GNSS Radio Occultation: Where We Are and Where We Are Going

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Fourth FORMOSAT-3/COSMIC Data Users Workshop

October 27-30, 2009

Boulder, Colorado

Overview

Now

- **Operational Weather**
- **Space Weather And Space Science**
- **Atmospheric Science**
- **Climate**

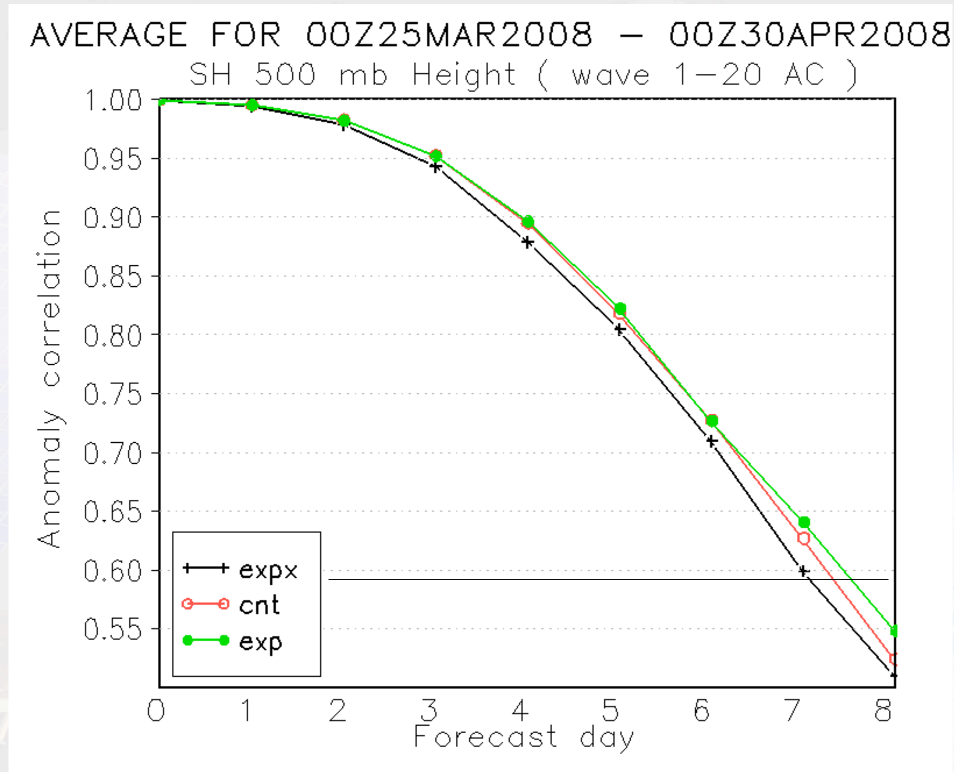
Future

- **Operational Weather: interest in larger constellations**
- **Space Weather: low latency, larger constellations**
- **Climate: CLARREO**
- **Atmospheric science: unique new capabilities**
- **Technology**

Operational Weather Benefits Now

L. Cucurull

- AC scores (the higher the better) as a function of the forecast day for the 500 mb gph in Southern Hemisphere
- 40-day experiments:
  - **expx (NO COSMIC)**
  - **cnt (operations - with COSMIC)**
  - **exp (updated RO assimilation code - with COSMIC)**
    - » Many more observations
    - » Reduction of high and low level tropical winds error

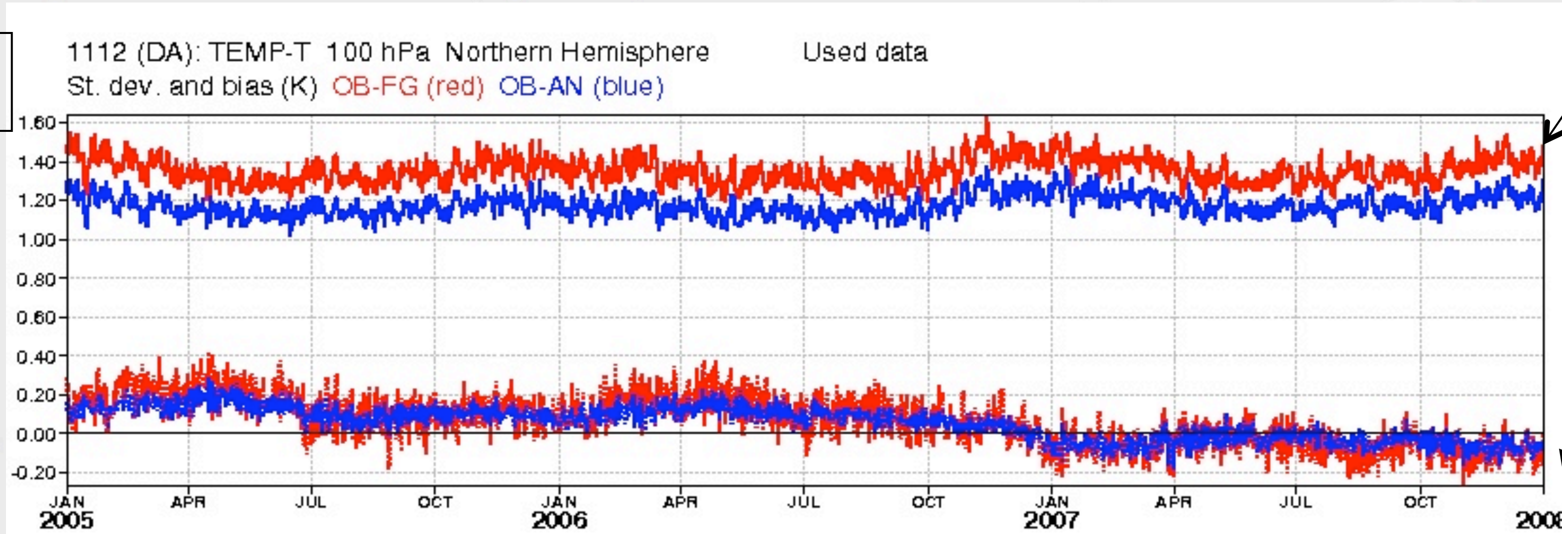


COSMIC provides 8 hours of gain in model forecast skill at day 4, up to 15 hours at day 7 – Southern Hemisphere!!!

Improved ERA-Interim Analyses

COSMIC introduced December 2006. Radiosonde T departures 100hPa

NH

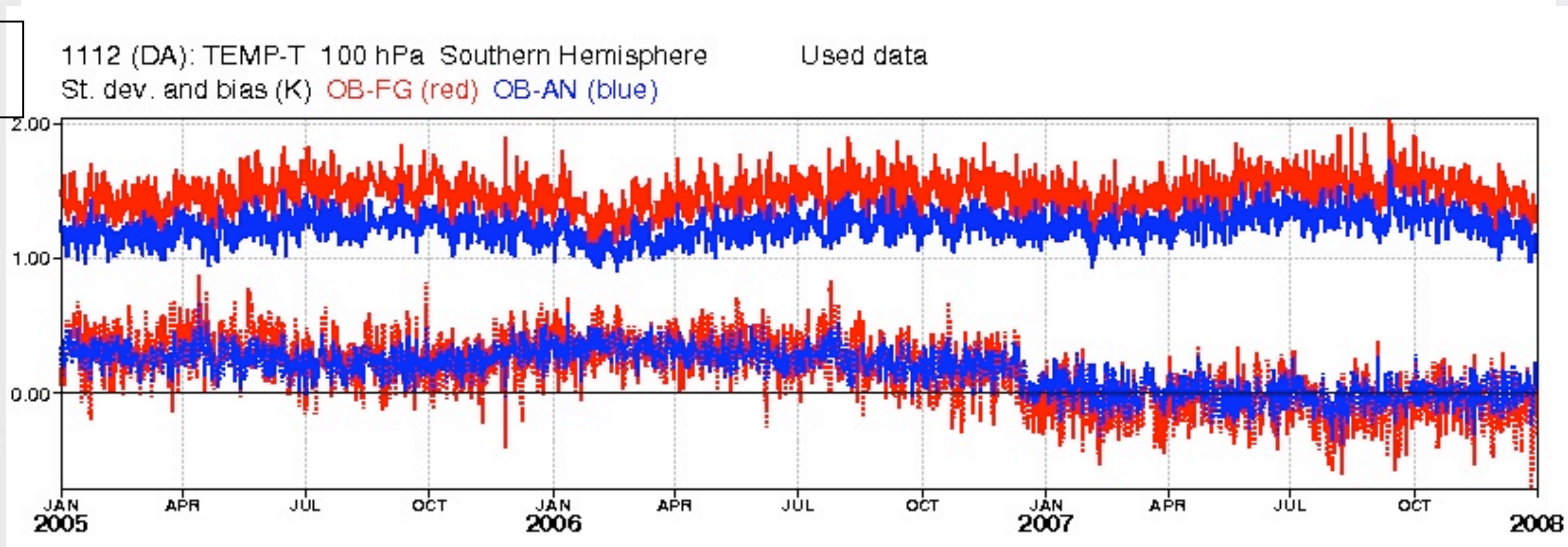


Std dev

Sean Healy, ECMWF

Bias

SH



Impact Assessment On Short-Term Forecast

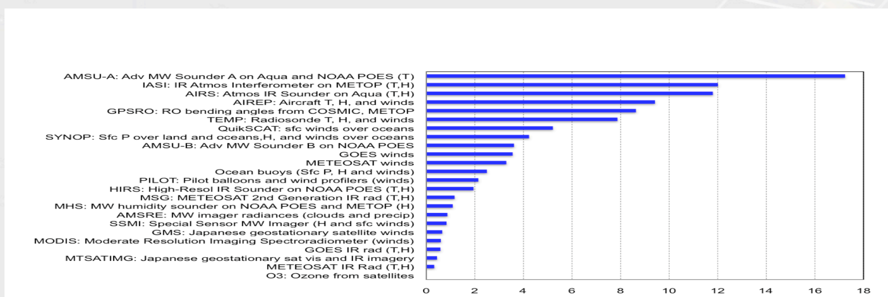
"Contribution to the reduction of **24-h forecast error** by all the different observational systems used by the ECMWF for the four-month period Sept.-Dec. 2008. **Forecast error metric is an integrated one** of total energy (kinetic + potential) and hence is a function of wind, temperature and surface pressure errors **throughout the entire global model domain**."

From: Rick Anthes, study summary October 2009

1. AMSU-A (4 satellites) 17.2%
2. IASI-12.0%
3. AIRS-11.8%
4. AIRREP (aircraft temperature and winds) 9.3%
5. GPSRO (bending angles)-8.5%
6. TEMP (radiosonde winds, humidity, and temperatures)-7.9%
7. QuikSCAT (scatterometer surface winds over the oceans)-5.2%

Many more radiances are assimilated

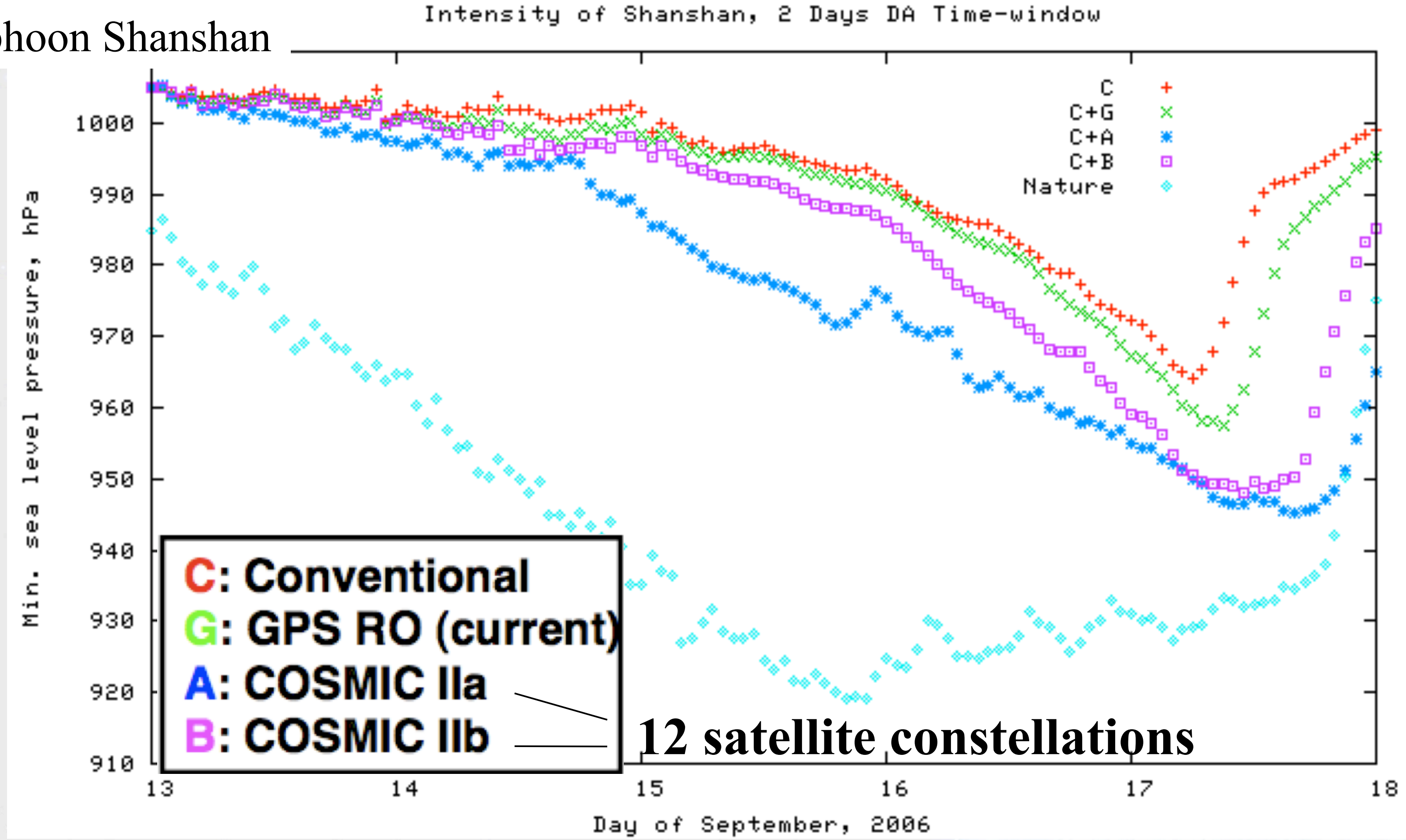
4.7% of total obs



OPERATIONAL WEATHER: FUTURE

Improved Tropical Cyclone Intensity Forecasts

Typhoon Shanshan



- Intensity Forecast Performance: C+A > C+B > C+G > C

From Bill Kuo and UCAR COSMIC team “Observing System Simulation Experiments for FORMOSAT-3 Follow-On Mission”, Presented at GNSS Radio Occultation Workshop, Pasadena, April 2009

SPACE WEATHER NOW

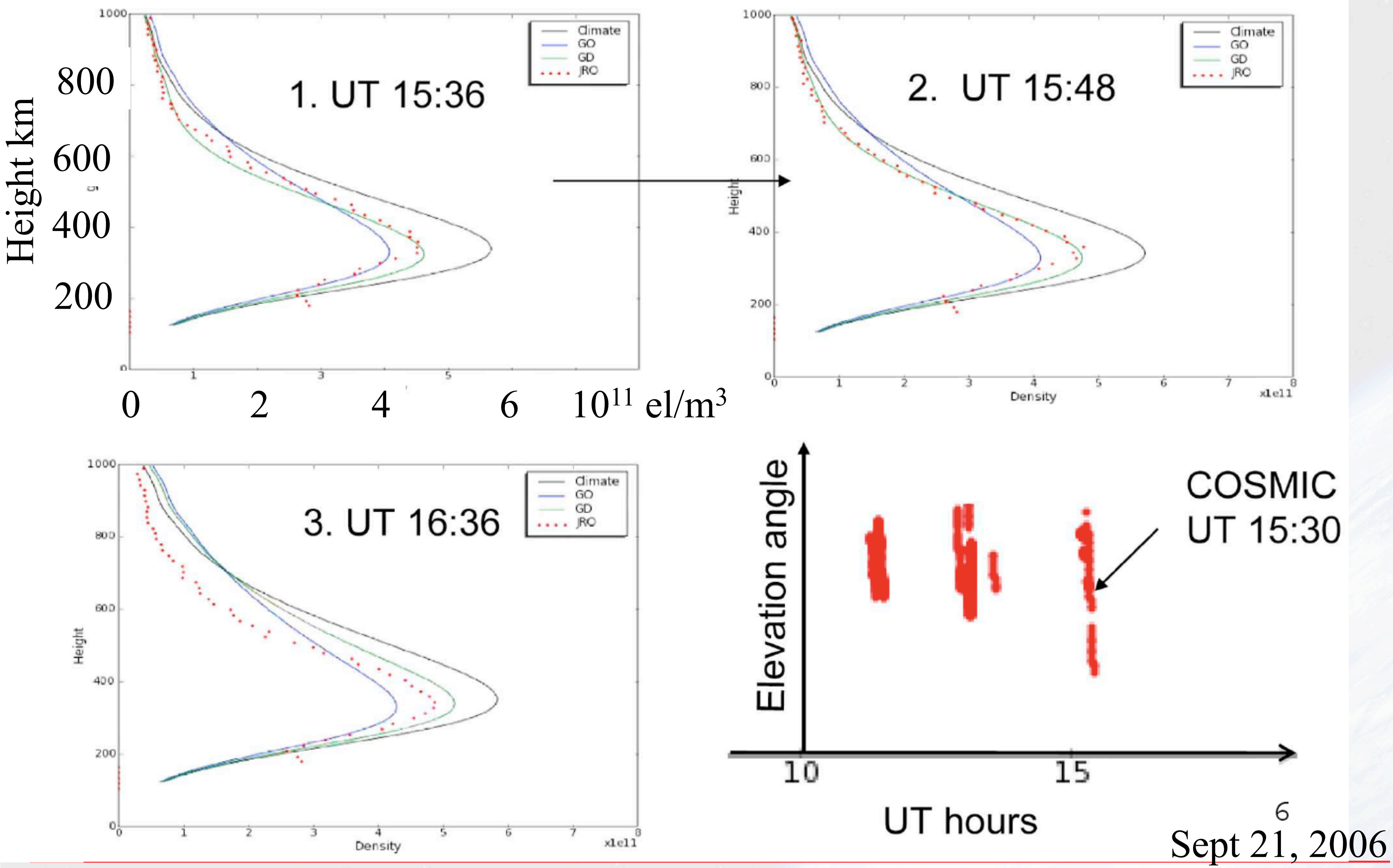
Space Weather Now: Assimilating COSMIC Data

- COSMIC/FORMOSAT-3 ionosphere measurements finding increasing use in data assimilation or tomographic schemes that estimate electron density
- Global Assimilative Ionosphere Model (GAIM)
  - Physics-based data assimilation “inspired” by numerical weather prediction models
- Other approaches: IDA3D (time-dependent tomographic), tomographic imaging algorithms

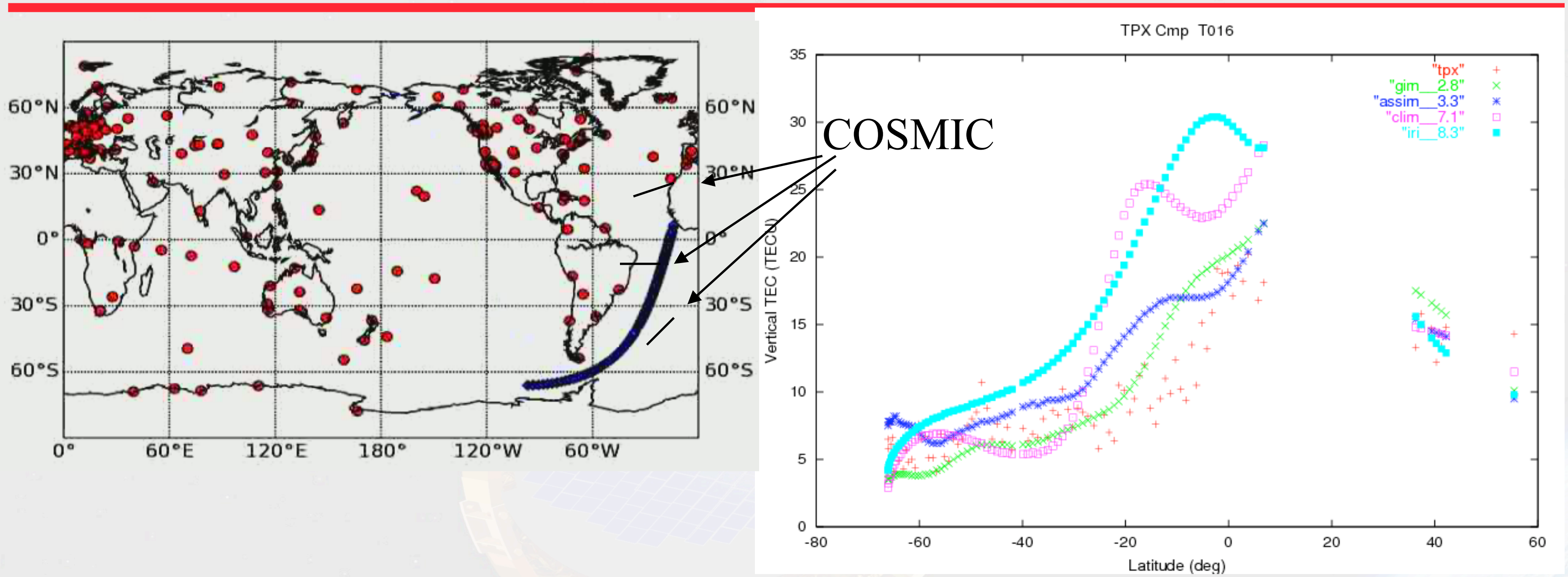
- These techniques assimilate total electron content (TEC), not the electron density profile retrievals (Abel)

- Not covered here: new science results

COSMIC Overflight Jicamarca Radio Observatory



Assimilating COSMIC: Comparisons to Altimeter TEC Over Oceans

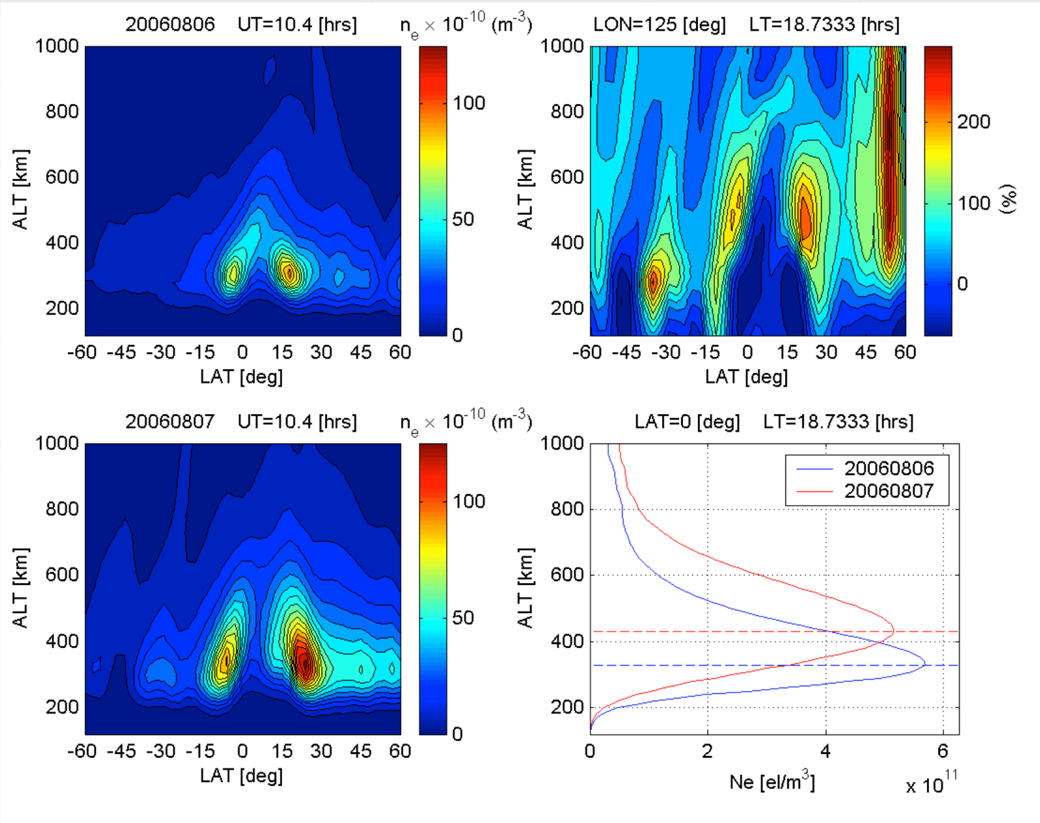


		Mean	Sigma	RMS	Min	Max
	GIM	-1.61	2.88	3.31	-12.5	9.1
06/26/06	**Ground**	-0.24	3.26	3.27	-17.26	11.7
	Ground+COSMIC	-0.29	2.26	***2.28***	-10	8.72

The use of COSMIC+ground-GPS data over ground-GPS only significantly improved TEC predictions for all 3 days processed: 30, 28 and 44% respectively.

Attila Komjathy, Brian Wilson, Xiaoqing Pi, Vardan Akopian, Miguel Dumett, Byron Iijima, Olga Verkhoglyadova and Anthony J. Mannucci, "JPL/USC GAIM: On The Impact of Using COSMIC And Ground-Based GPS Measurements To Estimate Ionospheric Parameters," JGR in press

Ionospheric Electron Density Storm-Time Perturbations



Storm-time data assimilation August 6-7 2006

Electron density contours showing the assimilative modeling results in altitude vs. latitude dimensions at 125° longitude, for the quiet day (August 6, 2006; upper left), storm day (August 7, 2006; lower left), and percentage difference between the disturbed and quiet state (upper right). A comparison of sample electron density profiles at the equator is also provided in the lower-right panel. The corresponding local time is 1844 for this longitude. The storm-time disturbance shows clear features of equatorial anomaly enhancement that must be driven by an enhancement of eastward electric field at low latitudes.

Xiaoqing Pi, Anthony J. Mannucci, Byron A. Iijima, Brian D. Wilson, Attila Komjathy, Thomas F. Runge, and Vardan Akopian (2008), "Assimilative Modeling of Ionospheric Disturbances with FORMOSAT-3/COSMIC and Ground-Based GPS Measurements," Journal Of Terrestrial, Atmospheric and Oceanic Sciences, 2008

SPACE WEATHER FUTURE

Space Weather Future

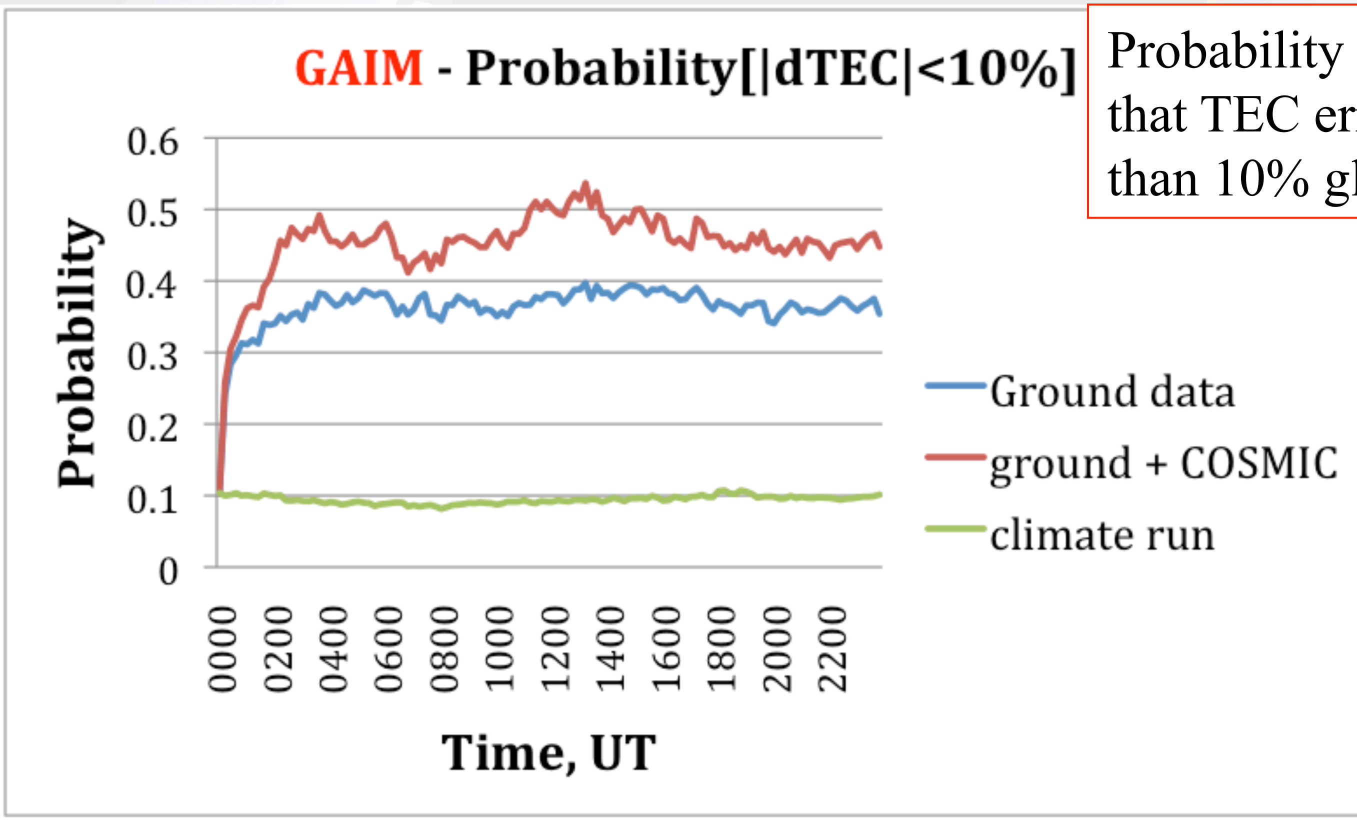
GNSS RO mission or "COSMIC-Follow On" is firmly embedded in future plans

- **Operational ingest of RO data into assimilative ionosphere models is planned by civilian agencies**
- **Continuous global coverage a key factor**
- **Stringent latency requirements are being pursued**
  - **15-45 minutes**
  - **Low latency implies broad coverage**
- **Defense Meteorological Satellite Group is placing an RO receiver on a C/NOFS "follow on" mission**

➡ **Larger constellations are likely a significant benefit**

Space Weather: Observation System Simulation Experiment

Observation System Simulation Experiments Using JPL-USC GAIM with COSMIC and Ground-Based GPS Observations
Xiaoqing Pi et al., Session 6, Wednesday October 28



Probability over time that TEC error is less than 10% globally

- **Constellations larger than COSMIC appear to produce significant benefits**

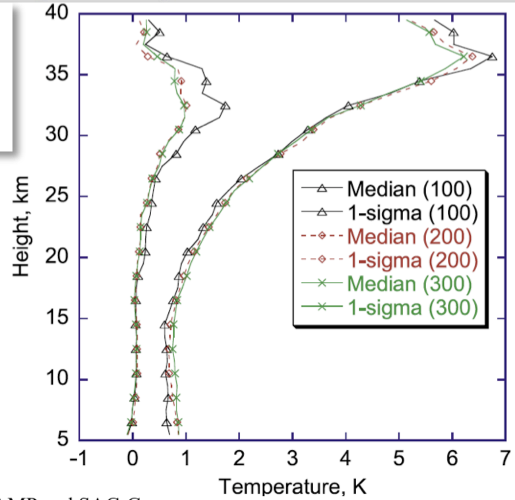
CLIMATE RESULTS

Full Characterization Of Measurement Precision, Bias < 0.1 K

CHAMP vs SAC-C

Observations Within 1/2 hour 100-300 km

Jul '01-Mar'03
N = 212



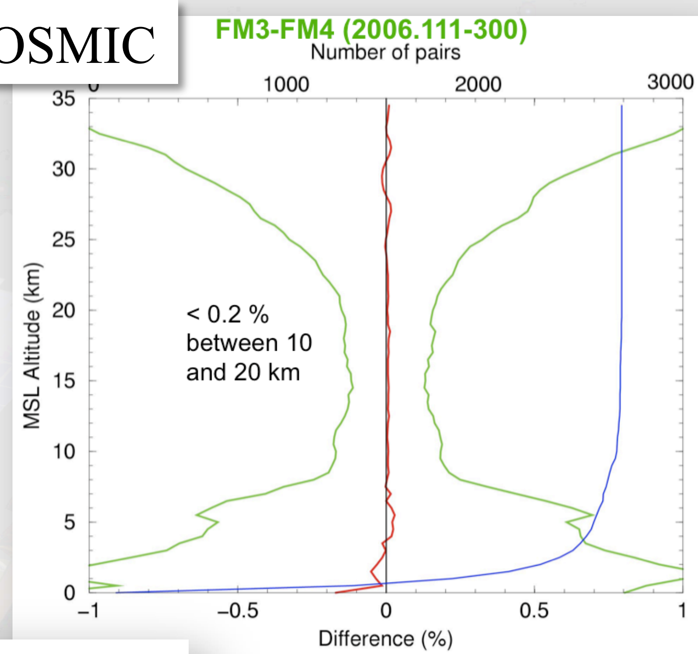
Differences: Median and standard deviation versus separation

Hajj et al., (2004) "CHAMP and SAC-C atmospheric occultation results and intercomparisons", JGR.

Careful accounting for decorrelation with distance

Hajj, G. A., C. O. Ao, B. A. Iijima, D. Kuang, E. R. Kursinski, A. J. Mannucci, T. K. Meehan, L. J. Romans, M. de la Torre Juarez, and T. P. Yunck (2004), CHAMP and SAC-C atmospheric occultation results and intercomparisons, J. Geophys. Res., 109, D06109, doi: 10.1029/2003JD003909.

COSMIC

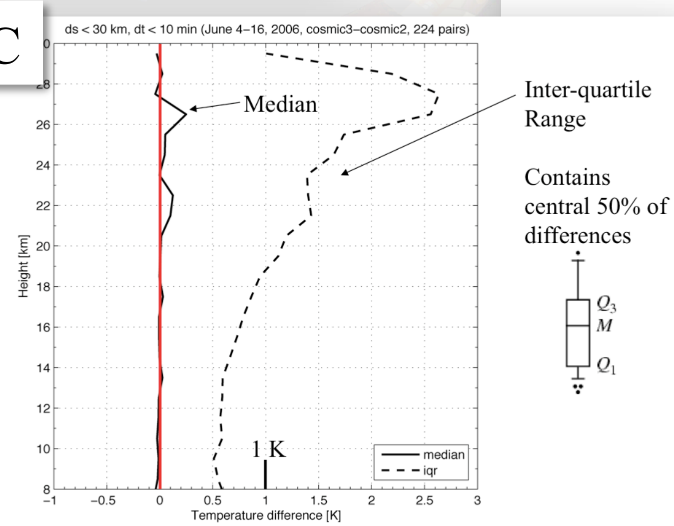


Refractivity

COSMIC

COSMIC3 - COSMIC2

Window:
30 km
10 minutes
June 4-16, '06
224 pairs



See also:
Schreiner, W., C. Rocken, S. Sokolovskiy, S. Syndergaard, and D. Hunt (2007), Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission, Geophys. Res. Lett., 34, L04808, doi: 10.1029/2006GL027557.

Other Recent Climate Results

- **RO Trends: "Estimating the Uncertainty of using GPS Radio Occultation Data for Climate Monitoring: Inter-comparison of CHAMP Refractivity Climate Records 2002-2006 from Different Data Centers" (UCAR, JPL, GFZ, Wegener Center)**
  - **Ho et al., JGR in press**
- **After sampling error removal, 0.03%/5yr trend upper bound (refractivity) for monthly mean**

~0.06-0.08K/5 yr

- **Multi-satellite decadal scale upper air trends: "Atmospheric temperature change detection with GPS radio occultation 1995 to 2008"**
  - **Steiner et al., GRL 2009**
  - **Used GPS/MET and CHAMP**

    "Statistically significant" cooling trend in LS

    February 1997-2008: -1.79 ± 0.29 K/12 years

CLIMATE FUTURE

CLARREO Decadal Survey Mission

Launch ~2016

SOCIETAL NEED: Accurate climate change observations and projections to inform mitigation and adaptation policies.
MISSION GOAL: Enable rigorous decadal-scale climate change observation and climate change forecast verification.
SCIENCE OBJECTIVE: Make highly accurate and SI -traceable decadal change observations sensitive to key uncertain climate radiative forcings, responses, and feedbacks.

1. Sampling sufficient to characterize global climate
2. Calibration traceable to unit standards (e.g. the second)
3. Archiving of calibration data products

Radio Occultation Decadal Survey

See poster by Hurst

The NRC Decadal Survey (Earth Science) states:

. . . All of the appropriate low Earth orbit (LEO) missions should include a Global Positioning System (GPS) receiver to augment operational measurements of temperature and water vapor. (pg 39)

and

. . . In view of the importance of the occultation measurement and the accurate positioning of the satellite for other sensor measurements, GPS receivers should be a standard part of both NASA and NPOESS low-Earth-orbit payloads. . . . (pg 280)

ATMOSPHERIC SCIENCE NOW

Atmospheric Science Now

- **GNSS RO has made contributions where the measurement is unique: high vertical resolution, cloud penetrating, well calibrated**
  - **Gravity waves**
  - **Tropopause structure and climatology**
  - **Planetary waves and tides**
  - **Water vapor**
  - **Planetary boundary layer**
  - **Reference calibration (e.g. sondes)**

ATMOSPHERIC SCIENCE FUTURE

What Is Unique About GNSS RO?

- **Radiation is coherent – we measure amplitude and *phase***
  - **Other techniques (AIRS, IASI, MODIS, MISR, etc.) count photons. There is no phase information.**
- **Earth science radars measure phase also, but from a scatterer that randomizes phase**
  - **CloudSat**
- **As a transmission method, radio occultation does not require scattering centers to receive a signal**
  - **We can detect turbulence as well as non-turbulent but "sharp" structure**
- **Disadvantage: lack of direct sensitivity to location along the raypath**
  - **Reliant on spherical symmetry assumption**

Radio Occultation Physics

Wavelength of the radiation	0.19	meters
Diffraction limited resolution	200-1000	
Synthetic Aperture Size	100,000	radius
Diffraction corrected resolution	6-60	6 reflects "ideal"
Distance traveled to shift phase 1/2 wavelength	850	at 2 km altitude

$$U(k_x, z_{LEO}) = \int_{-\infty}^{+\infty} u(x, z_{LEO}) e^{-ik_x x} dx$$

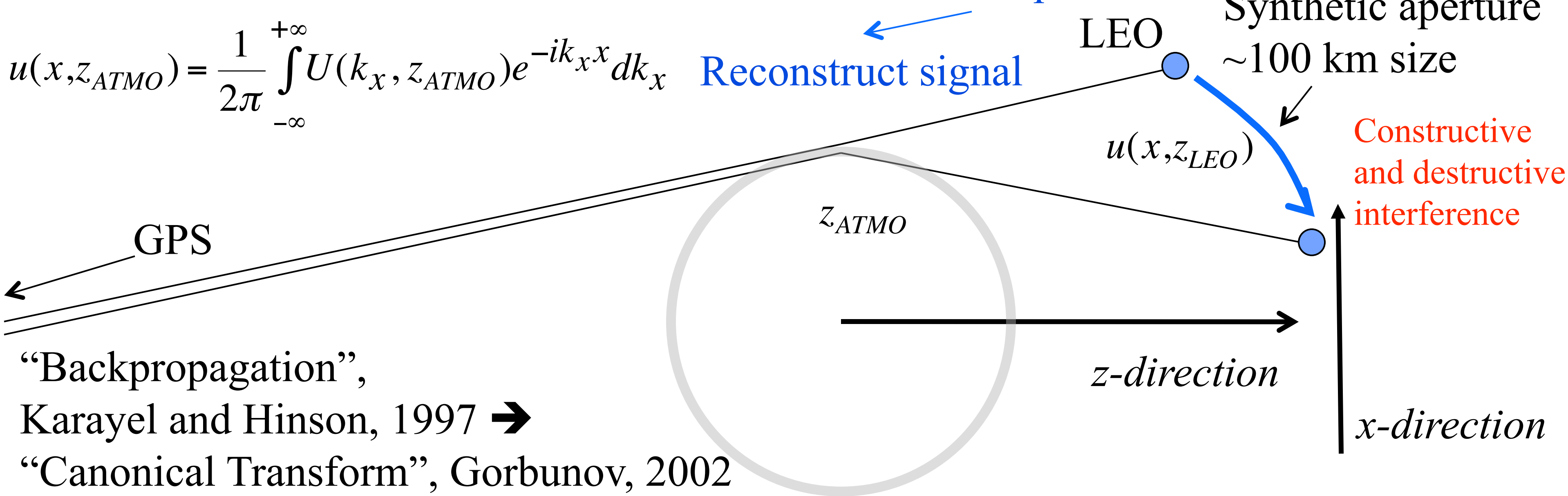
Decompose signal into plane waves

$$U(k_x, z_{ATMO}) = U(k_x, z_{LEO}) e^{-ik_z (z_{LEO} - z_{ATMO})}$$

Back-propagate plane waves to atmosphere

$$u(x, z_{ATMO}) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} U(k_x, z_{ATMO}) e^{-ik_x x} dk_x$$

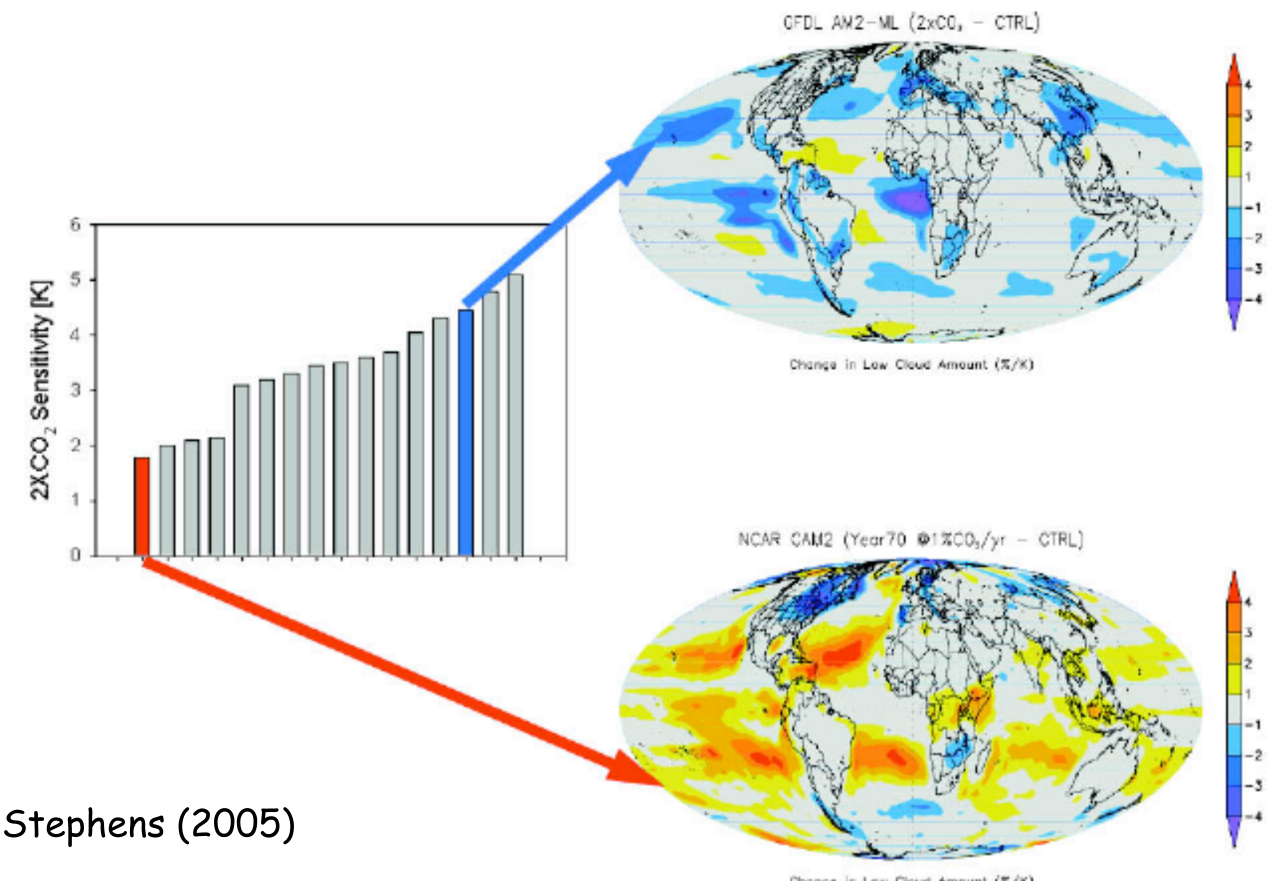
Reconstruct signal



“Backpropagation”,
Karayel and Hinson, 1997 ➔
“Canonical Transform”, Gorbunov, 2002

Science Future: Cloud Feedbacks

IPCC 2007: "Cloud feedbacks remain the largest source of uncertainty"



Stephens (2005)

Doubling CO_2 ➔ less low clouds in GFDL ➔ 4 K global warming

Doubling CO_2 ➔ more low clouds in NCAR ➔ 2 K global warming

We do not know if low clouds are going to increase or decrease – Why?

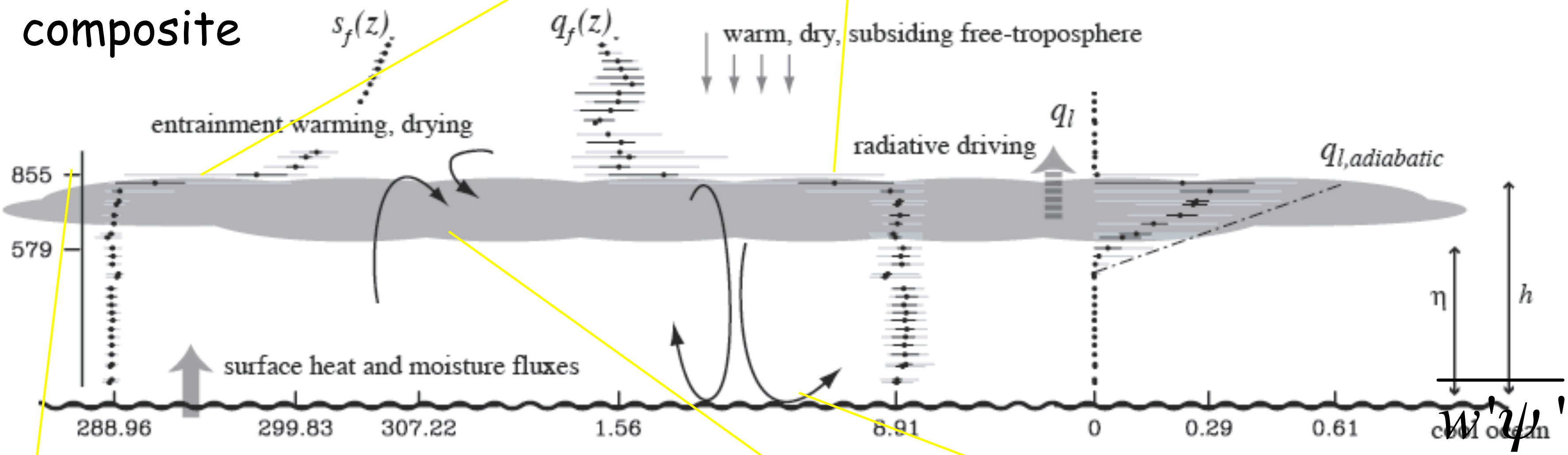
Joao Teixeira, JPL

Science Future: Planetary Boundary Layer

Strong gradients of temperature and water vapor

DYCOMS II composite

Courtesy: B. Stevens



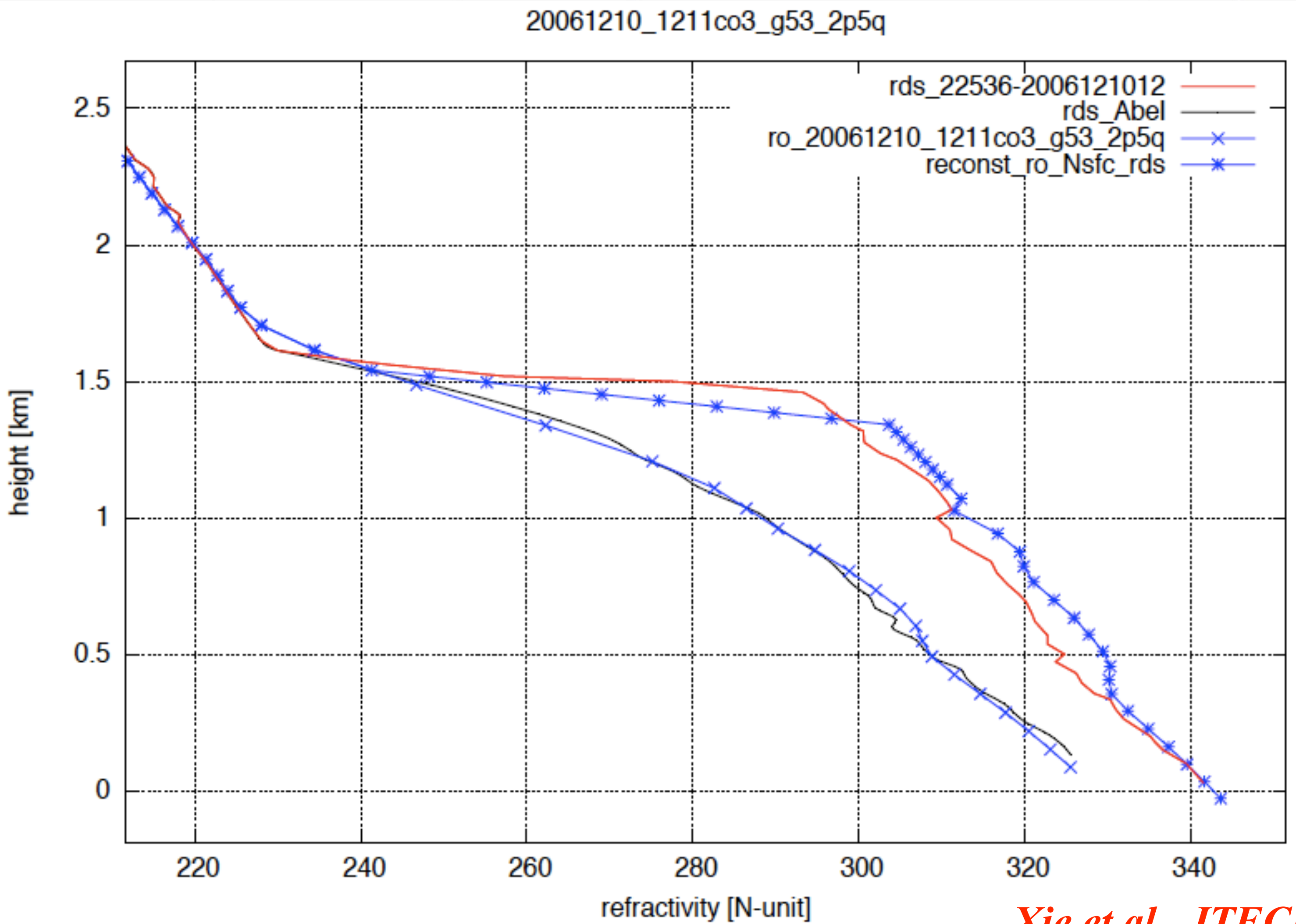
Even just detecting accurately the height of the gradient is essential

Small-scale turbulent mixing

Main Observation and Modeling Problems:

a) Strong vertical gradients;
b) Small-scale turbulent mixing.

Science Future: Planetary Boundary Layer Measurement

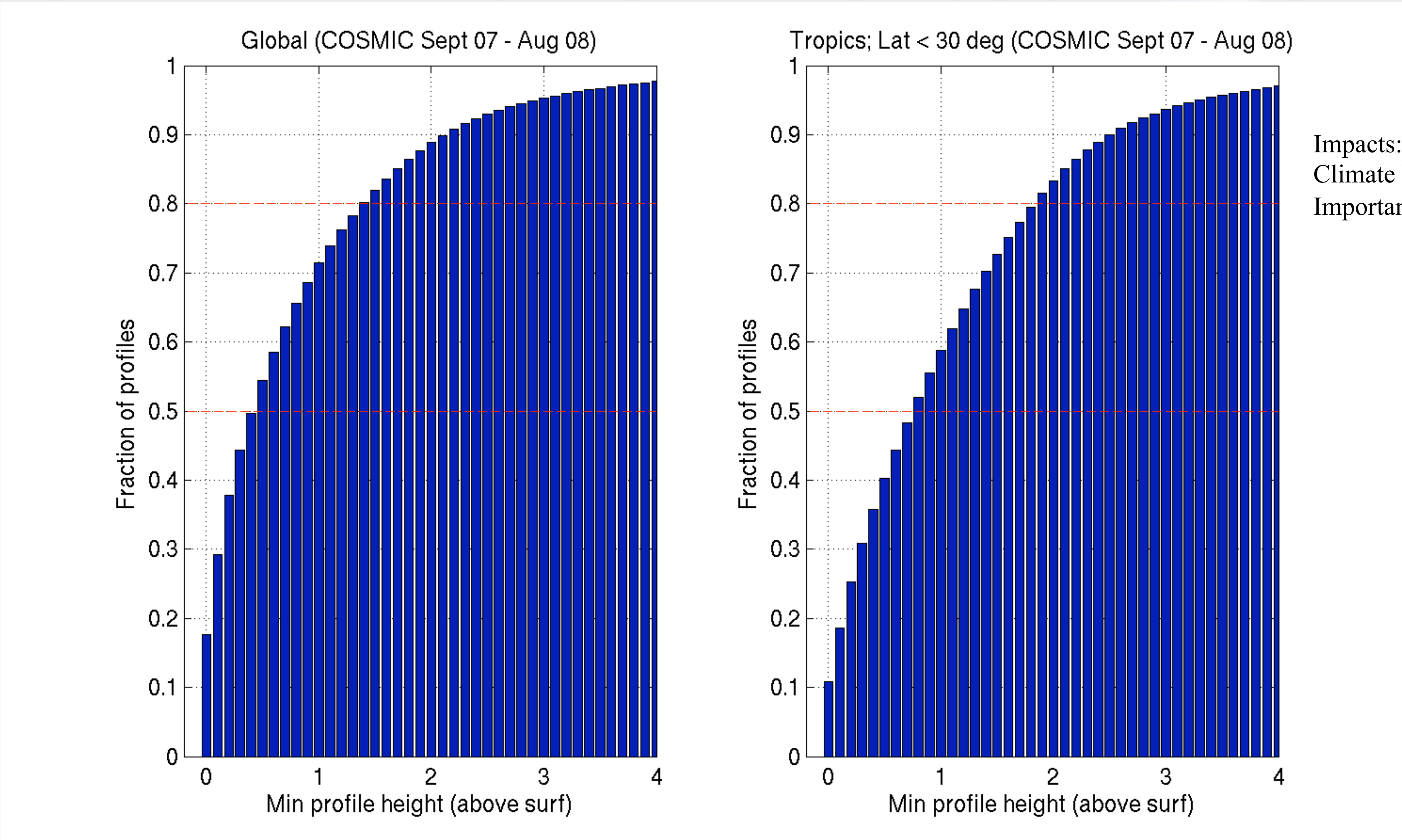


Xie et al., JTECH, 2006

FUTURE INSTRUMENTS

Number Of Occultations Reaching 0-4 km Altitude

What are the drivers for new technology?



Impacts:
Climate bias
Important science

Future Technology Development: JPL/Broadreach TriG Receiver

What are the drivers for new technology?

Results from JPL's Actively Steered, Multi-beam, Phased Array Antenna

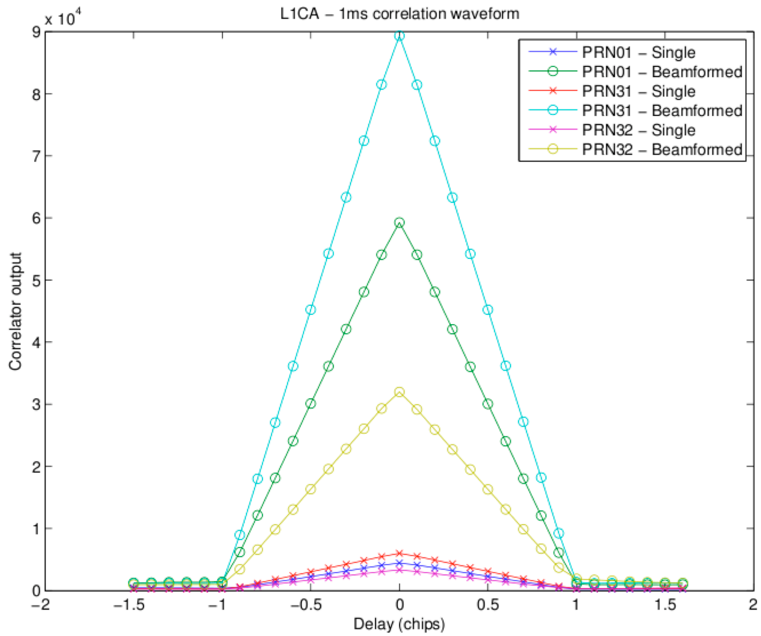


Figure 1: RSS of correlation waveform before and after L1 beamforming. Three simultaneous beam were formed pointing at PRN1,PRN31 and PRN32 with 16 antennas

A multi-beam actively-steered phased array GNSS antenna has been designed and tested

– Ground tests confirm expected SNR gain

– Aircraft tests demonstrate ability to direct beams from a dynamic platform

– Multi-frequency: tracked GPS CA, P(Y)1, P(Y)2, L2C and L5(from WAAS), Galileo E1 and E5A signals from GIOVE-A and GIOVE-B. This demonstrates steering multiple beams at three frequencies.

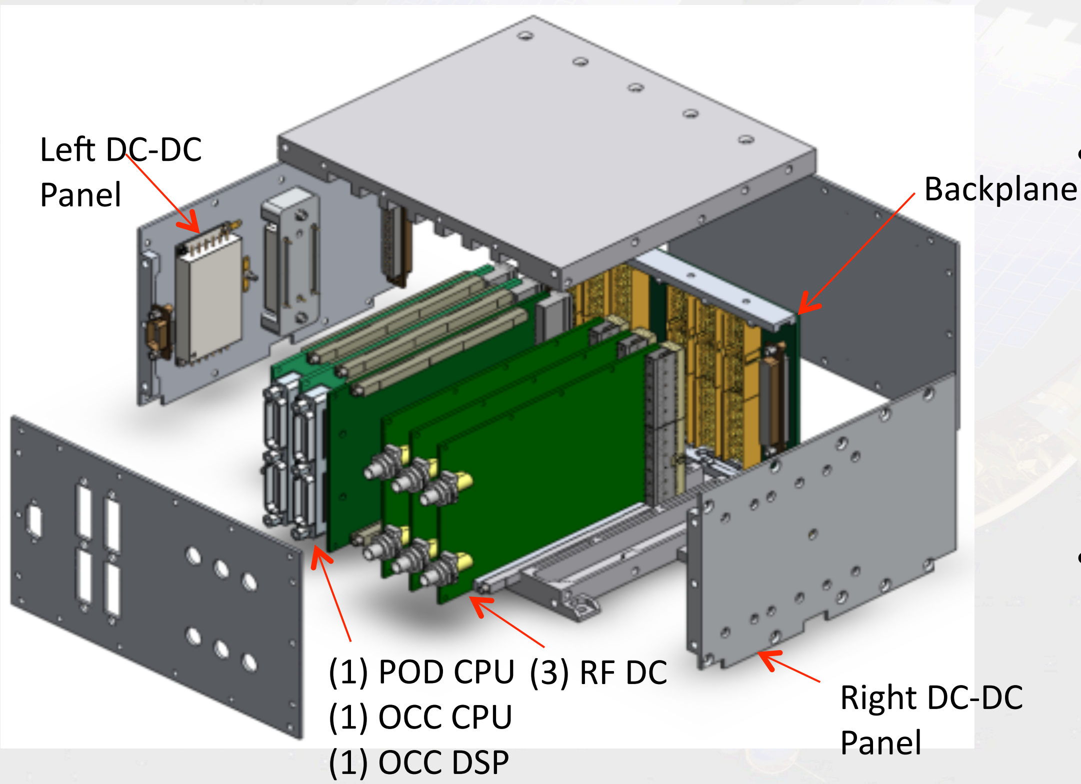
• This active array technology is ready for insertion into occultation missions

090407

Lawrence Young, JPL

Future Technology Development: GNSS Capable

Additional Measurements: Modular design, 2 processors, offline occultation science processing, multiple frequencies



TriG Receiver

- **Capable of tracking modernized GPS and Galileo signals (E1 and E5a)**
  - **GLONASS capable after CDMA upgrade, possible FDMA**
  - **L1, L2, L2C, L5, E1, E5a**
  - **4+ antennas, all signals all the time**
- **Captures all available occultations at all times**

Current And Future Opportunities

- COSMIC-Follow On Mission – Joint US-Taiwan NOAA lead in US, NSPO in Taiwan
- GRAS Receiver on METOP
  - In principle, higher SNR due to the improved antenna
  - Raw sampling mode of 1000 Hz
  - Data from this receiver could help point the way towards new experiments and improved designs
- ROSA receiver on OceanSat
  - Thales-Alenia radio occultation receiver
- Other platforms for radio occultation
  - Iridium NEXT
  - Geooptics LLC
  - NASA missions of opportunity (DESDynI, ICESAT-2, etc.)

Summary: Now And Future

Weather

- Forecast improvement: 8 hours at day 4, 15 hours at day 7

- Larger constellations will produce additional improvements
- Tropical cyclone forecasts

Space Weather

- Demonstrated benefits to assimilative models

- Larger constellations will produce significantly improved space weather forecasts & lower latency

Climate

- Characterization of structural uncertainties and measurement quality
- Evidence of stratospheric cooling trends

- CLARREO: rigorous observation of decadal climate change

Atmospheric Science

- Improved analyses (high latitudes)
- Resolving fine-scale vertical structure (gravity waves, tropopause, boundary layer)

- Resolving key climate process uncertainties
- And much more

Final Word (Promise!)

New technology is needed to meet future potential of GNSS RO