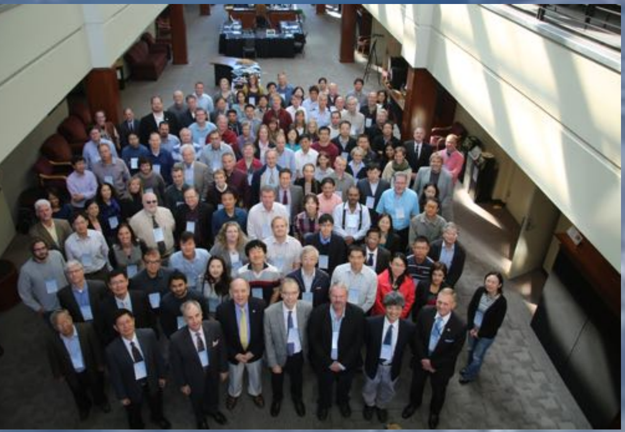
Science Highlights from COSMIC/FORMOSAT-3



Bill Schreiner

UCAR COSMIC Program

COSMIC/IROWG 2017

Sept 21, 2017

NSPO

www.cosmic.ucar.edu

Outline

- COSMIC Mission Overview
- Retrieval Challenges and Breakthroughs
- Neutral Atmospheric Science Highlights
- Ionospheric Science Highlights
- Summary

Happiness is? A successful satellite launch!

Photo by Rick Anthes' camera

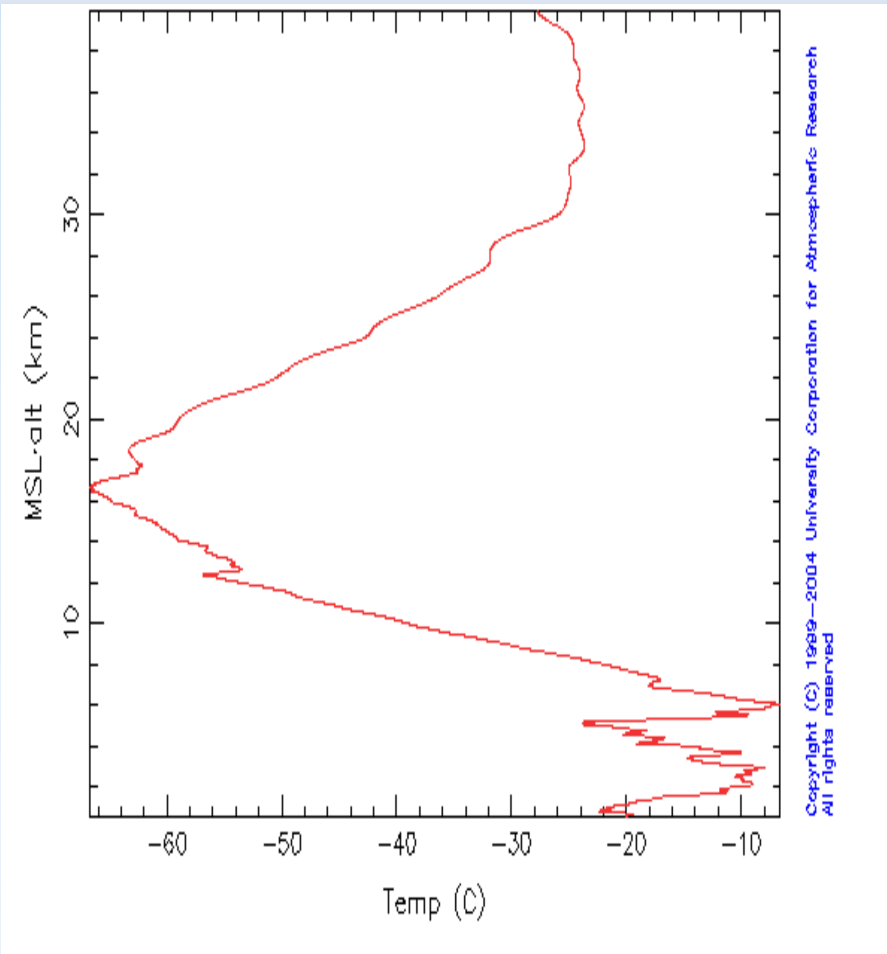
Lasting Happiness is ..?

ICGPSRO-2016 Student PROGRAM

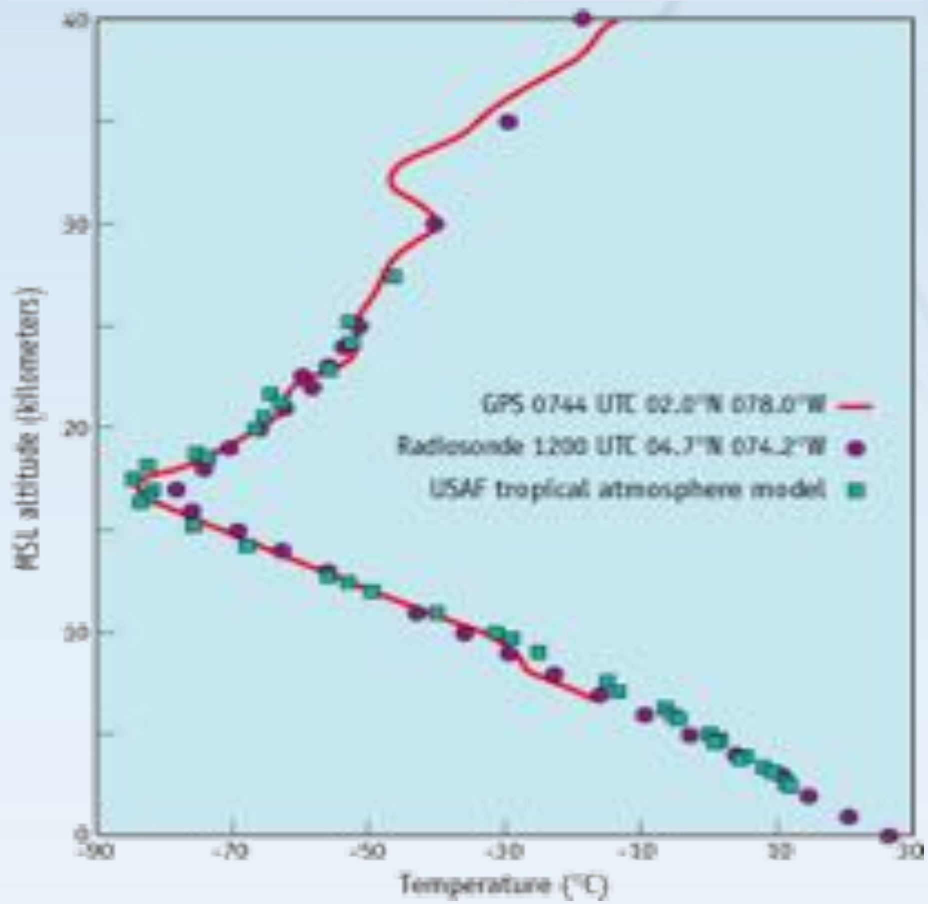
A first profile after launch!

Initial GPS RO Soundings from COSMIC and GPS/MET

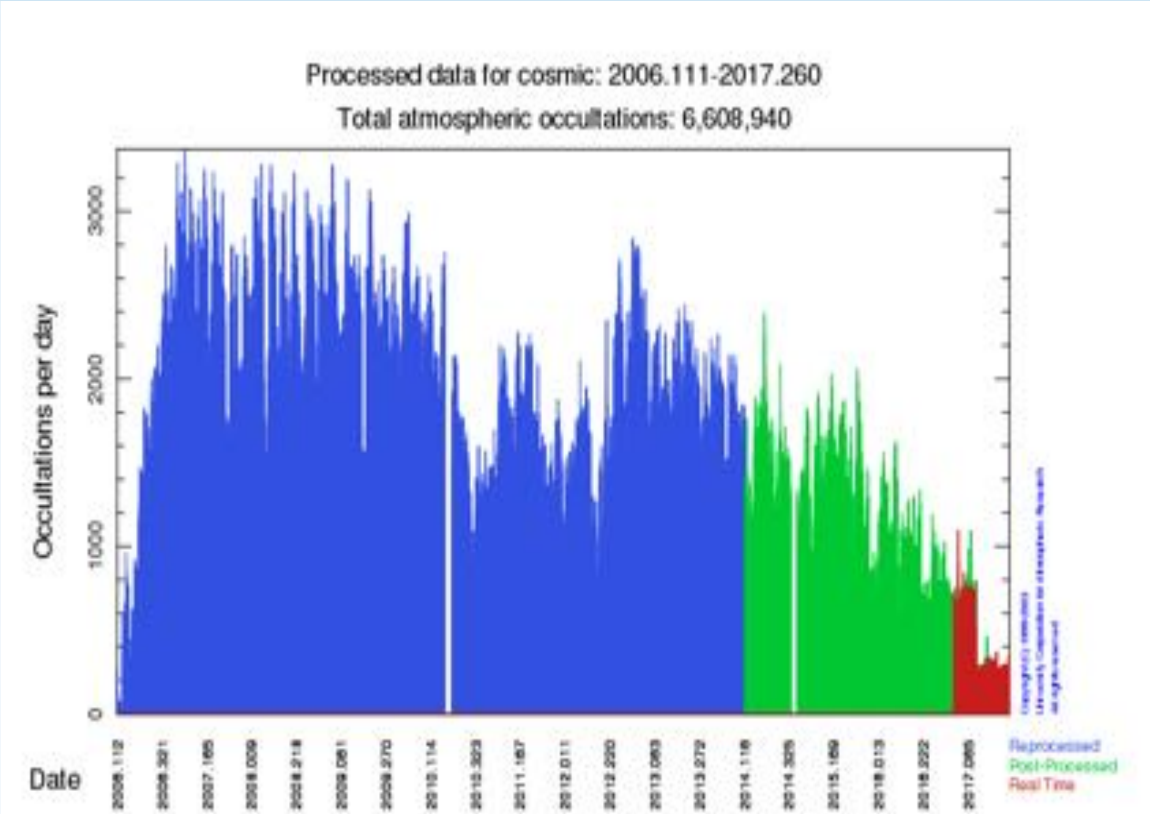
COSMIC
The first COSMIC Sounding,
UCAR, Apr 21, 2006



GPS/MET
The first GPS RO sounding of Earth,
UCAR, Apr 16, 1995



> 6.6 Million COSMIC Profiles
4/21/06 – 9/17/2017



Last Updated: Mon Sep 18 23:25:02 MDT 2017

MISSION	Total Atm Occs	Total Ion Occs
CHAMP	468029	306318
CNOFS	150772	0
COSMIC	6633961	4449234
GPSMET	5002	0
GPSMETAS	4666	0
GRACE	522698	242634
KOMPSAT5	201298	0
METOPA	2121734	0
METOPB	974528	0
SACC	353756	0
TSX	666333	0
Total	**12102777**	**4998186**

COSMIC: 1-2 spacecraft still operating 11+ years after launch (design life: 2-3 yr)

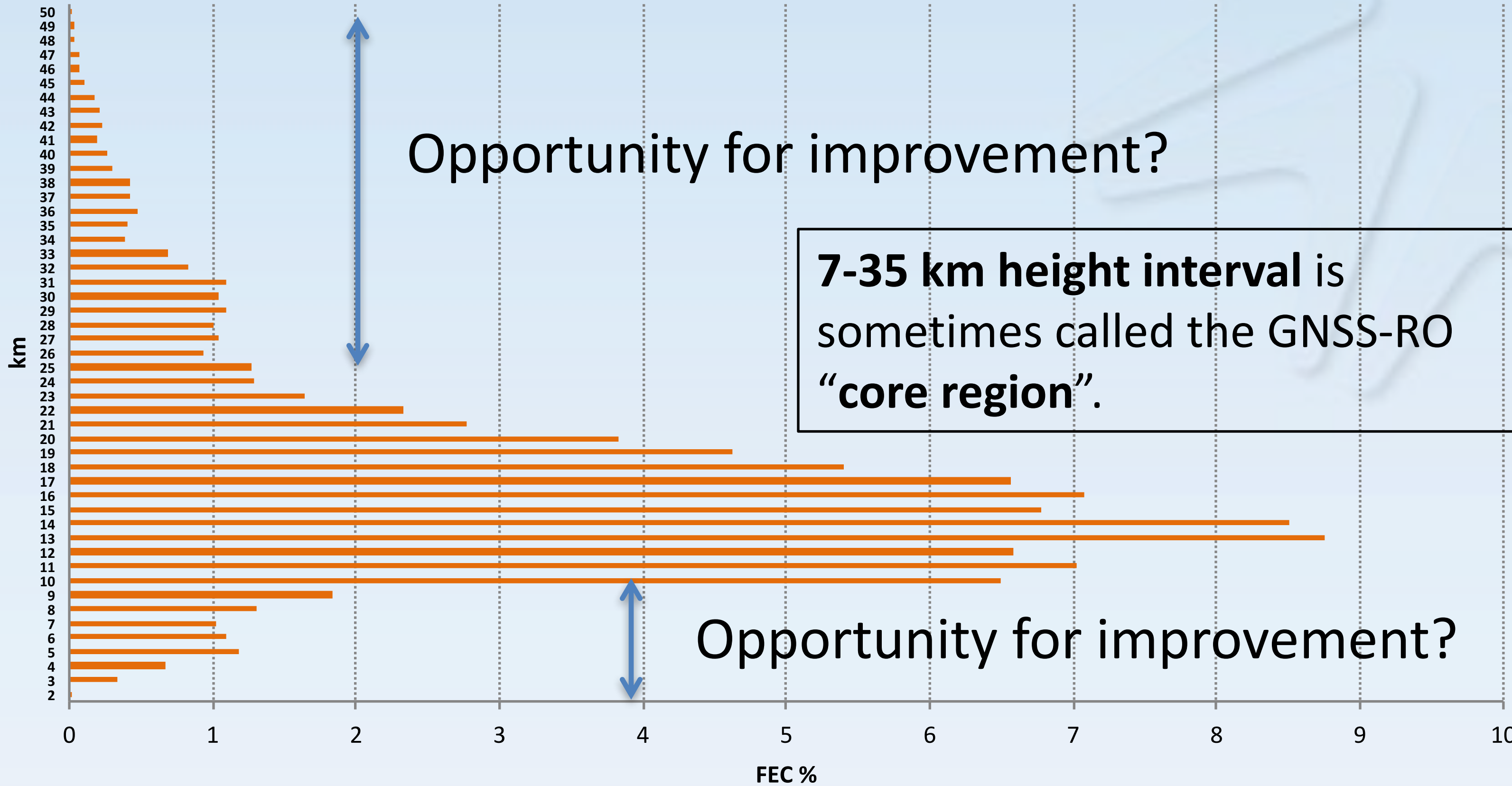
COSMIC continues to provide up to ~300 GPS soundings per day

COSMIC Achievements

- Executed nearly on schedule and budget
- ~ 6.6 M globally distributed occultations over last 10 years
- ~ 4.4 M Total Electron Content (TEC) arcs and ionospheric profiles
- L1CA open-loop tracking implemented in lower troposphere
- L2C tracking implemented for closed-loop and open-loop tracking on occultation link
- Tracking of deep signals down to -350 km HSL for test period
- The COSMIC dataset has allowed great science to be conducted!

Retrieval Challenges and Breakthroughs

Heights where GNSS-RO is reducing the 24hr forecast errors



7-35 km height interval is sometimes called the GNSS-RO "**core region**".

Florian Harnisch, Sean Healy, Peter Bauer, Steve English, Nick Yen, 2013

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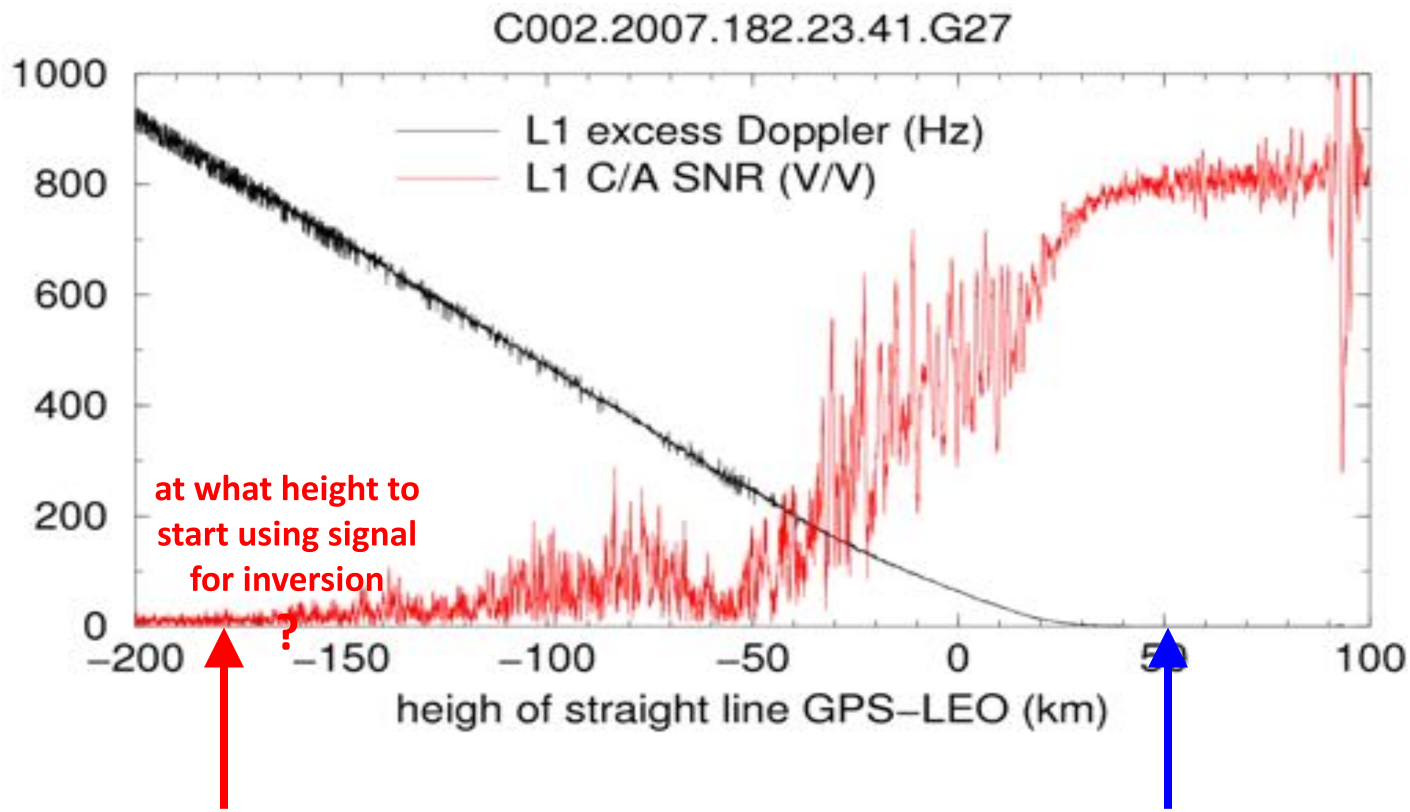
Upper stratosphere and lower troposphere are regions of maximum uncertainty for GPS RO inversions



In the lower troposphere:
the signal reduces below noise level in terms of the amplitude so high SNR (high gain RO antenna and accurate model-aided open-loop tracking) is needed

In the upper stratosphere:
The signal reduces below noise level in terms of the phase (Doppler), so it is important to model all non-atmospheric effects on the phase as accurately as possible

COSMIC Open-Loop Tracking Advances RO Science

Phase-lock loop (PLL) tracking: generic for GPS receivers; an optimal tracking for signals with sufficient SNR and limited phase acceleration.

PLL initially applied in RO receivers (GPS/MET, CHAMP). Performs well above the moist lower troposphere (LT).

Multipath propagation in the moist LT results in strong phase and amplitude fluctuations. PLL receiver produces data with errors or loses lock.

Open-Loop (OL) model-aided tracking:

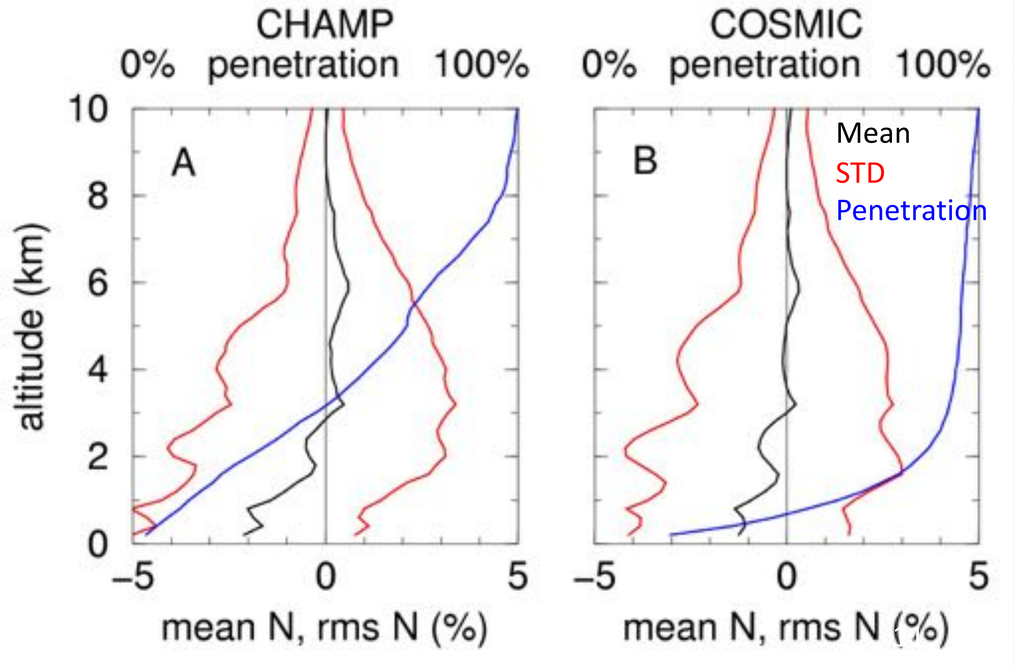
Developed for Earth's RO (Sokolovskiy 2001).

Implemented by JPL for COSMIC.

Free of tracking errors if properly implemented.

OL tracking improves penetration of RO soundings as compared to PLL (see blue line at right).

Refractivity Comparisons of RO vs ECMWF for CHAMP and COSMIC



Anthes et al., 2008, BAMS 89(3), 313-333

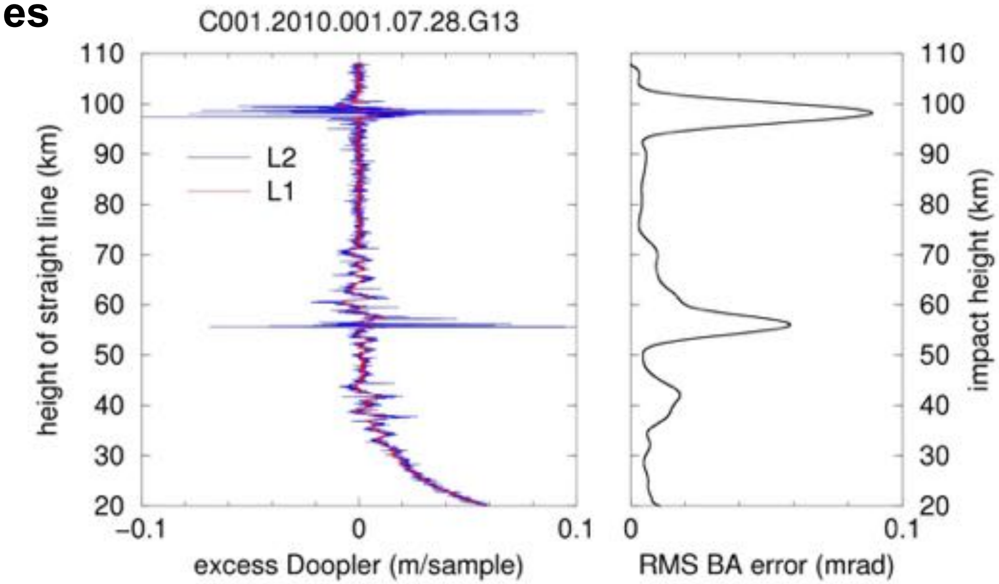
Dynamic (individual for each occ.) BA error characterization

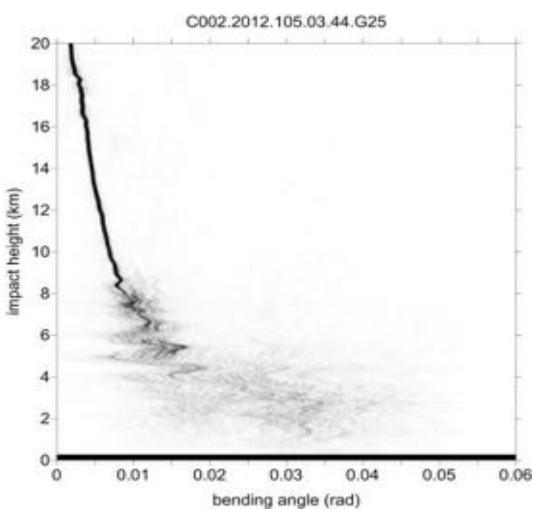
Available in UCAR atmPrf and bfrPrf files

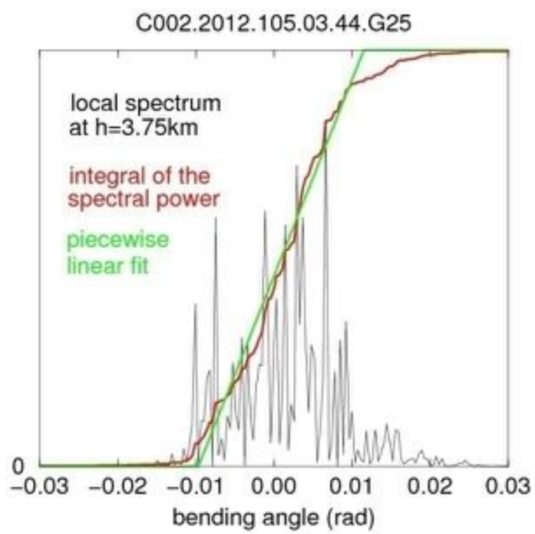
In the stratosphere: based on RMS fluctuation of the LC Doppler in 1 s sliding window.

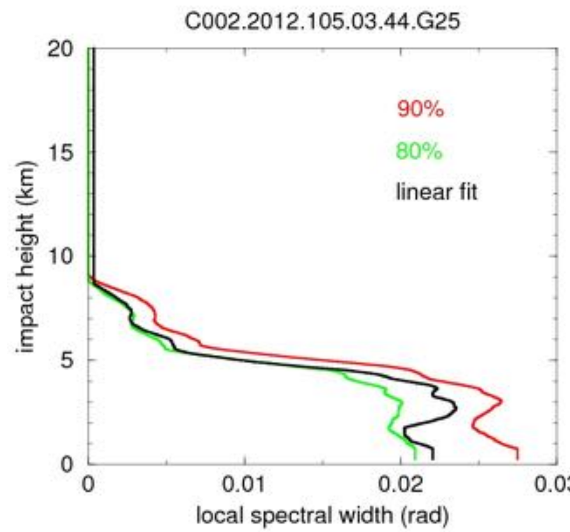
In the troposphere: based on local spectra of WO-transformed RO signal (Gorbuonv et al., JGR, 2006) but with different definition of the local spectral width.

May help to improve NWP impact





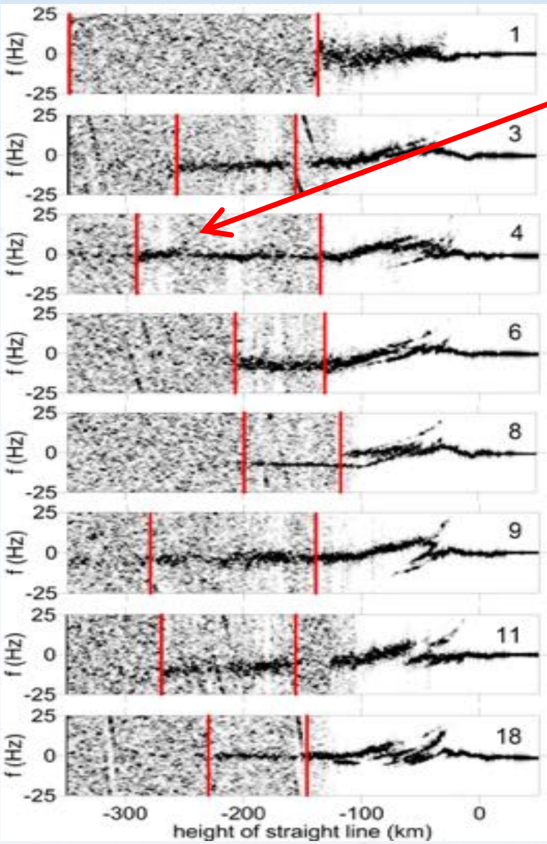


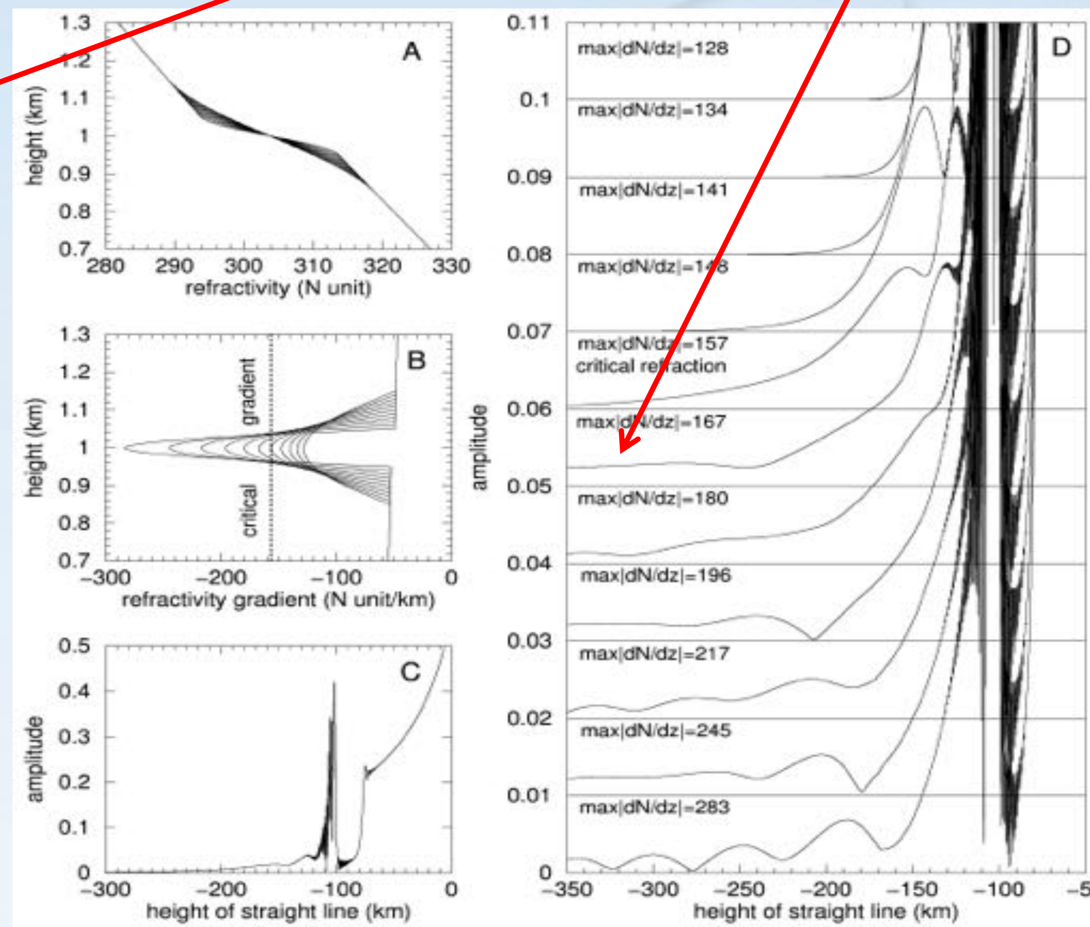


High SNR allows detection of super-refraction

- When N-gradient exceeds critical, i.e. < -157/km, super-refraction (SR) occurs, and a "tail" of RO signal appears at large negative straight line altitudes (-300 km)
- Existence of this deep tail can be used as the indicator of SR
- Reliable detection requires 1-Hz SNR ~2000 V/V

- **Detection of SR will provide cleaner RO BA dataset for NWP data assimilation and should improve RO impact on forecasts in lower troposphere**





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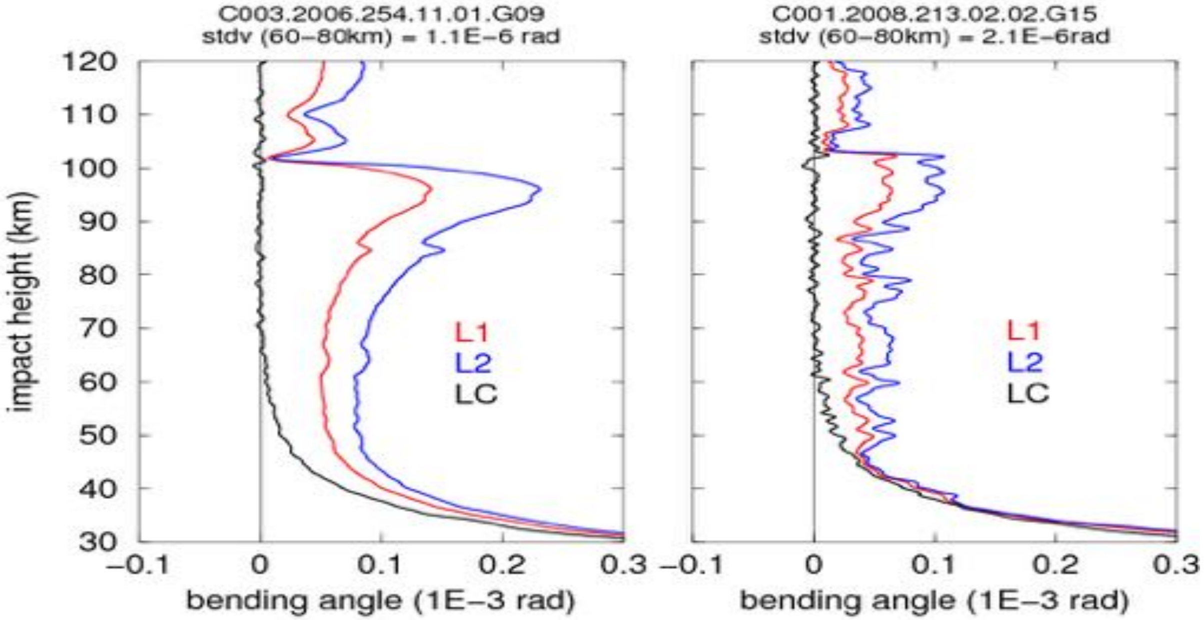
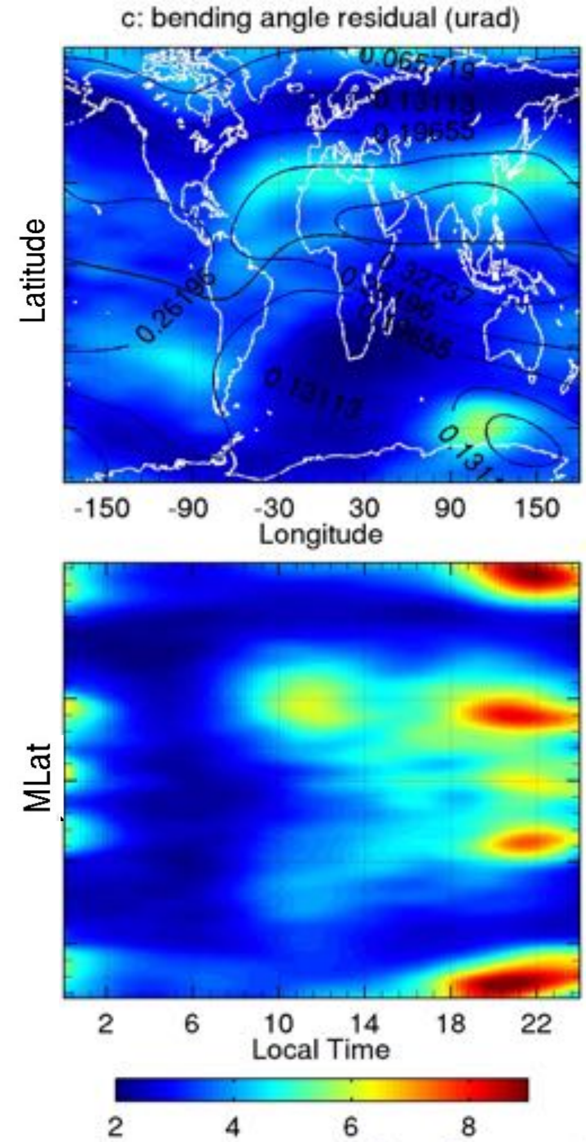
(Sokolovskiy et al., 2014)

Residual bending angle noise between 60-80 km altitude





(Yue et al., IROWG-4, 2015)

<u>Dominant contributors to BA noise at high altitudes</u>

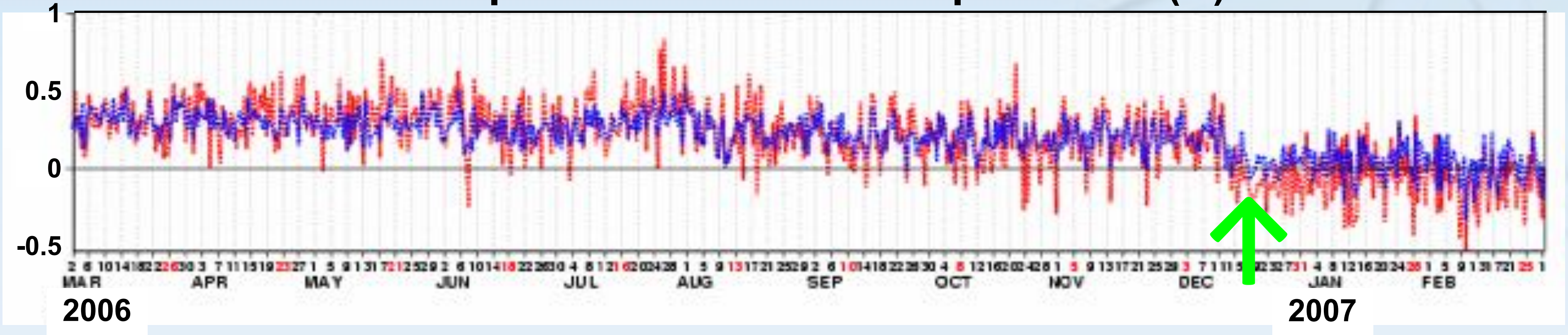
1) ionospheric correction of L1 and L2 BA leaves uncalibrated small-scale effects in the "ionosphere-free" LC BA
2) receiver thermal phase noise contributes noise to BA on occultation and and clock reference links
3) Unmodeled GNSS clock fluctuations

$$\sigma_{BA} = \sqrt{\sigma^{2}_{TGRS-thermal} + \sigma^{2}_{iono-res} + \sigma^{2}_{gnss-clk}}$$

Science Highlights

ECMWF Operational implementation of GPSRO on Dec 12, 2006

Mean departures of analysis (blue) and background (red) from southern hemisphere radiosonde temperatures (K) at 100hPa



Obvious improvement in time series for operational ECMWF model.

Dec 12, 2006 Operational implementation represented a quite conservative use of data. No measurements assimilated below 4 km, no rising occultations.

Nov 6, 2007 Operational assimilation of rising and setting occultations down to surface

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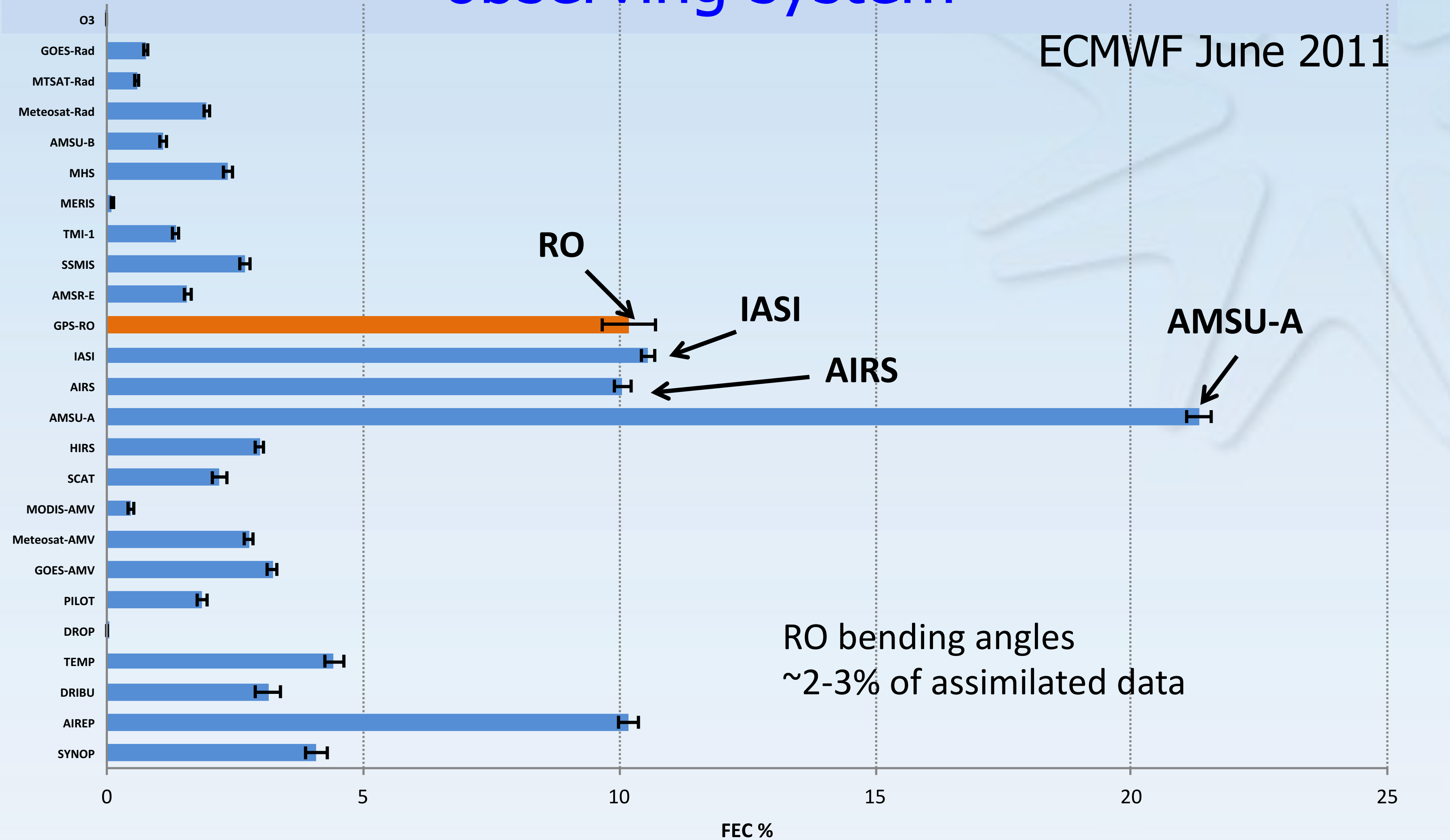
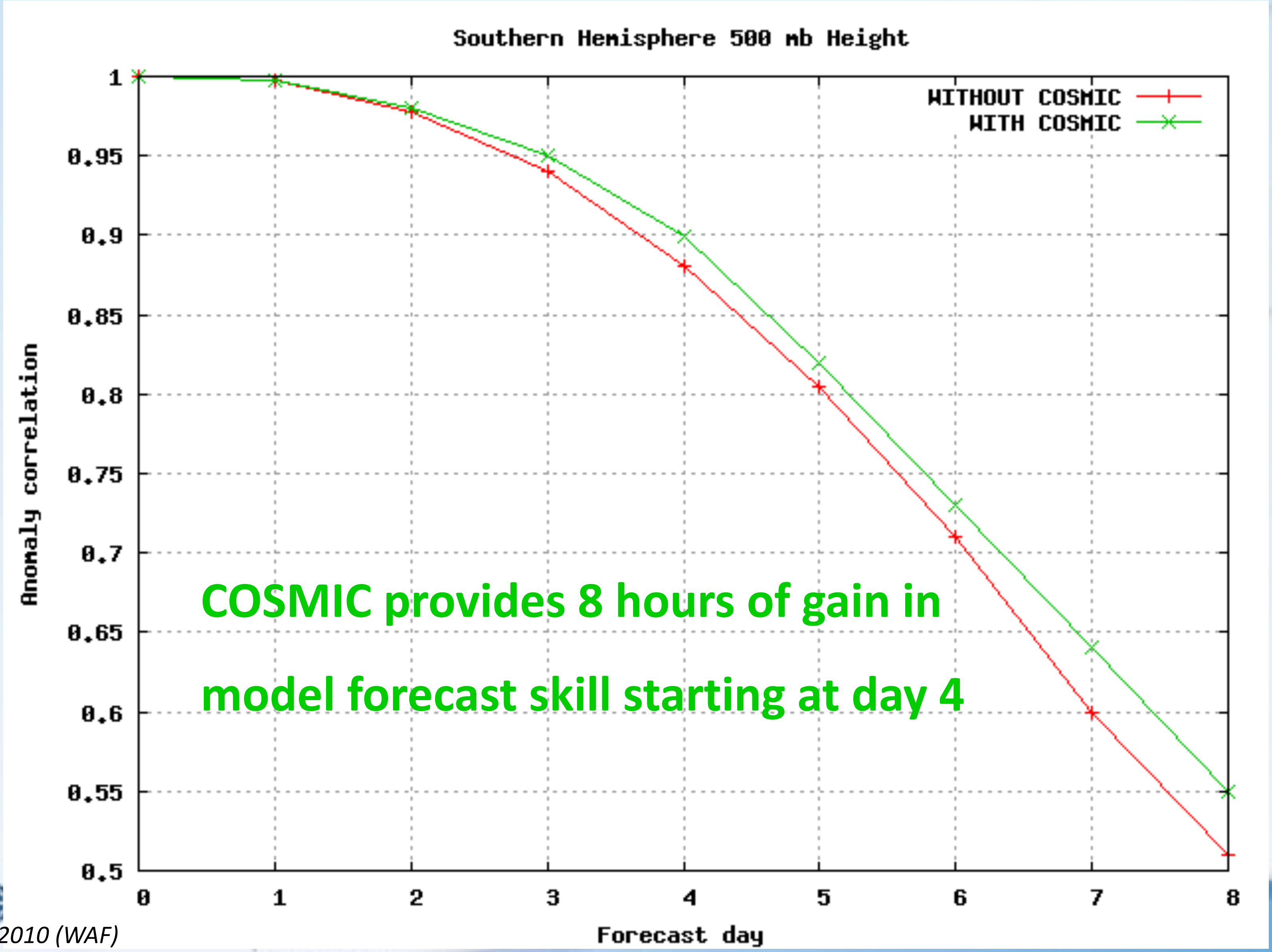
Contributions to forecast accuracy by observing system



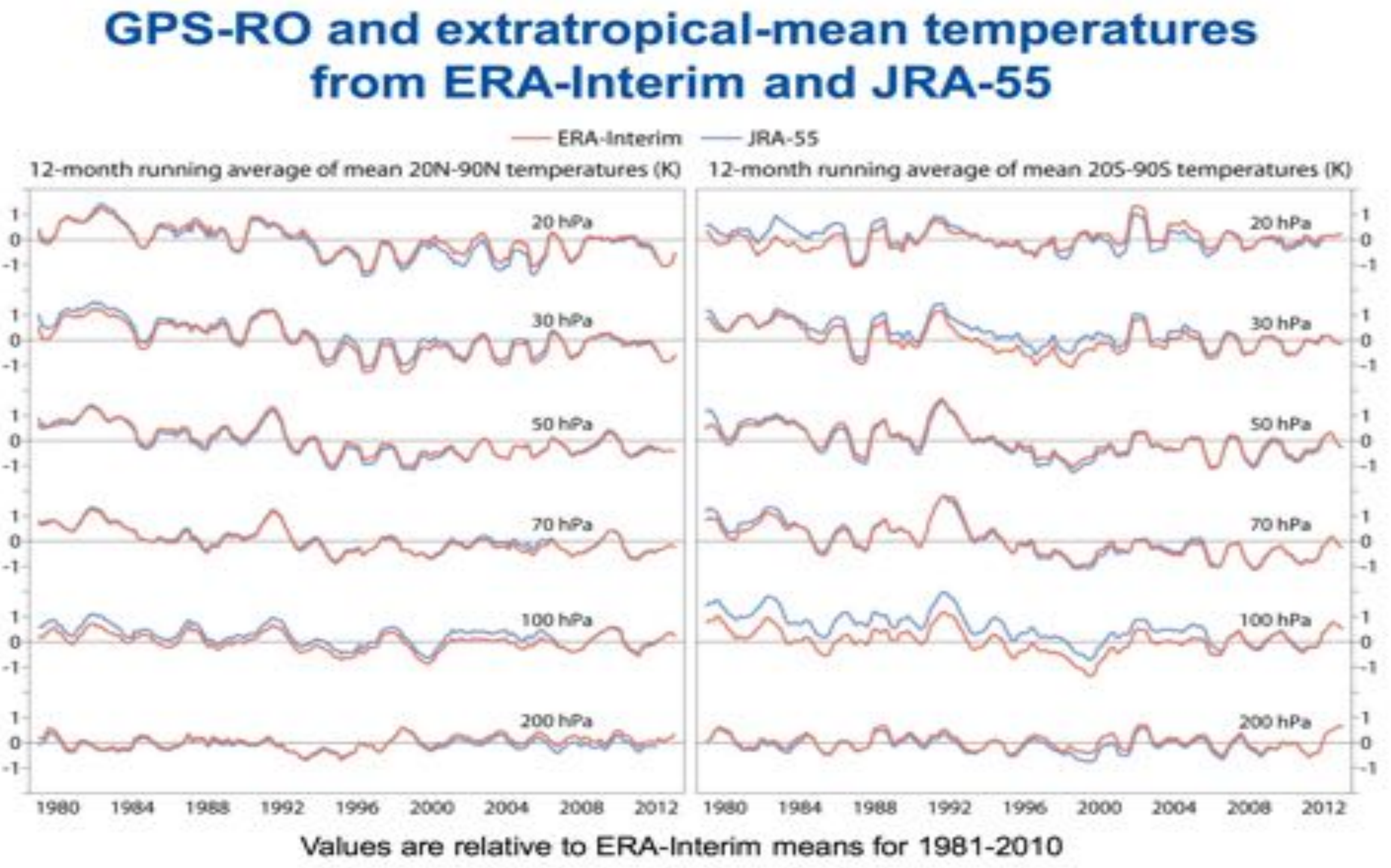
Four of the type five observational systems contributing the operational weather forecasting accuracy are sounding systems. RO is typically in the top five, even though the number of soundings is small compared to other sounding systems

Impact of COSMIC at NCEP



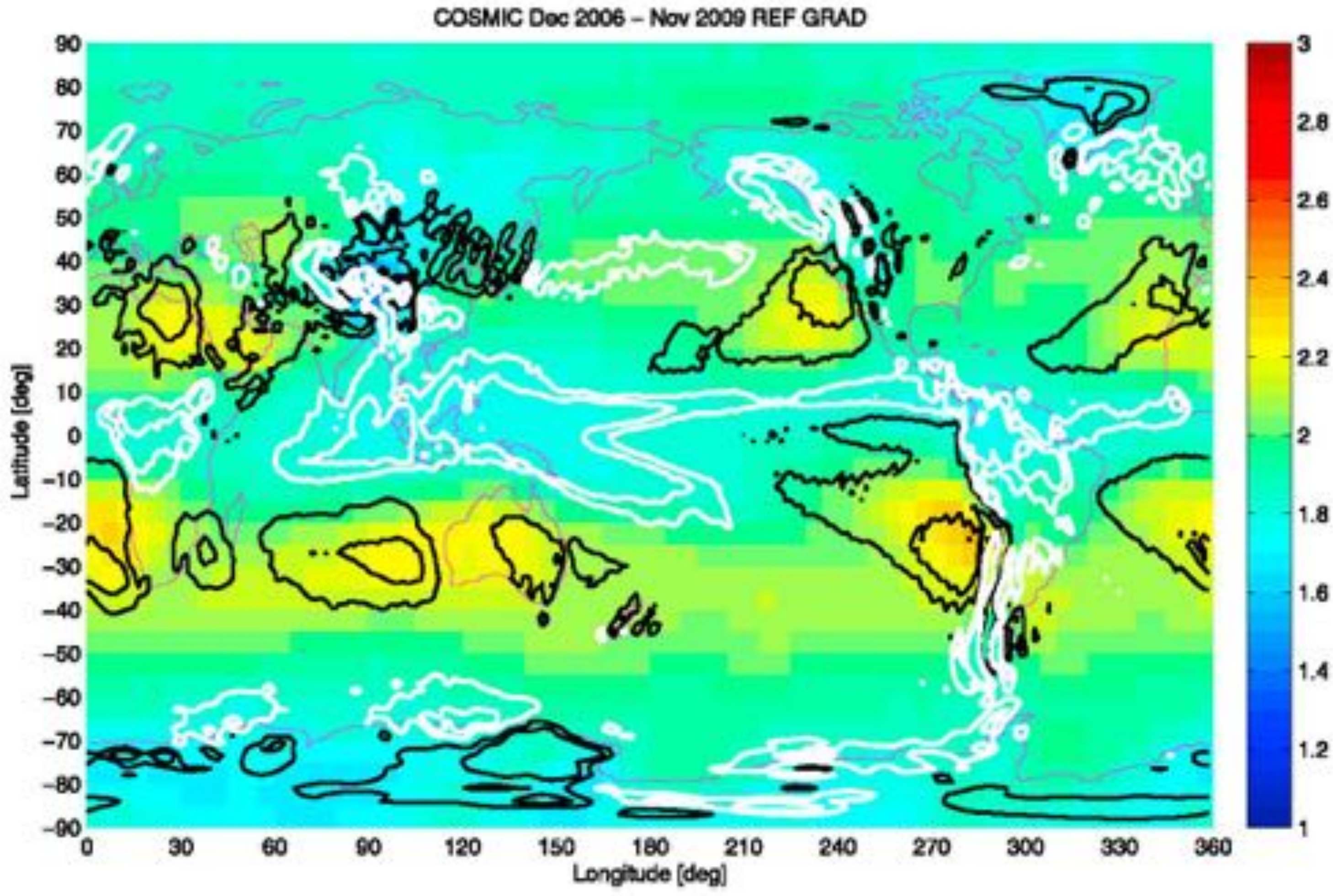
Cucurull 2010 (WAF)

Improved Consistency between Re-Analyses since GPS RO have been Assimilated



Courtesy S. Healy (OPAC/IROWG-2016)

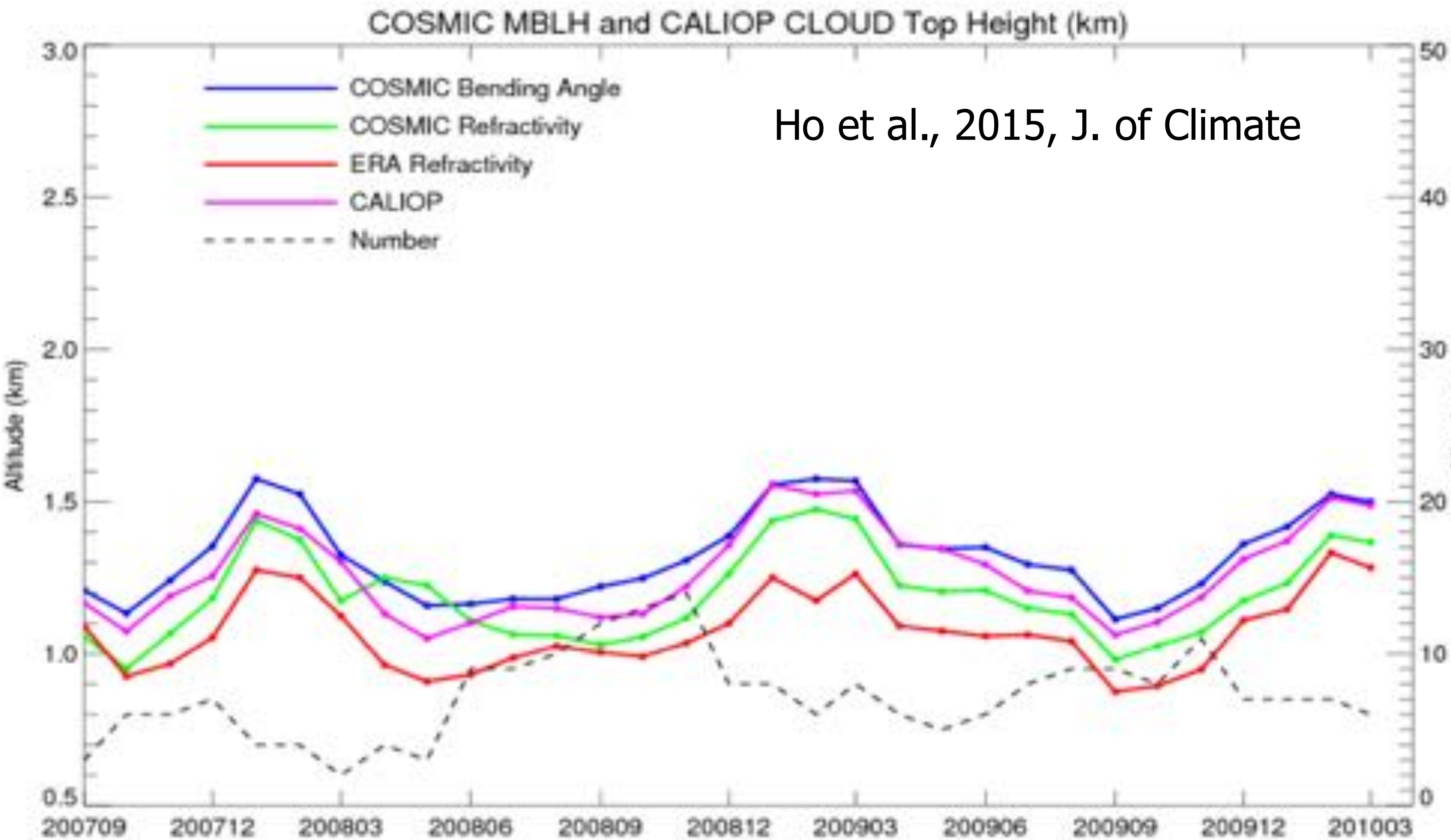
ABL climatology from COSMIC refractivity profiles



RO is an effective way to observe the ABL globally. The ABL is an important aspect of the weather and climate system.

(From Ao et al., 2012)

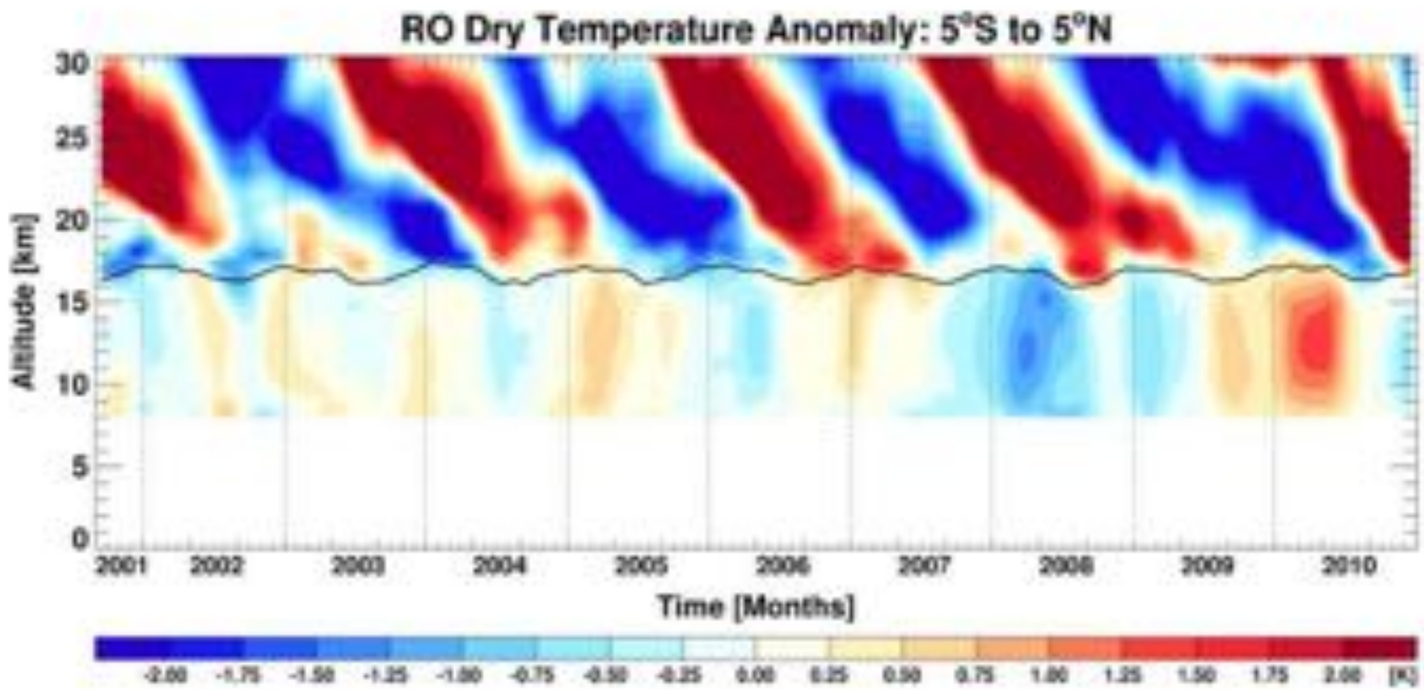
Comparison of CALIPSO Cloud Top Heights and COSMIC ABL Heights in the VOCALS region Sept 2009-Mar 2010



Ho et al., 2015, J. of Climate

ENSO and QBO – Climate Variability in RO Data

- **El Niño Southern Oscillation (ENSO)**
- Phenomenon with quasi-periodicity of 3 to 7 years **in troposphere**
- changes in sea surface temperature of tropical Pacific
- ocean-atmosphere coupling
- **ENSO, QBO – natural variability modes in trend detection**

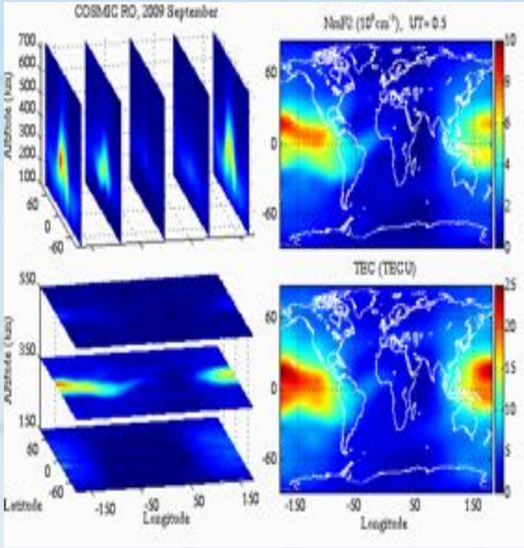


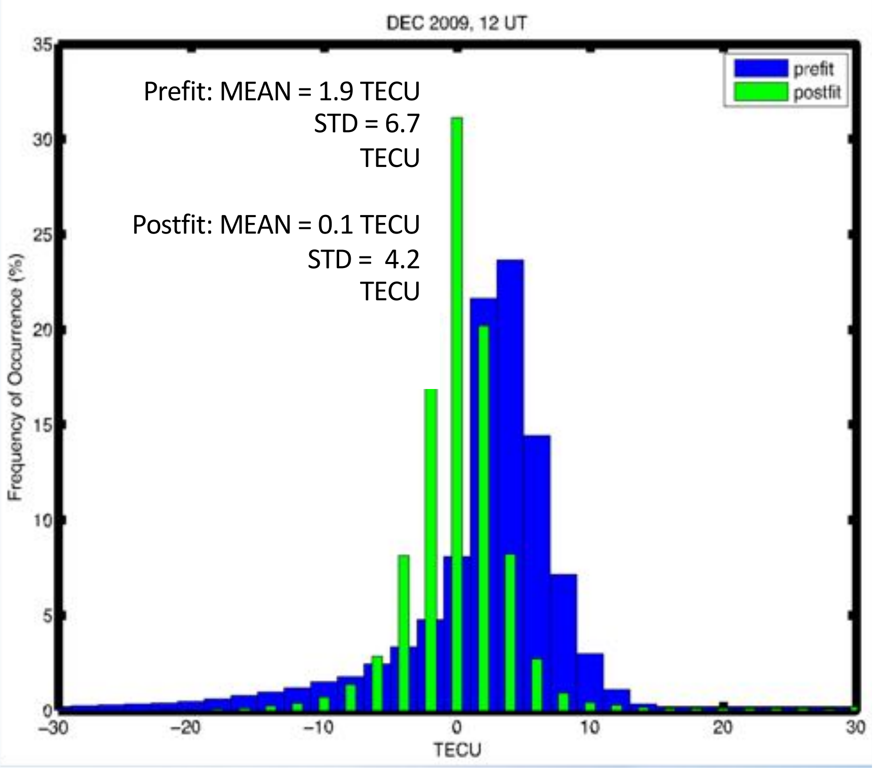
Courtesy A. Steiner (ICGPSRO-2013)

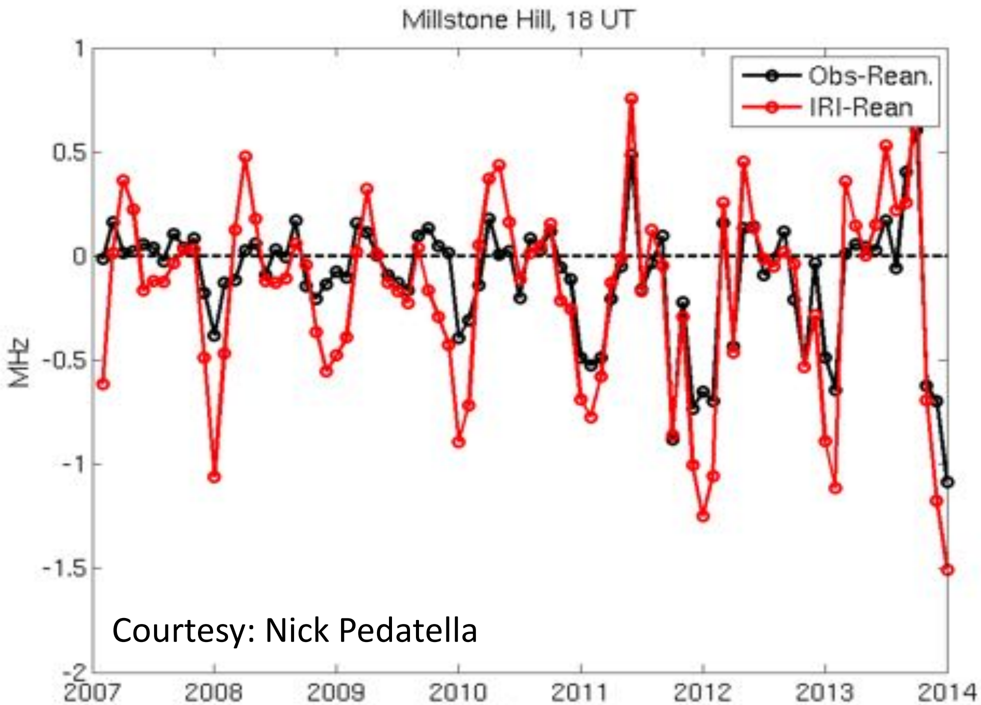
[Scherllin-Pirscher et al. 2012]

Ionosphere Reanalysis with COSMIC

- Assimilation of COSMIC and ground based GPS total electron content observations into the International Reference Ionosphere (IRI) model (Yue et al., 2012)
- Provides monthly mean 4-dimensional (universal time, latitude, longitude, height) gridded electron density product
- Pre- and post-fit residuals (left) and comparison with independent ionosonde data of the F-region peak height (NmF2, right) illustrate that the assimilation results improve upon the empirical IRI model.

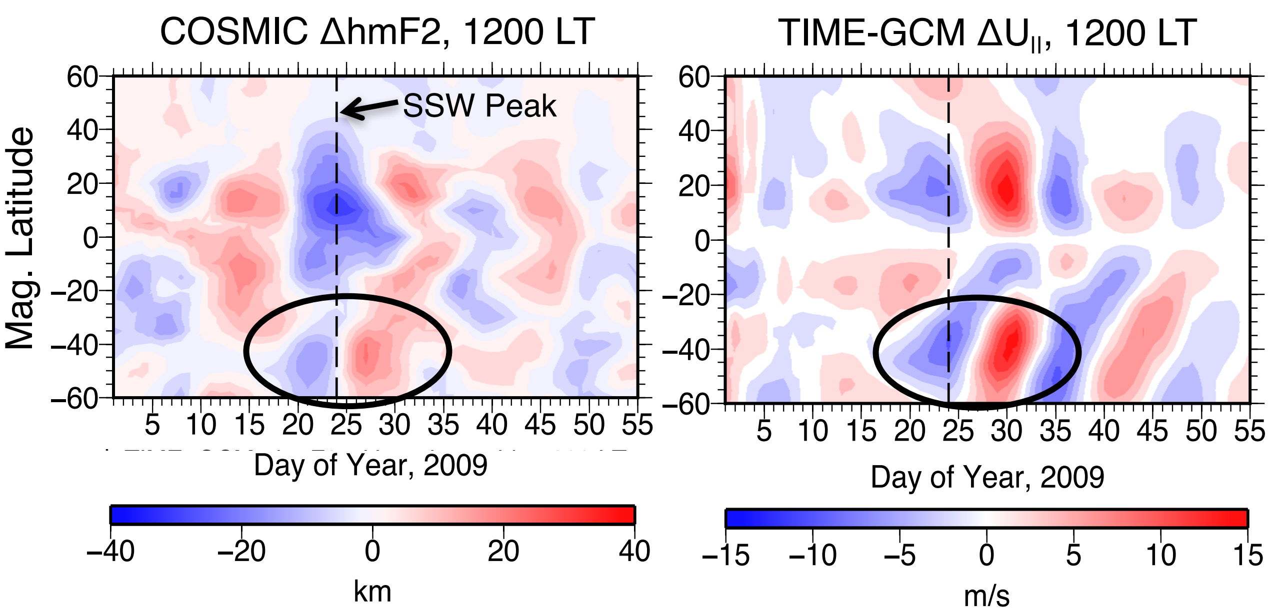




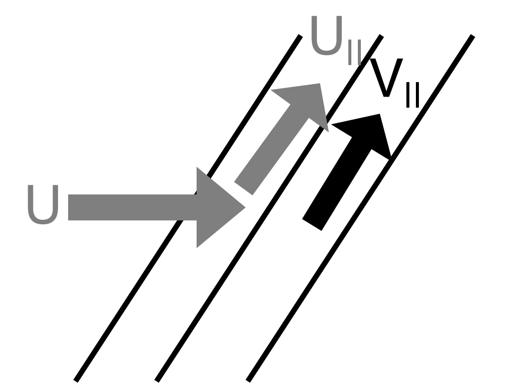


Ionosphere Variability During Sudden Stratosphere Warmings

- Sudden Stratosphere Warming (SSW): warming of the high-latitude winter stratosphere; associated with dramatic changes in temperatures and winds in the middle atmosphere at high-latitudes.
- SSWs are known to influence the low-latitude ionosphere
- COSMIC observations reveal F-region peak height (hmF2) variability occurs at mid to high latitudes in the Southern Hemisphere during SSWs.
- Model simulations reveal that mid-latitude variability is due to neutral winds which raise and lower the F-region peak height at mid-latitudes.
- Since no other observations provide the necessary global coverage, especially in the Southern Hemisphere, COSMIC data are critical for studying these perturbations.



(Pedatella and Maute, 2015)

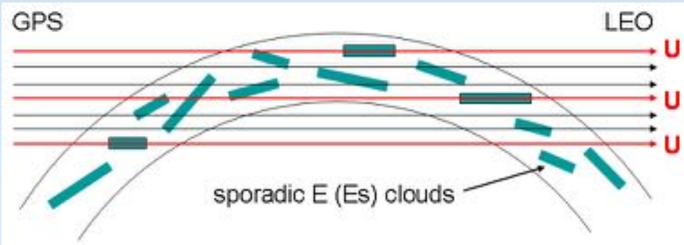


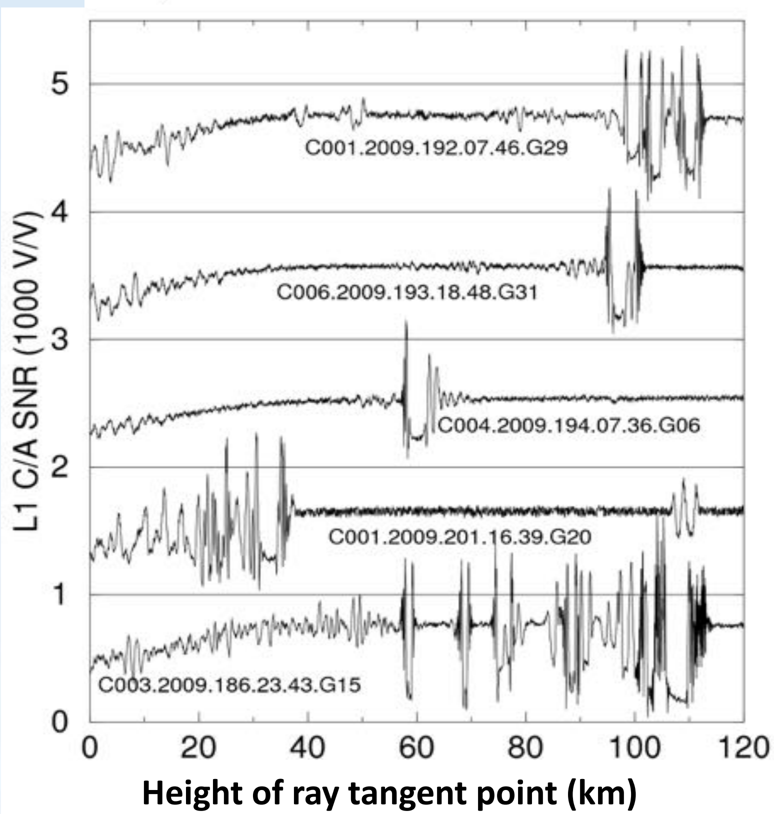
Equatorward wind in Southern Hemisphere will increase hmF2

U – Neutral wind
U$_{II}$ - Field-aligned wind
V$_{II}$ - Field-aligned plasma velocity

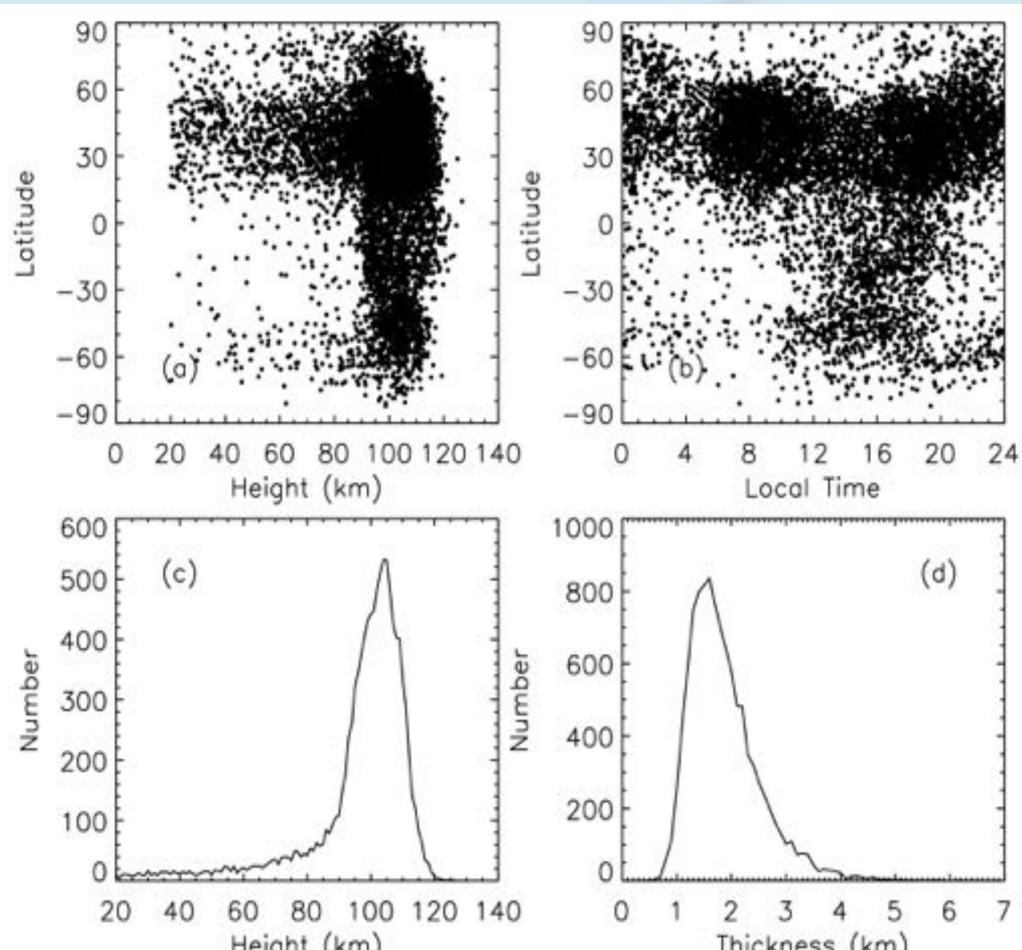
Study of sporadic E (Es) layers by GPS RO

Previously, Es layer was studied by GPS RO based on scintillation. When Es clouds are aligned with the propagation direction they result in specific **U-shaped** structures (due to defocusing) observed in the amplitude of GPS RO signals. This allows to study morphology of the Es clouds.





July 2009



Z.Zeng and S.Sokolovskiy, GRL, 2010

Publications before and after COSMIC launch

	1965-17	2006-17
• Radio occultation	1942	1197
• RO and (COSMIC)	459	442
• RO and weather	330	248
• RO and climate	430	378
• RO and (space wx or ionosphere)	769	583

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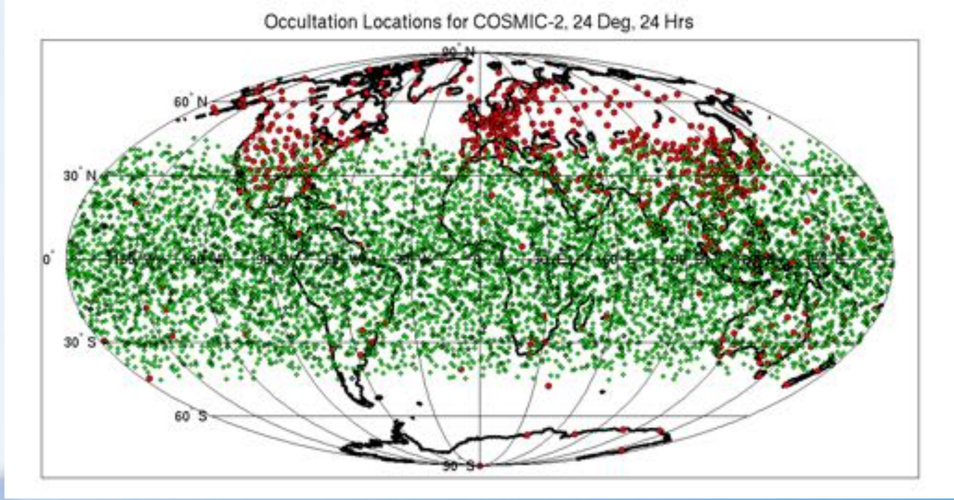
Web of Science 20 Sept 2017

Summary

- The COSMIC/FORMOSAT-3 mission has been a huge success for research and operations!
- The COSMIC dataset has enabled retrieval advancements (some significant challenges remain for GPS RO in upper stratosphere and lower troposphere)
- COSMIC data have provided significant positive impact on weather forecasts, climate studies, and ionospheric research
- With COSMIC-2, an even greater impact is expected

Launch: Q2 2018
~5000 RO soundings
Between 40 N – 40 S



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COSMIC Sponsors and Partners

US Government

- NSF
- NOAA
- NASA/JPL
- Air Force
- Navy (ONR, NRL)

International

- NSPO, Taiwan
- CWB, Taiwan
- TTFRI, Taiwan
- EUMETSAT, Europe
- KASI, Korea
- IEEC, Spain

Other

- Universities
- NCAR
- Private sector
- Broad Reach Engineering
- Orbital Sciences