Radio Occultation Observations for Weather, Climate and Ionosphere

Overview and Infrastructure Needs

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Overview

• Radio Occultation (RO) introduction
• Societal and scientific impact of RO
  – Weather
  – Climate
  – Ionosphere
• Future missions - and infrastructure needs
The velocity of GPS relative to LEO must be estimated to $\sim 0.1 \text{ mm/sec}$ (10 ppb) to determine precise temperature profiles.

The LEO tracks the GPS phase while the signal is occulted to determine the Doppler.
Evolving COSMIC Constellation

Temperature [°C] at 100 mb (16km)
Comparison of collocated Profiles
Leading Weather Center Newsletters

News in This Quarter
Science Update

Cosmic Data to be Assimilated Operationally at NOAA

After successful testing at the JCSDA, Global Positioning System (GPS) radio occultation (RO) soundings from the COSMIC mission will go into operational use with the implementation of the Orgridac Statistical Inflation (OASIS) Global Forecast System (GFS) system at NOAA/ESRL on May 1st, 2007.

In preparations for the assimilation of COSMIC data, the JCSDA developed, tested and incorporated the necessary components to assimilate GPS RO profiles. These components include forecast operators and associated tangent linear and adjoint models, quality control algorithms, error characterization models, data handling, deprioritization, verification and impact evaluation techniques.

Impact tests indicate that the assimilation of GPS RO observations improves the fit to reanalysis observations by reducing the mean and root-mean-square differences in the upper troposphere and stratosphere. The assimilation produces AC scores for both the Northern and Southern Hemispheres also improved with the use of COSMIC data for the test period, November 2006. In general, the performance in AC scores will be more or less significant depending on the mesoscale variability and the model performance for the period under study. The accompanying figure shows the 500 mb geopotential height (AC) as a function of the forecast range in the Southern Hemisphere for November 1st to 30th 2006. The assimilation of COSMIC data (PR) to 2006 improves the AC scores when compared to the control run (PR, no assimilation). Both PR/AC and PR/PR runs assimilate all the observations currently being used in operational. Therefore the difference between the runs is due to the impact of assimilating COSMIC data.

COSMIC, the Constellation Observing System for Meteorology, Imageries and Climate, a joint European U.S. project, was launched in April 2006. The satellite provides high vertical resolution inflation on atmospheric temperature/humidity at a thousand locations each day.

(From Coonfield, JCSDA-NOAA)

Assimilation of MLS Ozone Observations Improves Antarctic Ozone Hole Depiction

NASA's S0S Aura satellite provides comprehensive atmospheric chemical composition measurements. For example, the Aura Microwave Limb Sounder (MLS) instrument captures ozone profiles with the vertical resolution of about 3 km in the stratosphere. These data can be used to constrain atmospheric ozone in atmospheric models, potentially improve assimilation of inferred radiances, and provide a better field for radiative computations. In combination with Aura's Ozone Monitoring Instrument (OMI) total column ozone measurements, the MLS ozone data can also be used to estimate tropospheric ozone, which is an important component of the air quality.

The Goddard Earth Observing System-5 (GEOS-5) Data Assimilation System at NASA Goddard's Global Modeling and Assimilation Office (GMAO) uses the Orgridac Statistical Inflation (OASIS) Global Forecast System (GFS) system at NOAA/ESRL to assess the impact of assimilation of ozone profiles, such as those produced by ozone sensors on the Aura MLS.

The results from a recent one-month assimilation of MLS ozone data are very encouraging. The figure below shows the comparison of ozone partial pressure (nPa) at the end of the one-
ECMWF SH T Forecast Improvements from COSMIC
Assimilation of bending angles above 4 km

Sean Healy, ECMWF

ccontrol normalised ox01 minus oetyg
Root mean square error forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20060914 00UTC to 20061125 12UTC
100hPa Temperature
Confidence: 95%
Population: 100
Impact of COSMIC on Hurricane Ernesto (2006) Forecast

With COSMIC

Without COSMIC

Results from Hui Liu, NCAR
Impact of COSMIC on Hurricane Ernesto (2006) Forecast

With COSMIC

GOES Image

GOES Image from Tim Schmitt, SSEC
Climate
Upper Air Temperature Trends

Figure from S. Leroy
The uncertainty of the trend of fractional refractivity anomalies is within +/-0.045 %/5 yrs ( +/-0.06K/5 yrs), which is mainly caused by sampling errors.
Comparability of CHAMP to COSMIC: Long-term stability

Global COSMIC-CHAMP Comparison from 200607-200707

- Comparison of measurements between old and new instrument
- CHAMP launched in 2001
- COSMIC launched in 2006

Challenges:
- Different inclination angle
- Different atmospheric paths
- Temporal/spatial mismatch
- Reasonable sample number
Space Weather
3-D structure of the feature during daytime (constant LT)

Weaker EIA  Stronger EIA  Weaker EIA  Stronger EIA  Weaker EIA

12:00 LT

Tiger Liu, NCU
Characteristics of RO Data

- Limb sounding geometry complementary to ground and space nadir viewing instruments
- Global 3-D coverage 40 km to surface
- High accuracy (equivalent to <1 K; average accuracy <0.1 K)
- High precision (0.02-0.05 K)
- High vertical resolution (0.1 km surface – 1 km tropopause)
- Only system from space to resolve atmospheric boundary layer
- All weather-minimally affected by aerosols, clouds or precipitation
- Independent height and pressure
- Requires no first guess sounding
- Independent of radiosonde calibration
- Independent of processing center
- No instrument drift
- No satellite-to-satellite bias
- Compact sensor, low power, low cost
The GPS Observation Equation

\[ L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys}^s + \delta \rho_{trp} + \delta \rho_{ion} + \delta \rho_{rel} + \delta \rho_{mul} + \lambda \cdot N_r^s + \ldots + \epsilon \]

- \( \rho_r^s \): Geometrical distance between satellite and receiver
- \( c \): Speed of light in vacuum
- \( \delta t_r \): Station clock correction: *receiver clocks* (time and frequency transfer)
- \( \delta t_{r,sys} \): Delays in receiver and its antenna (cables, electronics, ...)
- \( \delta t^s \): Satellite clock correction: *satellite clocks*
- \( \delta t_{s,sys} \): Delays in satellite and its antenna (cables, electronics, ...)
- \( \delta \rho_{trp} \): Tropospheric delay: *troposphere parameters* (meteorology, climatology)
- \( \delta \rho_{ion} \): Ionospheric delay: *ionosphere parameters* (atmosphere physics)
- \( \delta \rho_{rel} \): Relativistic corrections (Special and General Relativity)
- \( \delta \rho_{mul} \): Multipath, scattering, bending effects
- \( \lambda \): Wavelength of the GPS signal (\( L_1 \) or \( L_2 \))
- \( N_r^s \): Phase ambiguity: *ambiguity parameters* (ambiguity resolution)
- \( \epsilon \): Measurement error
From Phase to Excess Phase

\[ L_r^s = \rho_r^s + c \cdot \delta t_r + c \cdot \delta t_{r,sys} - c \cdot \delta t^s - c \cdot \delta t_{sys} + \delta \rho_{trp} + \delta \rho_{ion} + \delta \rho_{rel} + \delta \rho_{mul} + \lambda N_r^s + \ldots + \epsilon \]
Data from (parts of) this network are presently used to estimate GPS satellite clocks in real-time (@UCAR) or for double differencing GPS clocks (@JPL).

Hydrogen masers (57) are indicated in brown, cesiums (32) in green, and rubidiums (30) in blue. Stars indicate clocks at BIPM timing laboratories (includes standard labs at NIST, Paris, Braunschweig, ....)
Coverage of possible future LEO constellations

12 sat constellation - 24 Hours

28 GPS
Add 24 GLONASS
Add 30 Galileo

Future constellations will track Galileo + possibly Glonass
GNSS Infrastructure Needs for RO

• Weather
  – Near-Real-Time (<15 min) global ground fiducial data
    (1-sec from ~50 sites GPS + Galileo + Glonass)
  – High quality GNSS orbits (real-time / predicted) and clocks (5 sec)

• Climate
  – Stable long-term (decades) reference frame
  – Reliable fiducial data & meta-data

• Space Weather
  – Real-Time reference data
  – Satellite + tracking station DCBs

• All will need PCVs for transmitters and receivers
Summary

• Atmospheric sensing with RO has important operational and scientific applications
• All applications depend in GNSS infrastructure provided by the non-atmospheric community
• Future RO missions are planned and the atmospheric community (climate community) will need many decades of infrastructure support