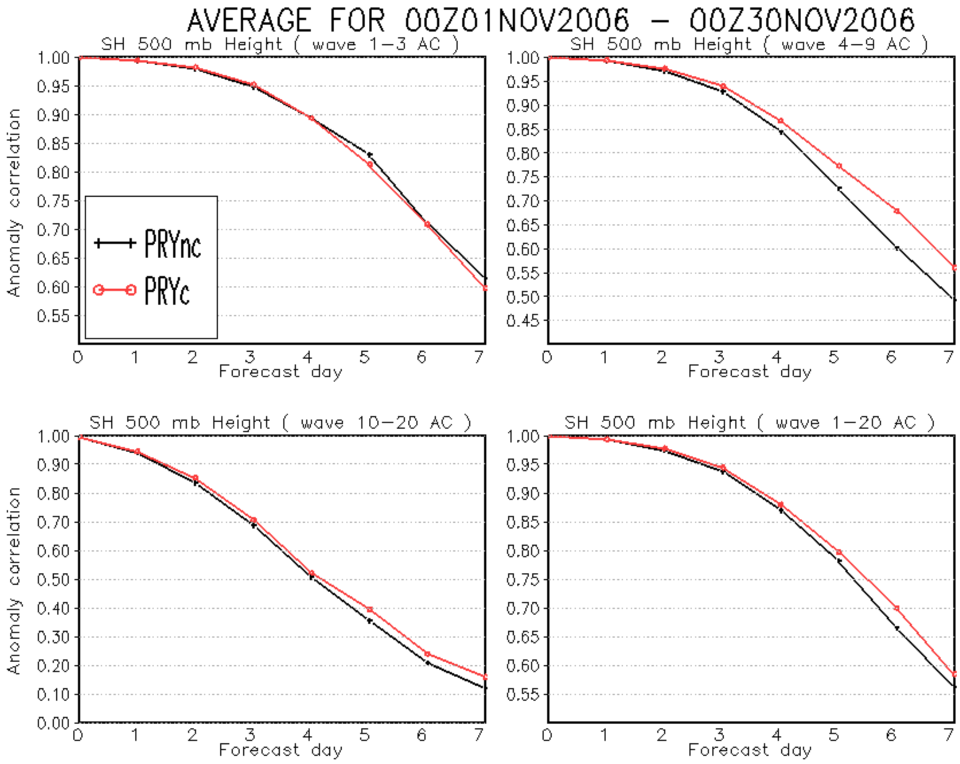
As in the case of refractivity, an observation is rejected if it deviates more than three standard deviations from its forecast counterpart or, if it is below 10 km, any observation above it in the same profile is rejected. The statistics are based on the same-month comparison between observations and forecasts of α as used in the case of refractivity.

The implementation of the forward operators for refractivity and bending angle passed all the tangent linear and adjoint tests. In the minimization algorithm, surface pressure and model profiles of temperature and humidity are adjusted to fit the observations of *N*. The geopotential heights of the model levels are updated through the increments in model (virtual) temperatures and surface pressure. Consequently, the observations are allowed to change their location in the vertical within the model.

Preliminary experiments with COSMIC showed better model skill when profiles of refractivity were assimilated into the system than with the use of bending angles. As a result, the use of refractivity was selected for operational implementation at NOAA/NCEP on 1 May 2007 along with the implementation of the new NCEP's data assimilation system. The tuning of the system to improve the model skill when assimilating soundings of bending angle is under current research at the JCSDA.Impact studies with COSMIC refractivities showed an increase of the anomaly correlation scores as a function of the forecast day for the mass (temperature and geopotential height) field. The improvement in model skill was found to be significant in the Northern and Southern hemispheres. A significant overall reduction of the mass and humidity model bias and root-squared error was also achieved when profiles of COSMIC were assimilated in the system. The reduction of the temperature model error was more significant in the upper troposphere and stratosphere. The benefits of the use of COSMIC data on top of the other observations being used in operations were found for the different periods being tested.

The two plots below show the impact of the COSMIC data on top of the other observations being used operationally at NCEP for November 2006 (pre-operational implementation tests). The plots show the anomaly correlation scores as a function of the forecast length for the 500-hPa geopotential heights for the Northern and Southern hemispheres. The improvement of the run PRYc (with COSMIC data) on top of PRYnc (without COSMIC data) is evident.





Some of the recent achievements at the JCSDA after operational implementation of COSMIC GPS RO observations are the following:

- Monitor transition of COSMIC data into operations.
- Improve diagnostic files for GPS RO in the GSI code.
- Generalize the GPS RO code in GSI to use any vertical coordinate system.
- Analysis of more impact studies with COSMIC for different areas and periods. (The use of COSMIC improves model skill).
- Improve assimilation of GPS RO over areas of complex topography.
- Testing, evaluation and feed-back to UCAR on stratospheric bug-fixed profiles. (UCAR improved the quality of the profiles in the stratosphere in November 2007).
- Correct weights associated to the vertical levels surrounding a GPS RO observation in GSI.
- Transition of (GFZ) CHAMP & GRACE-A data into the operational tanks.

Other (ongoing) GPS RO activities:

- Evaluation & assimilation of GPS RO data into the new NCEP's reanalysis system (CFSRR project, NCEP/EMC).
- Assess the use of COSMIC data to retrieve ABL heights for assimilation into the real-time mesoscale analysis system (RTMA). [NASA-funded Homeland Security project, within the Air Quality Group at NCEP/EMC].

- Use of GPS RO derived products of temperature and water vapor to validate other satellite instrument data and extend the NOAA/NESDIS 1dvar capability to include GPS RO (NOAA/NESDIS).
- Evaluation of the requirements needed to add the GPS RO capability to conduct OSSEs within the international Joint OSSE project (CEOS Category 1 action WE-07-1_3).
- POC at NESDIS/OSD & NWS (and EMP) for user requirements for GPS RO data. [Evaluation/planning for a possible GPS RO follow-on mission].

Current and future work at the JCSDA include the following tasks:

- Update quality control checks & observation error characteristics for GPS RO data in NCEP's system. (Some parallel runs are underway).
- Improve (refractivity) forward operator for GPS RO data.
- Evaluation, testing, tuning and (likely) assimilation of GPS RO from (GFZ) CHAMP & GRACE-A (in pre-operational mode) and MetOp/A GRAS (when available). [Possible availability of SAC-C data in real-time as well. Negotiations are underway].
- Develop the necessary code infrastructure to monitor the GPS RO statistics (perl-based statistics tool developed in collaboration with Doug Hunt from UCAR/CDAAC) and transition to operations.
- Assimilation of COSMIC observations (and other GPS RO missions) into NCEP's regional model (NAM).
- Improve the performance of the assimilation of observations of bending angle (switch to bending angle in operations? Global and regional systems?).
- Explore more complex forward operators to take into account horizontal gradients of refractivity (2D forward operators).

References:

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Radio Occultation concept. n An occultation occurs when a GNSS satellite rises or sets across the limb wrt to a LEO satellite n A ray passing through the atmosphere is refracted due to the vertical gradient of refractivity (density and moisture) n During an occultation (~ 3min) the ray path slices through the atmosphere. Raw measurement: change of the delay (phase) of the signal path between the GNSS and LEO during the occultation. (It includes the effect of the neutral atmosphere and the ionosphere). GPS transmits at two different. frequencies: ~1.6 GHz (L1). and ~1.3 GHz (L2).Â Â§ Operational assimilation of RO at NCEP switched from soundings of refractivity to soundings of bending angle in May 2012. Top of the profiles raised from 30 to 50 km. In general, the GPS RO data assimilation may improve prediction of severe weather such as typhoons and Mei-yu systems when COSMIC data were available, ranging from several points in 2006 to a maximum of about 60 in 2007 and 2008 in this region. Based on a number of experiments, regional model predictions at 5 km resolution were not significantly influenced by different observation operators, although the nonlocal observation operator sometimes results in slightly better track forecast.Â Cucurull L, Derber JC, Treadon R, Purser RJ (2007) Assimilation of global positioning system radio occultation observations into NCEPâ€™s global data assimilation system. Mon Wea Rev 135:3174â€“3193. Article Google Scholar. First, a rayâ€tracing observation operator that links the atmospheric state to the GPS refraction angle measurements is developed, the physics and numerics involved are described, and the simulated refraction angles, based on the NOAA National Centers for Environmental Prediction (NCEP) global analysis, are compared with the observed GPS/MET refraction angle measurements.Â Hui Liu, Ying-Hwa Kuo, Sergey Sokolovskiy, Xiaolei Zou, Zhen Zeng, Ling-Feng Hsiao, Benjamin C. Ruston, A Quality Control Procedure Based on Bending Angle Measurement Uncertainty for Radio Occultation Data Assimilation in the Tropical Lower Troposphere, Journal of Atmospheric and Oceanic Technology, 10.1175/JTECH-D-17-0224.1, 35, 10, (2117-2131), (2018). 2. GPS radio occultation profile retrieval using geometric optics. 2.1 Introduction. 2.2 The radio signal refraction in the atmosphere.Â 4.6 Comparison of GPS derived pressure with ECMWF, NCEP and ra-diosonde data . . . 4.6.1 GPS occultation dataset . . . 4.6.2 Method . . .Â The GPS occultation measurements are more suitable for climate study because of their comparable accuracy with radiosonde mea-surements and no need for heterogeneous instrument calibration [Kuo et al., 2005].