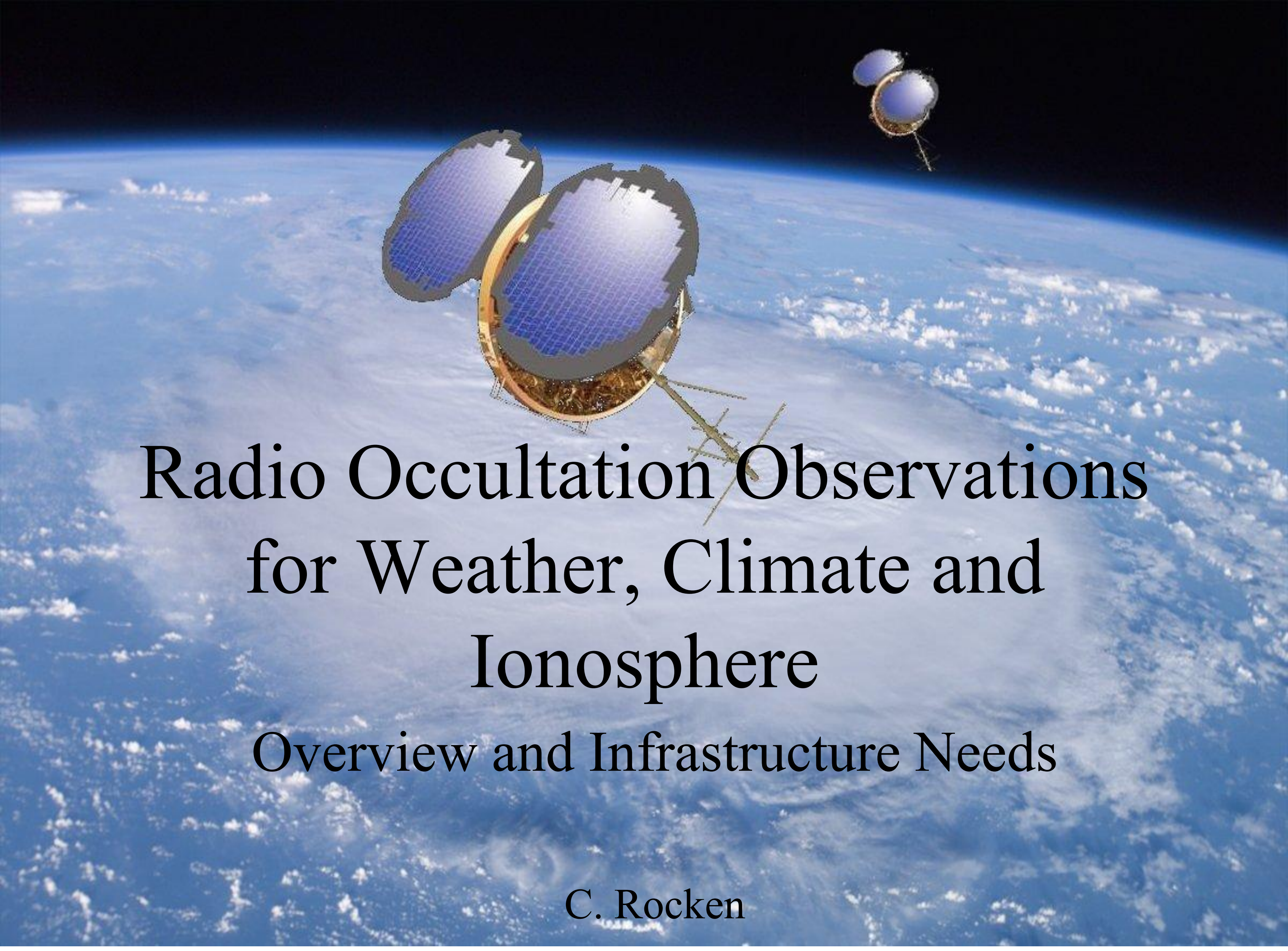


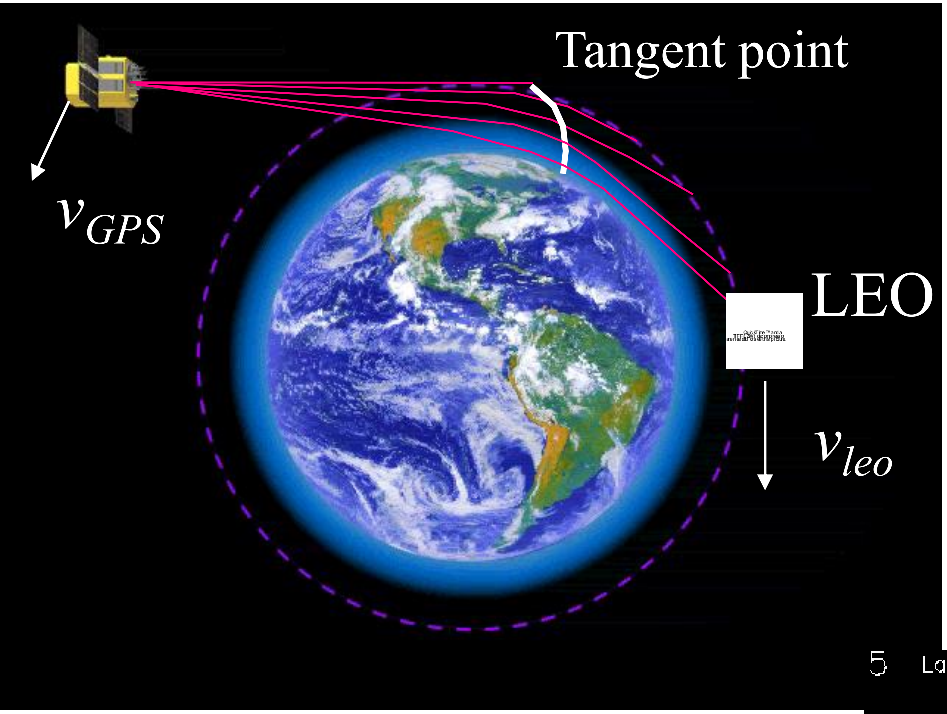
Radio Occultation Observations for Weather, Climate and Ionosphere

Overview and Infrastructure Needs

C. Rocken

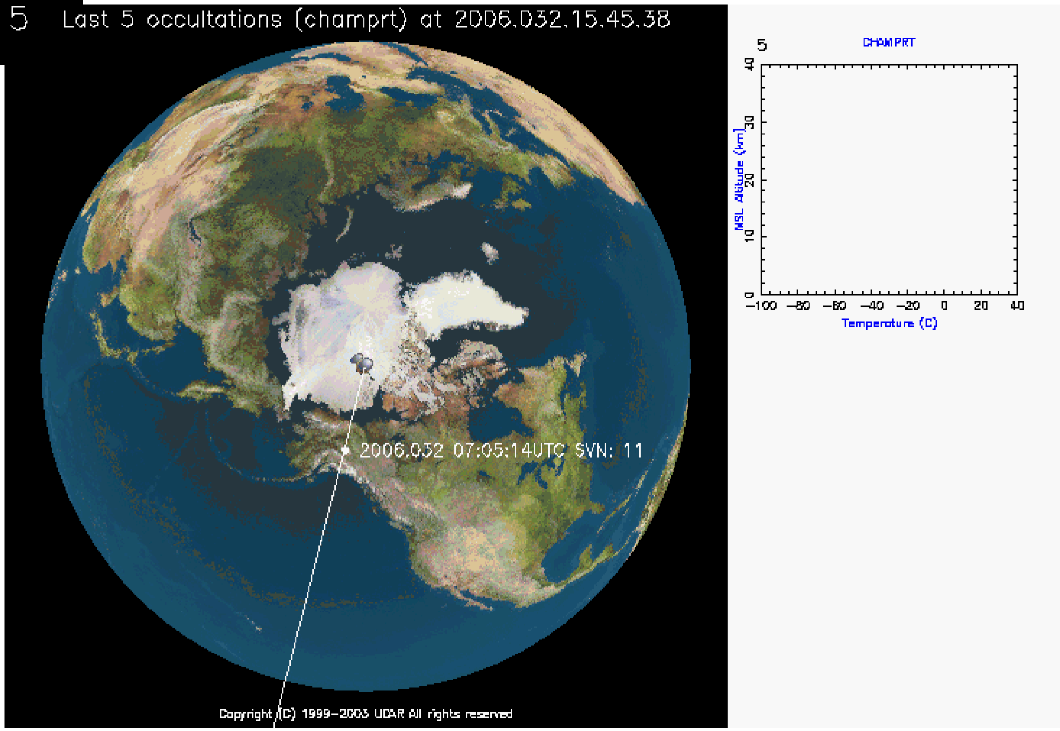
Overview

- Radio Occultation (RO) introduction
- Societal and scientific impact of RO
  - Weather
  - Climate
  - Ionosphere
- Future missions - and infrastructure needs



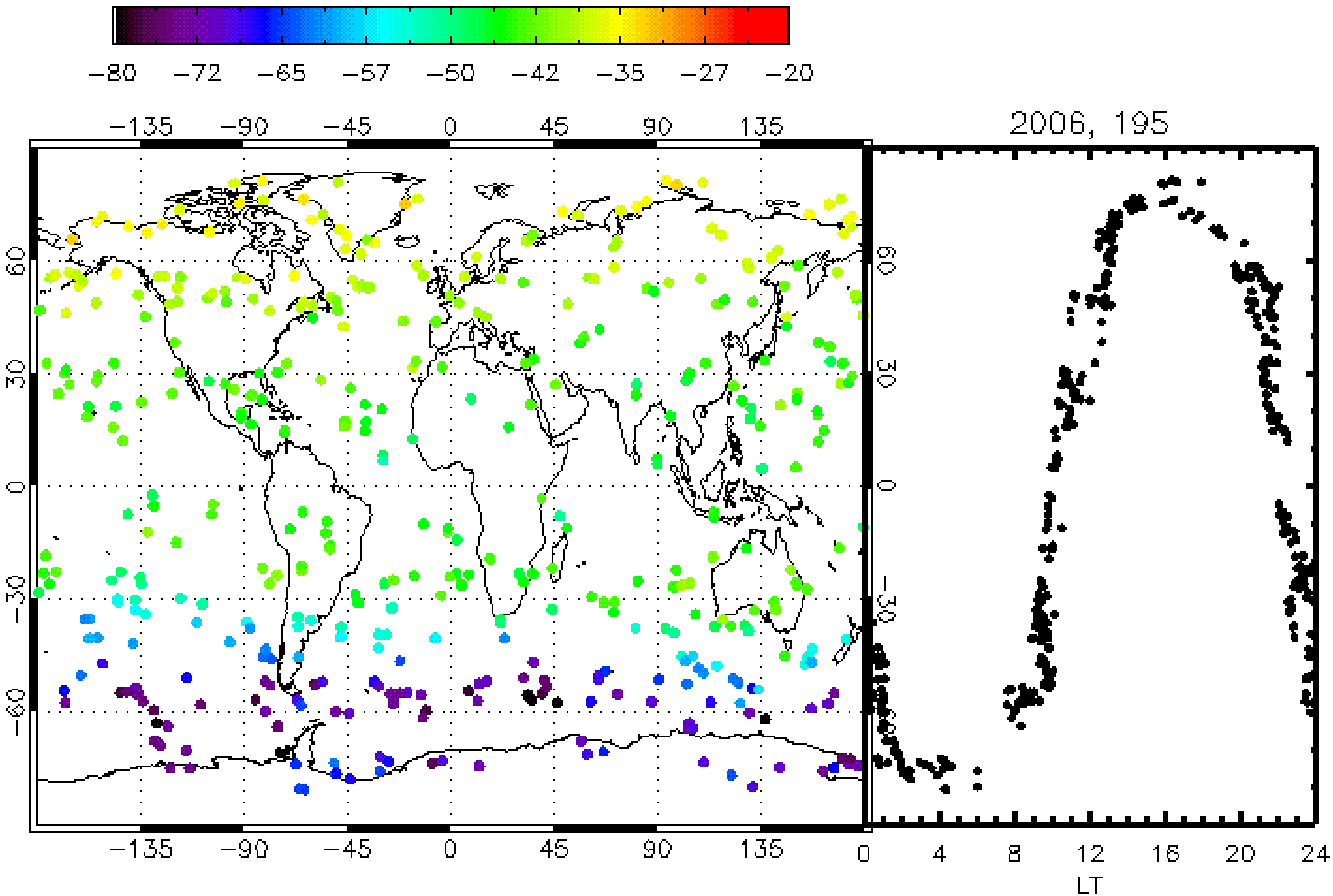
The LEO tracks the GPS phase while the signal is occulted to determine the Doppler

The velocity of GPS relative to LEO must be estimated to **~0.1 mm/sec** (10 ppb) to determine precise temperature profiles

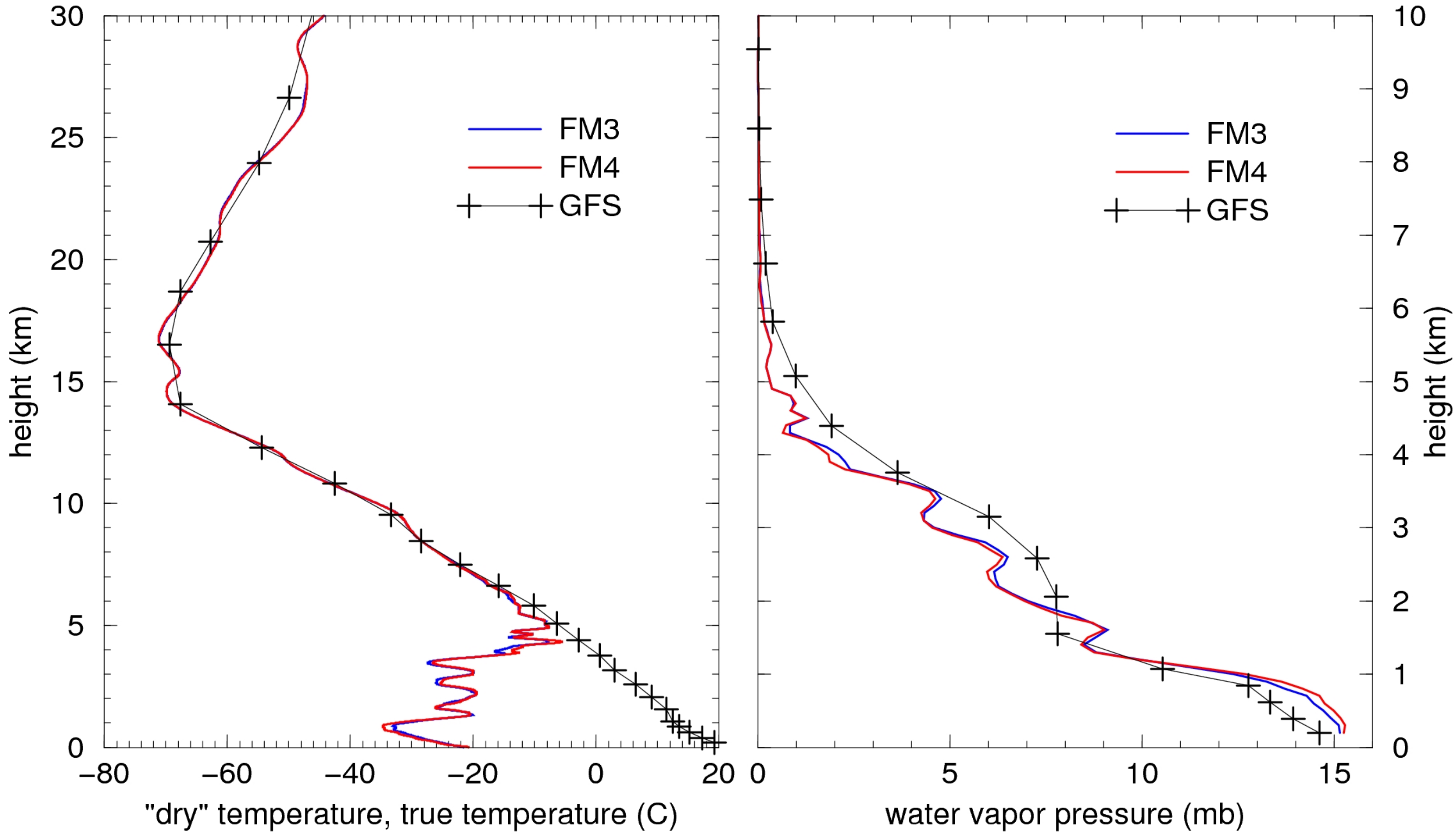


Evolving COSMIC Constellation

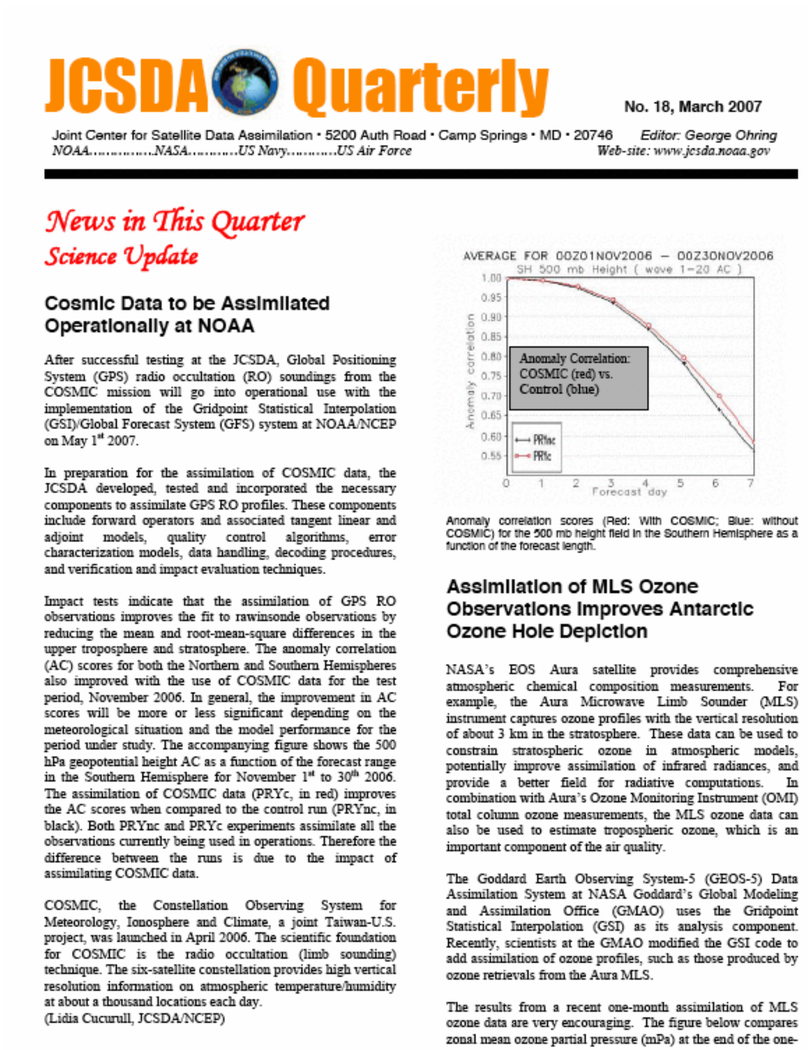
Temperature [C] at 100 mb (16km)



Comparison of collocated Profiles



Leading Weather Center Newsletters



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Joint Center for Satellite Data Assimilation • 5200 Auth Road • Camp Springs • MD • 20746 *Editor: George Ohring*
NOAA……………NASA…………US Navy…………US Air Force *Web-site: www.jcsda.noaa.gov*

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 Gridpoint Statistical Interpolation (GSI)/Global Forecast System (GFS) system at NOAA/NCEP on May 1st 2007.

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

Impact tests indicate that the assimilation of GPS RO observations improves the fit to rawinsonde observations by reducing the mean and root-mean-square differences in the upper troposphere and stratosphere. The anomaly correlation (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 improvement in AC scores will be more or less significant depending on the meteorological situation and the model performance for the period under study. The accompanying figure shows the 500 hPa 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 (PRYc, in red) improves the AC scores when compared to the control run (PRYnc, in black). Both PRYnc and PRYc experiments assimilate all the observations currently being used in operations. Therefore the difference between the runs is due to the impact of assimilating COSMIC data.

COSMIC, the Constellation Observing System for Meteorology, Ionosphere and Climate, a joint Taiwan-U.S. project, was launched in April 2006. The scientific foundation for COSMIC is the radio occultation (limb sounding) technique. The six-satellite constellation provides high vertical resolution information on atmospheric temperature/humidity at about a thousand locations each day.
(Lidia Cucurull, JCSDA/NCEP)

Anomaly correlation scores (Red: With COSMIC; Blue: without COSMIC) for the 500 mb height field in the Southern Hemisphere as a function of the forecast length.

Assimilation of MLS Ozone Observations Improves Antarctic Ozone Hole Depiction

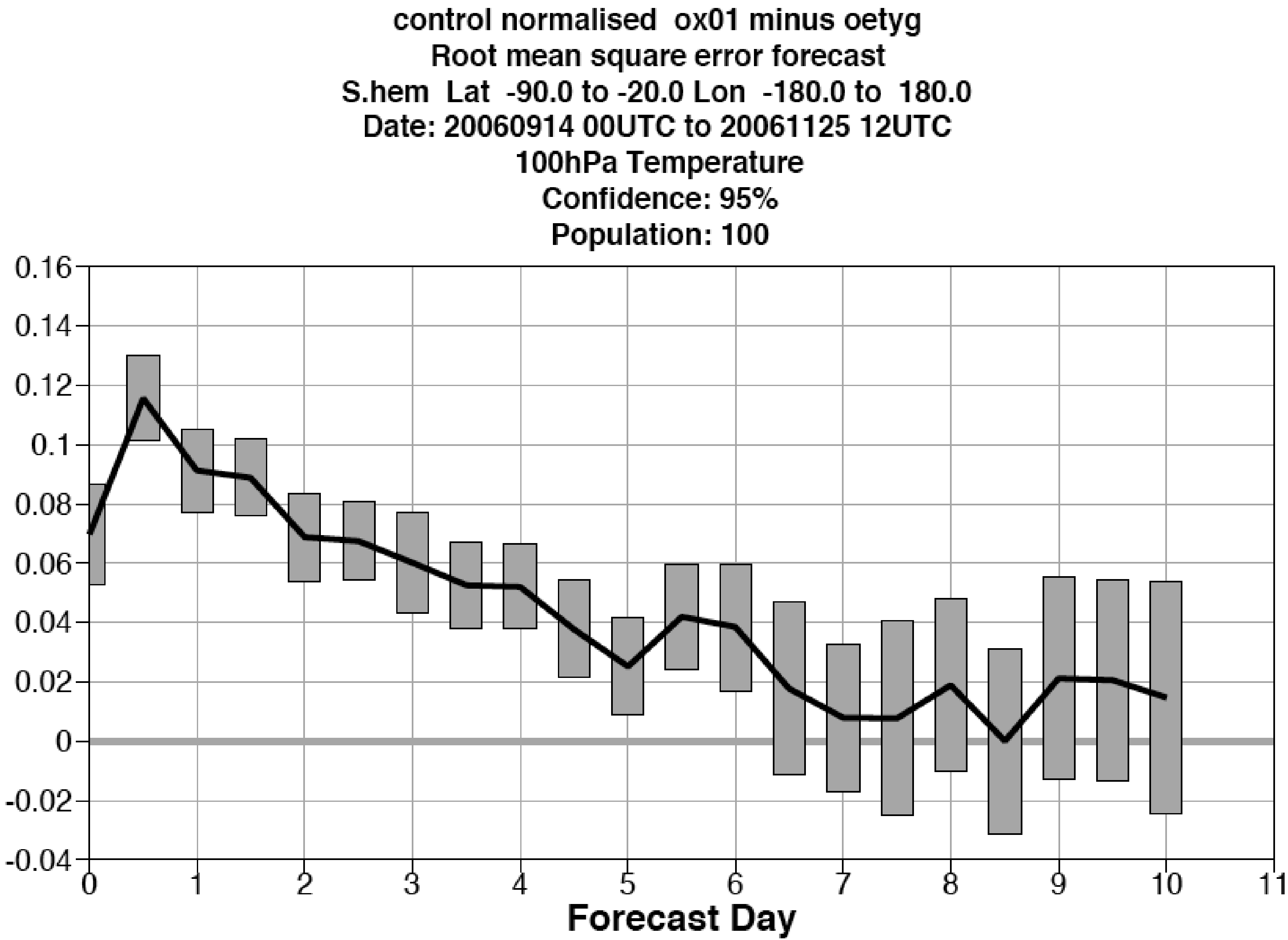
NASA's EOS Aura satellite provides comprehensive atmospheric chemical composition measurements. For example, the Aura Microwave Limb Sounder (MLS) instrument captures ozone profiles with the vertical resolution of about 3 km in the stratosphere. These data can be used to constrain stratospheric ozone in atmospheric models, potentially improve assimilation of infrared 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 Gridpoint Statistical Interpolation (GSI) as its analysis component. Recently, scientists at the GMAO modified the GSI code to add assimilation of ozone profiles, such as those produced by ozone retrievals from the Aura MLS.

The results from a recent one-month assimilation of MLS ozone data are very encouraging. The figure below compares zonal mean ozone partial pressure (mPa) at the end of the one-

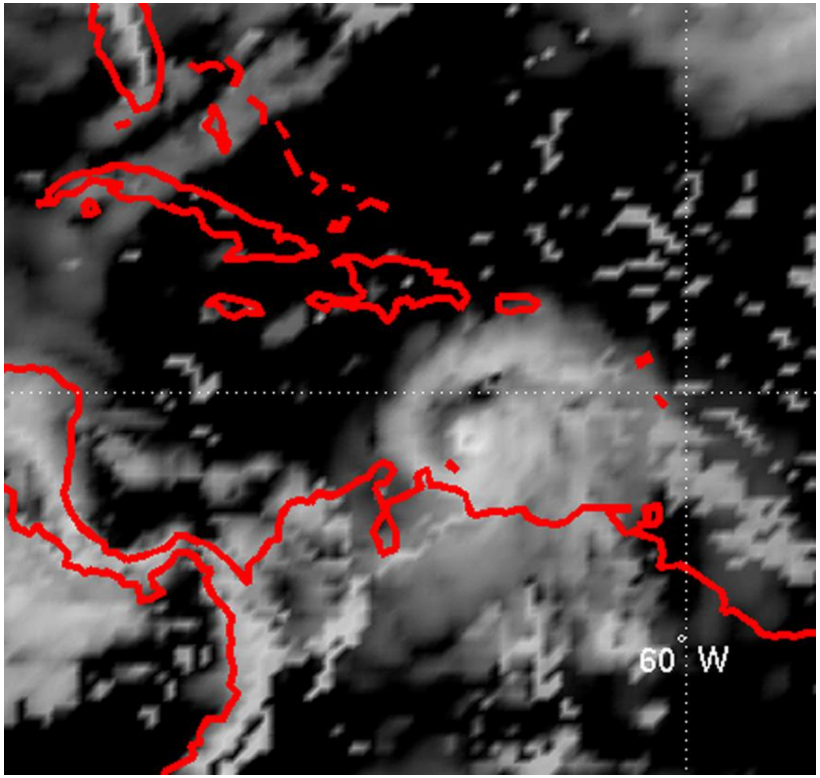
ECMWF SH T Forecast Improvements from COSMIC
Assimilation of bending angles above 4 km

Sean Healy, ECMWF

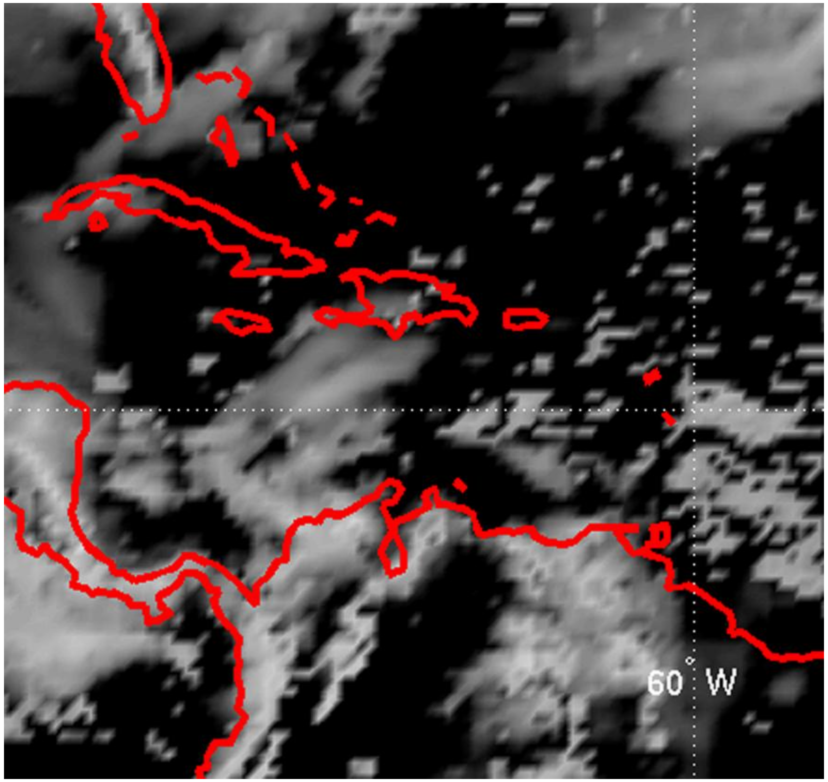


Impact of COSMIC on Hurricane Ernesto (2006) Forecast

With COSMIC



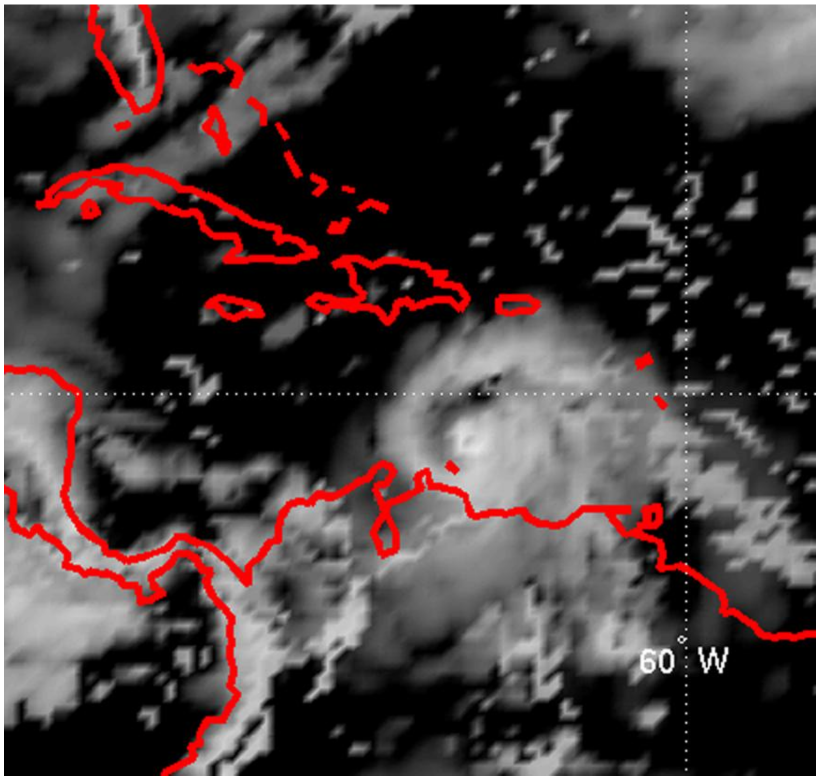
Without COSMIC



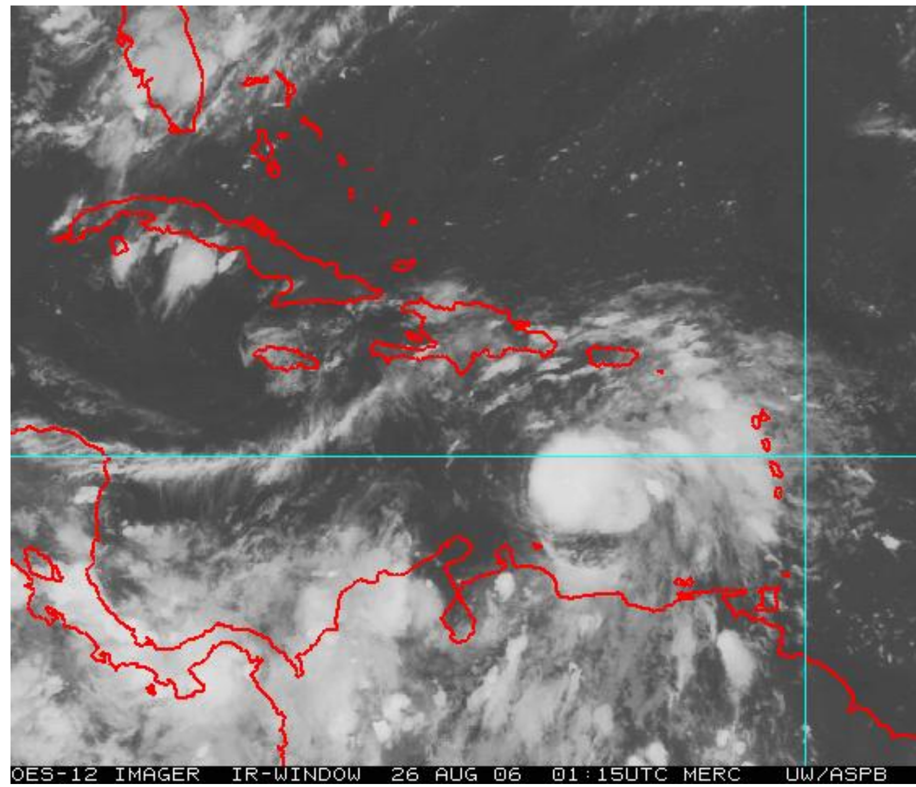
Results from Hui Liu, NCAR

Impact of COSMIC on Hurricane Ernesto (2006) Forecast

With COSMIC



GOES Image



GOES Image from Tim Schmitt, SSEC

Climate

Upper Air Temperature Trends

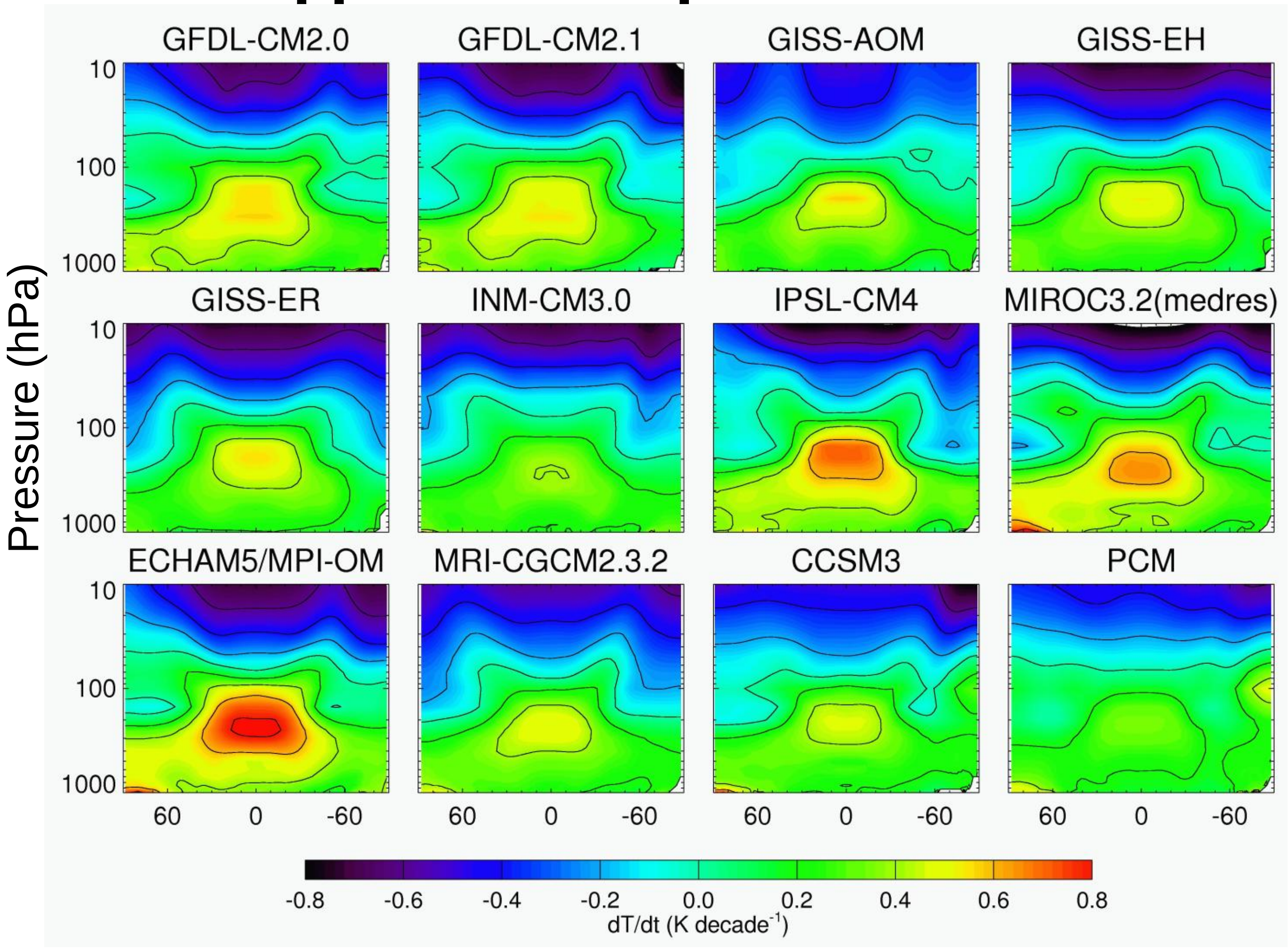
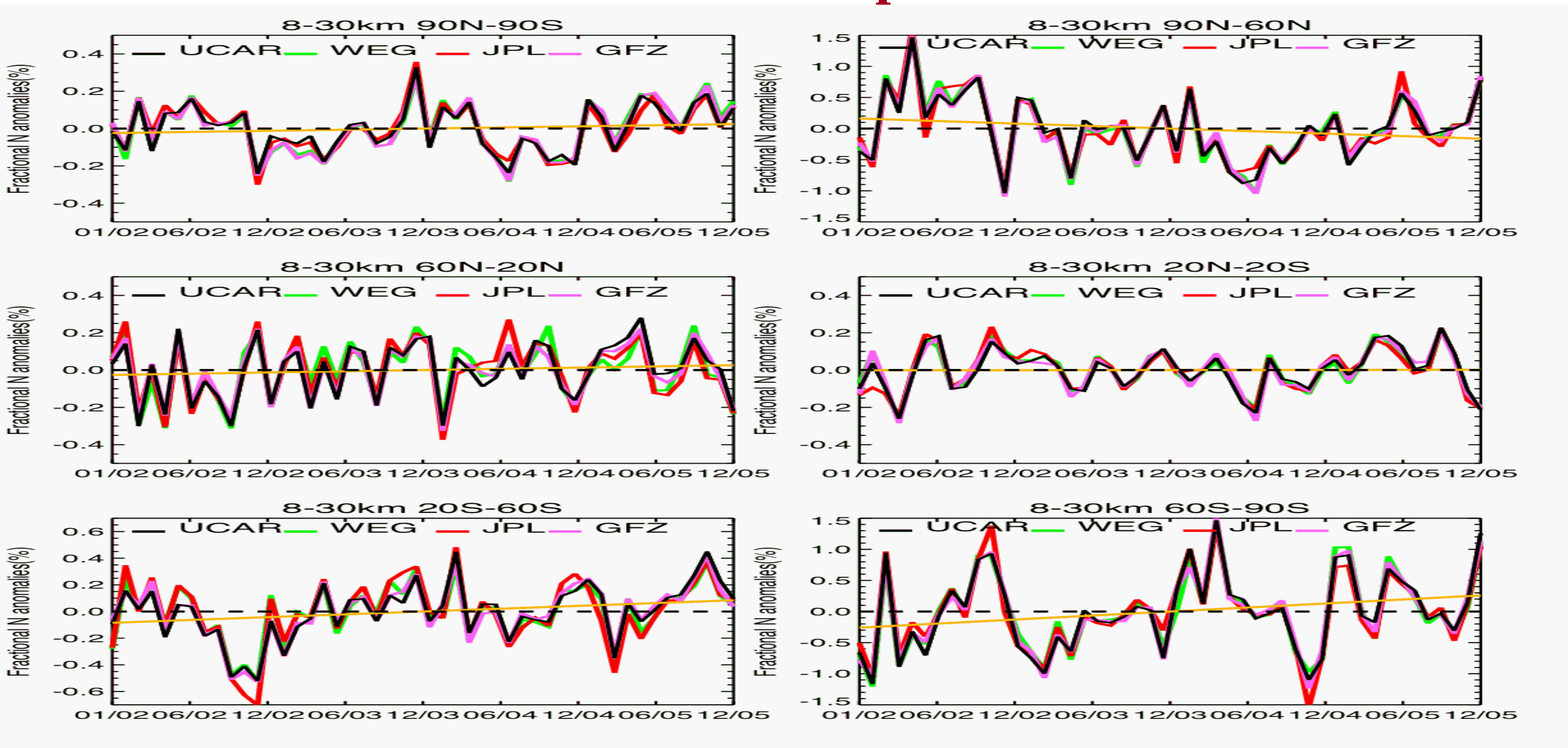
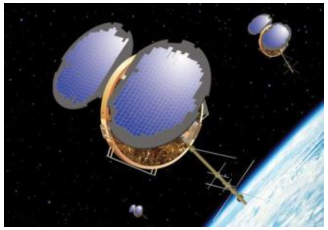


Figure from S. Leroy

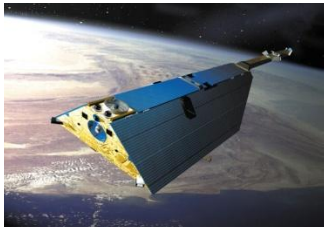
Estimates of the Uncertainty in RO Data for Climate Monitoring: Inter-Comparisons of Refractivity Derived from Four Independent Centers



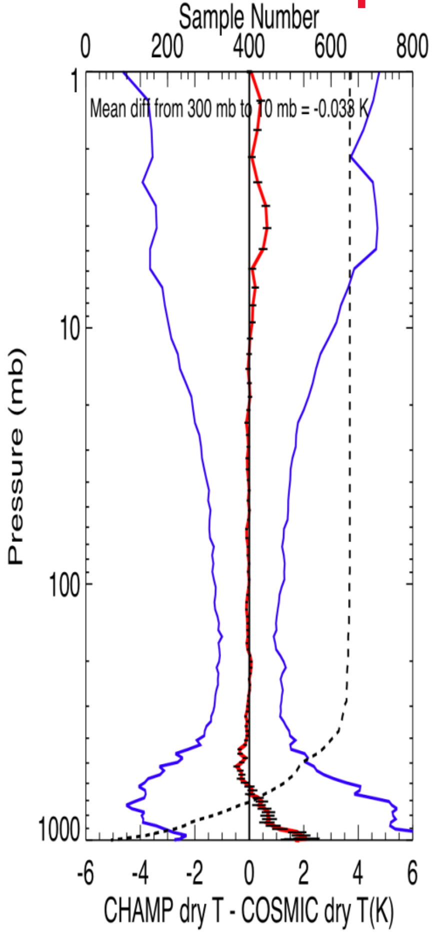
The uncertainty of the trend of fractional refractivity anomalies is within +/-0.045 %/5 yrs (+/-0.06K/5 yrs), which is mainly caused by sampling errors.



Comparability of CHAMP to COSMIC:Long-term stability



Global COSMIC-CHAMP Comparison from 200607-200707



Within 90 Mins and 100 Km

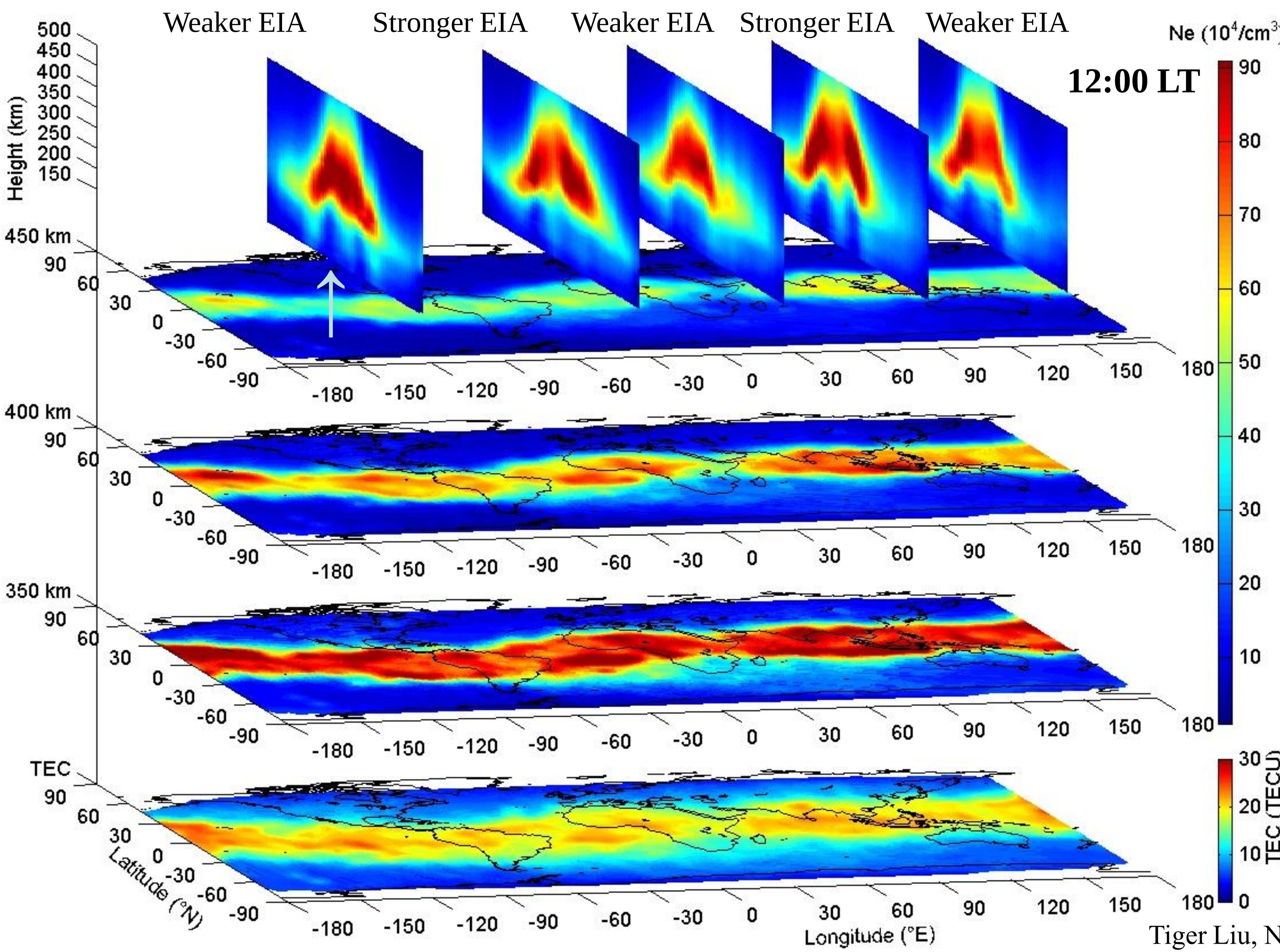
- Comparison of measurements between old and new instrument
- CHAMP launched in 2001
- COSMIC launched 2006

Challenges:

a. Different inclination angle
b. Different atmospheric paths
c. Temporal/spatial mismatch
d. Reasonable sample number


Space Weather

3-D structure of the feature during daytime (constant LT)



Tiger Liu, NCU

Characteristics of RO Data

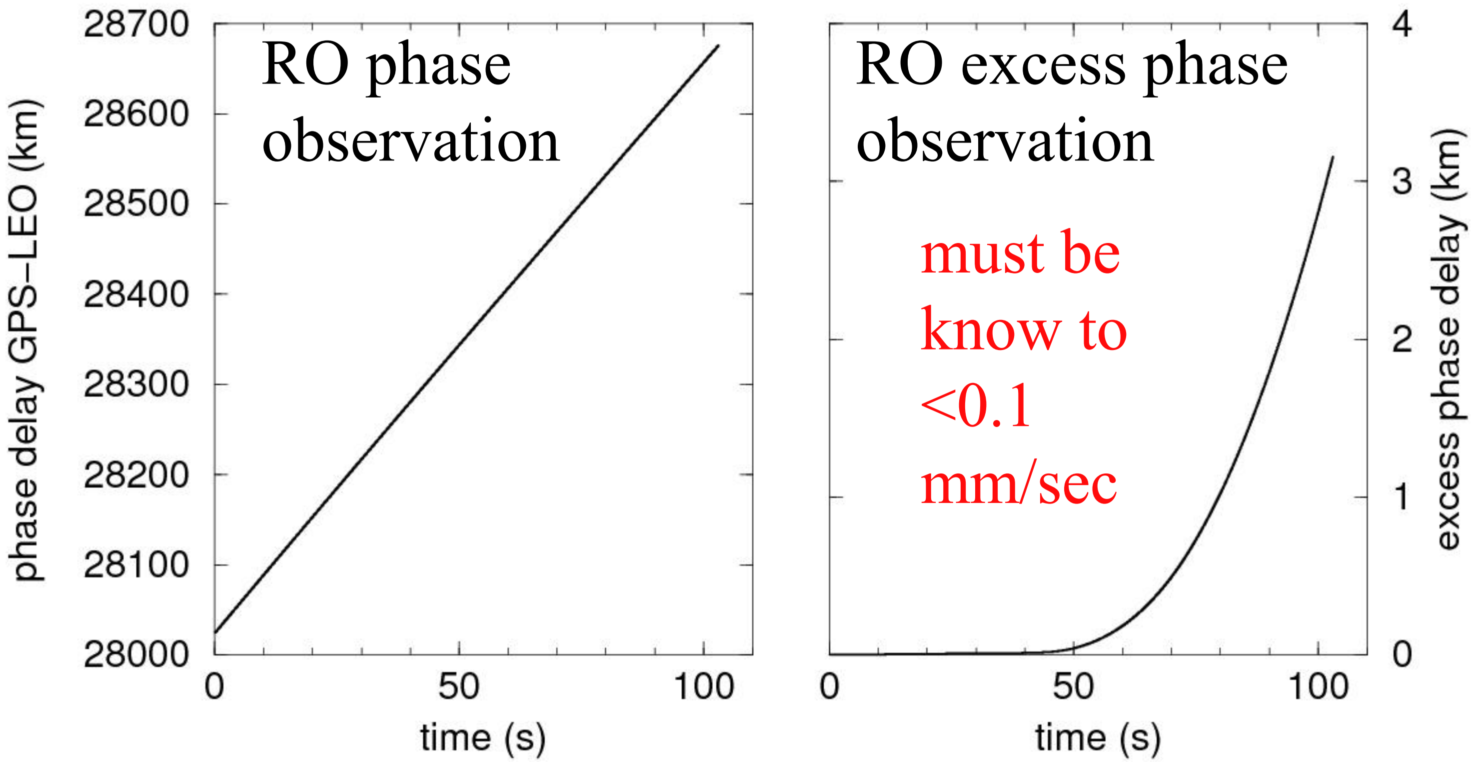
- **Limb sounding geometry complementary to ground and space nadir viewing instruments**
- **Global 3-D coverage 40 km to surface**
- **High accuracy (equivalent to <1 K; average accuracy <0.1 K)**
- **High precision (0.02-0.05 K)**
- **High vertical resolution (0.1 km surface – 1 km tropopause)**
- **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

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

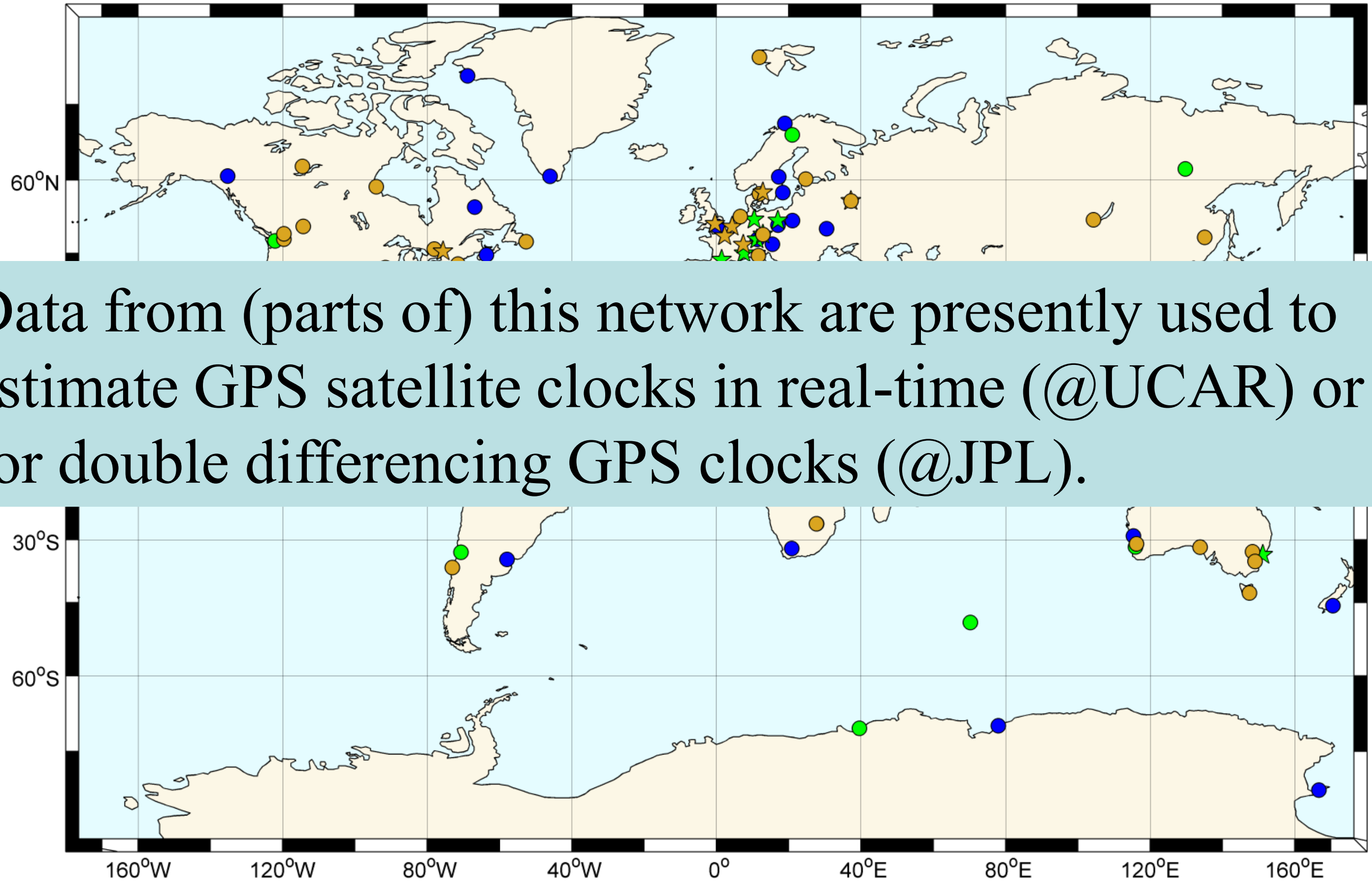
ρ_r^s	Geometrical distance between satellite and receiver
c	Speed of light in vacuum
δt_r	Station clock correction: *receiver clocks* (time and frequency transfer)
$\delta t_{r,sys}$	Delays in receiver and its antenna (cables, electronics, ...)
δt^s	Satellite clock correction: *satellite clocks*
$\delta t_{s,sys}$	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
λ	Wavelength of the GPS signal (L_1 or L_2)
N_r^s	Phase ambiguity: *ambiguity parameters* (ambiguity resolution)
ϵ	Measurement error

From Phase to Excess Phase



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

IGS Clock Estimation Network

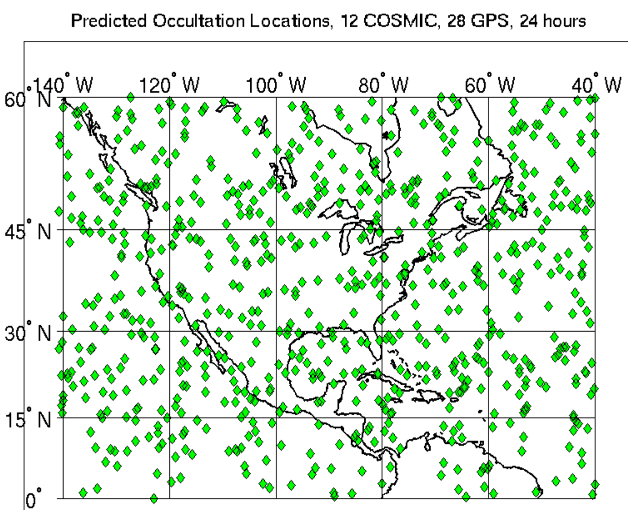


Data from (parts of) this network are presently used to estimate GPS satellite clocks in real-time (@UCAR) or for double differencing GPS clocks (@JPL).

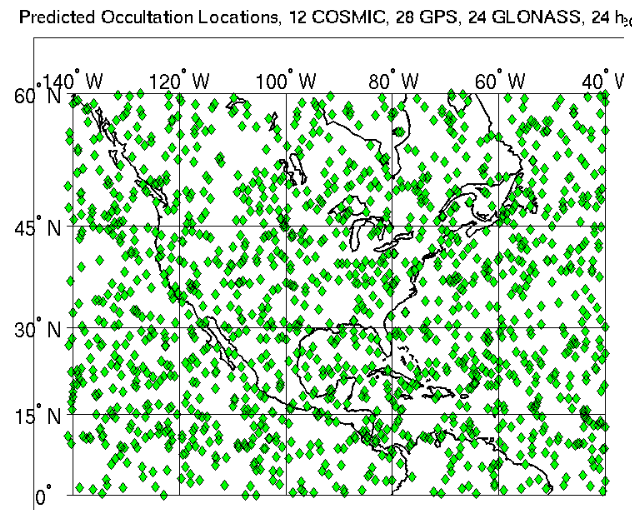
Hydrogen masers (57) are indicated in brown, cesiums (32) in green, and rubidiums (30) in blue. Stars indicate clocks at BIPM timing laboratories (includesstandard labs at NIST, Paris, Braunschweig, ….)

Figure courtesy J. Ray

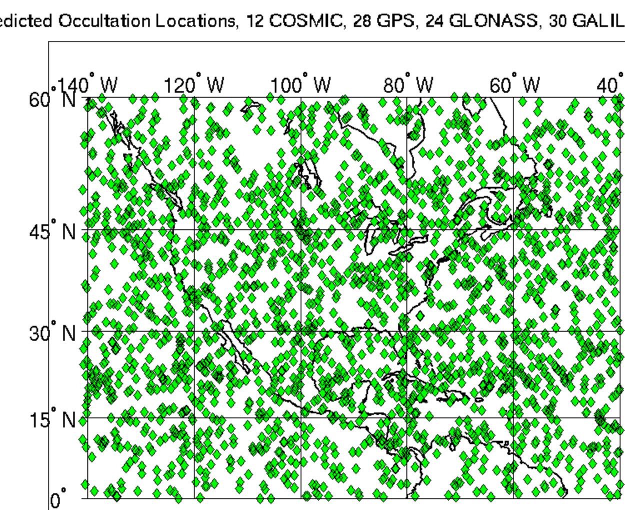
Coverage of possible future LEO constellations
12 sat constellation-24 Hours



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