Recent Advances in Radio Occultation Science and Applications and a Look at the Future

Richard A. Anthes

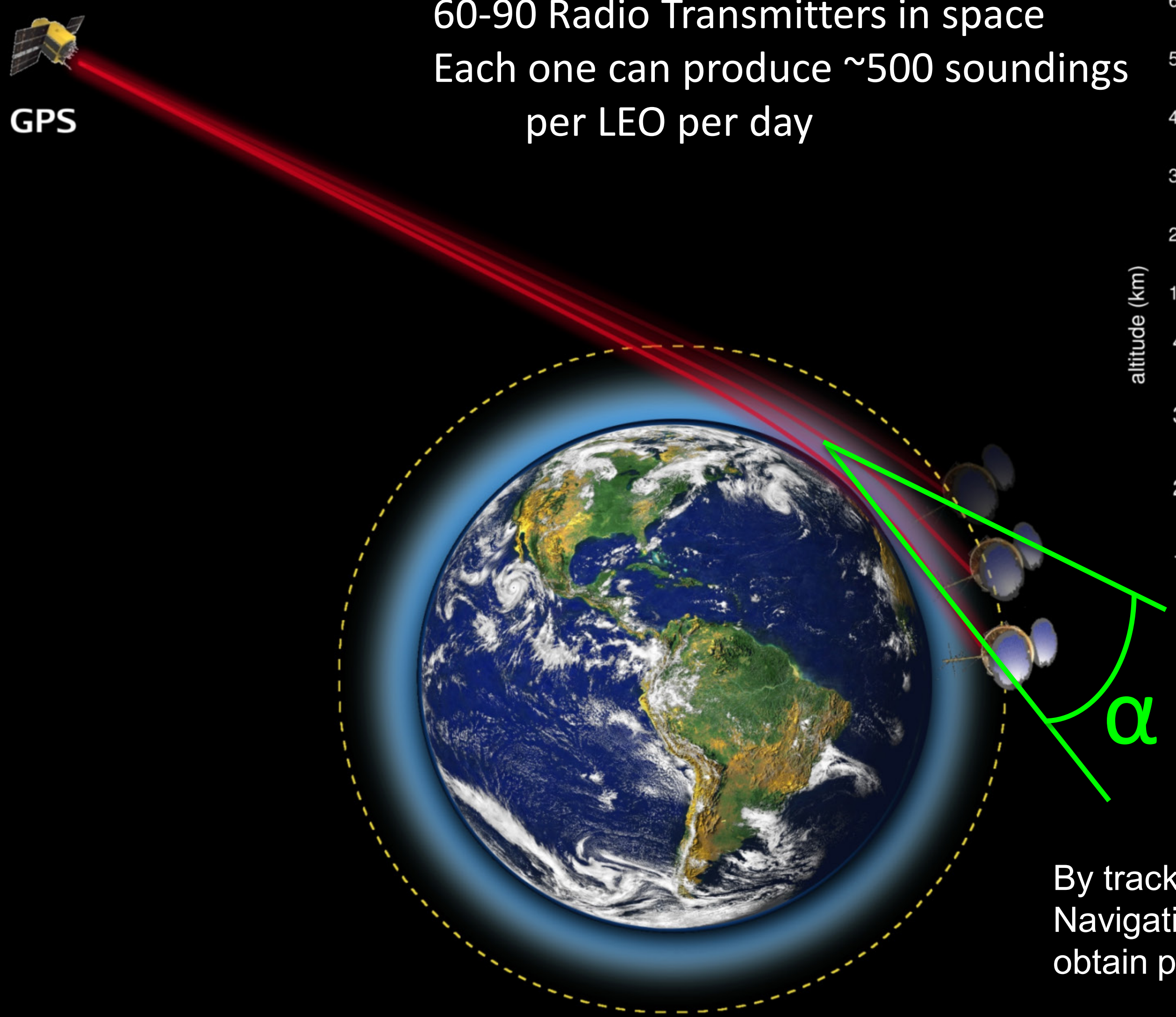
16 April 2015

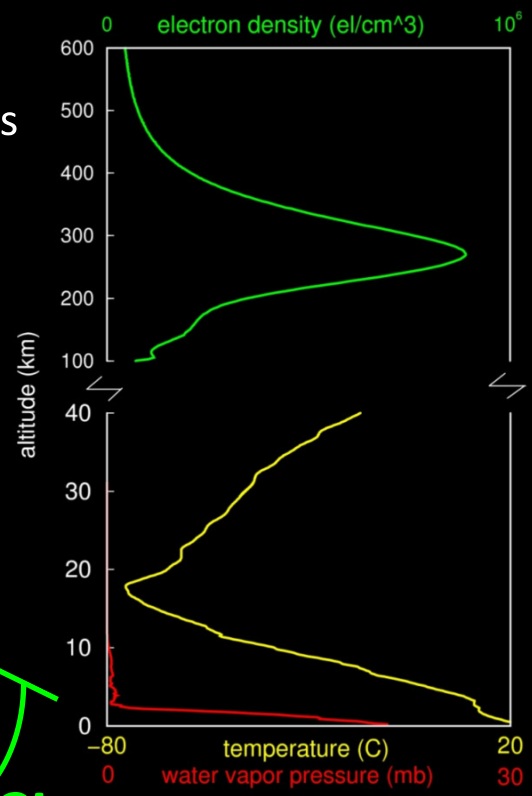
From OPAC-IROWG 2013 in Seggau Castle, Austria

to IROWG 2015 Melbourne, Australia

For our guests: Introduction to Radio Occultation

GPS, Glonass, Galileo
60-90 Radio Transmitters in space
Each one can produce ~500 soundings per LEO per day





By tracking signals transmitted by Global Navigation Satellite Systems, we can obtain profiles of atmospheric properties.

Planetary
Radio Occultation

Mariner IV

Mars July 1965

Radio occultation was first applied to planetary atmospheres by teams at Stanford U. and NASA/JPL

Characteristics of RO Data

- Limb sounding geometry complementary to ground and space nadir viewing instruments
- Global coverage
- Profiles ionosphere, stratosphere and troposphere
- High accuracy (equivalent to <0.5 K; average accuracy <0.1 K)
- High precision (0.02-0.05 K)
- High vertical resolution (0.1 km near surface – 1 km tropopause)
- Only system from space to profile atmospheric boundary layer (ABL)
- All weather-minimally affected by aerosols, clouds or precipitation
- Absolute TEC accuracy < 1-3 TECU
- Relative TEC accuracy < 0.3 TECU
- Independent height and pressure
- Requires no first guess sounding
- No calibration required
- Climate benchmark quality-tied to SI standards
- Independent of processing center
- Independent of mission
- No instrument drift
- No satellite-to-satellite bias
- Compact sensor, low power, low cost

All of these characteristics have been demonstrated in peer-reviewed literature.

Scientific Uses of Radio Occultation Data

- **Weather**
  - Improve global weather analyses, particularly over data sparse regions such as the oceans, tropics, and polar regions
  - Increase accuracy of numerical weather forecasts
  - Improve understanding of tropical, mid-latitude and polar weather systems and their interactions
- **Ionosphere and Space Weather**
  - Observe global electronic density distribution
  - Improve the analysis and prediction of space weather
  - Improve monitoring/prediction of scintillation (e.g. equatorial plasma bubbles, sporadic E clouds)
- **Climate**
  - Monitor climate change and variability with unprecedented accuracy- **world's most accurate, precise, and stable thermometer from space!**
  - Evaluate global climate models and analyses
  - Calibrate infrared and microwave sensors and retrieval algorithms

CLAIM

Radio Occultation: "World's most accurate and stable thermometer from space"

Origin of this claim

"World's most accurate and precise thermometer!"28 Nov. 2006 COSMIC Workshop Taiwan

"World's most accurate, precise and stable thermometer for climate monitoring" AGU Press Conference 11 Dec 2006 San Francisco

"World's most accurate thermometer! "CH Liu Symp 6 Oct. 2008 . Also 2nd COSMIC Data Users Workshop Oct 22-25, 2007 in Boulder.

"World's most accurate, precise, and stable thermometer from space!"
(Presentation at U. Wisconsin 2 Nov. 2009. Also OSTP/OMB Oct. 26, 2009.
Also U.OK seminar April 22, 2008, CWB Taiwan 21 Feb 2008

Is the Claim True?

The world's most accurate, precise and stable thermometer from space
Yes, say these scientists (among others, sorry for omissions)

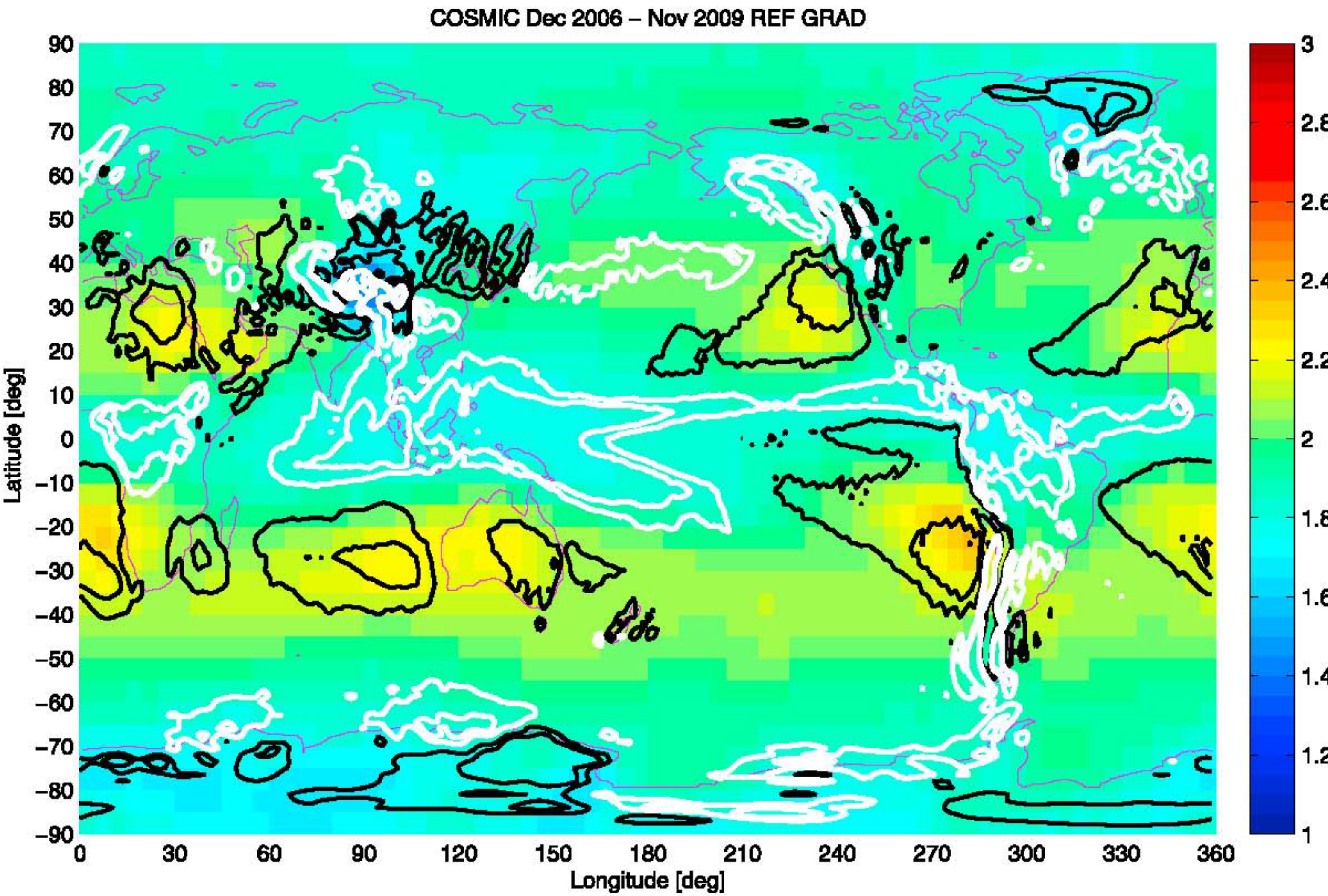
- **Rick Anthes**
- **Chi Ao**
- **Josep Aparichio**
- **Riccardo Biondi**
- **John Braun**
- **Lidia Cucurull**
- **Dave Ector**
- **Axel von Engeln**
- **Uli Foelsche**
- **Hans Gleisner**
- **Michael Gorbunov**
- **Sean Healy**
- **Stefan Heise**
- **Shu-Peng (Ben) Ho**
- **C.-Y. Huang**
- **Doug Hunt**
- **Gottfried Kirchengast**
- **Ying-Hwa (Bill) Kuo**
- **Rob Kursinski**
- **Kent B. Lauritsen**
- **C.-H Liu**
- **J.-Y. (Tiger) Liu**
- **Stephen Leroy**
- **Tony Mannucci**
- **Christian Marquardt**
- **Nick Pedatella**
- **Therese Rieckh**
- **Christian Rocken**
- **Barbara Scherllin-Pirscher**
- **Torsten Schmidt**
- **William Schreiner**
- **Sergey Sokolovskiy**
- **Stig Syndergaard**
- **Andrea Steiner**
- **C.-Y. Tsay**
- **Jens Wickert**
- **Nick Yen**
- **Xinan Yue**
- **Tom Yunck**
- **Zhen (Janet) Zeng**
- **Kefei Zhang**


RO
background
skill
Weather
weather
accuracy
C/NOFS
anchor
model
3DVAR
anomaly
bias
observations
data
NWP
saving
radio
assimilation
prediction
COSMIC
reduction
refractivity
models
error
forecasts
improvement
Sandy
SAC-C
precision
improved
correlation
typhoon
ECMWF
drift
angle
improvements
METOP
numerical
covariance
cost
CHAMP
occultation
NCEP
stability
hurricane
bending
increment
storms
winter
lives
Office
4DVAR
function

Planetary Boundary Layer Studies

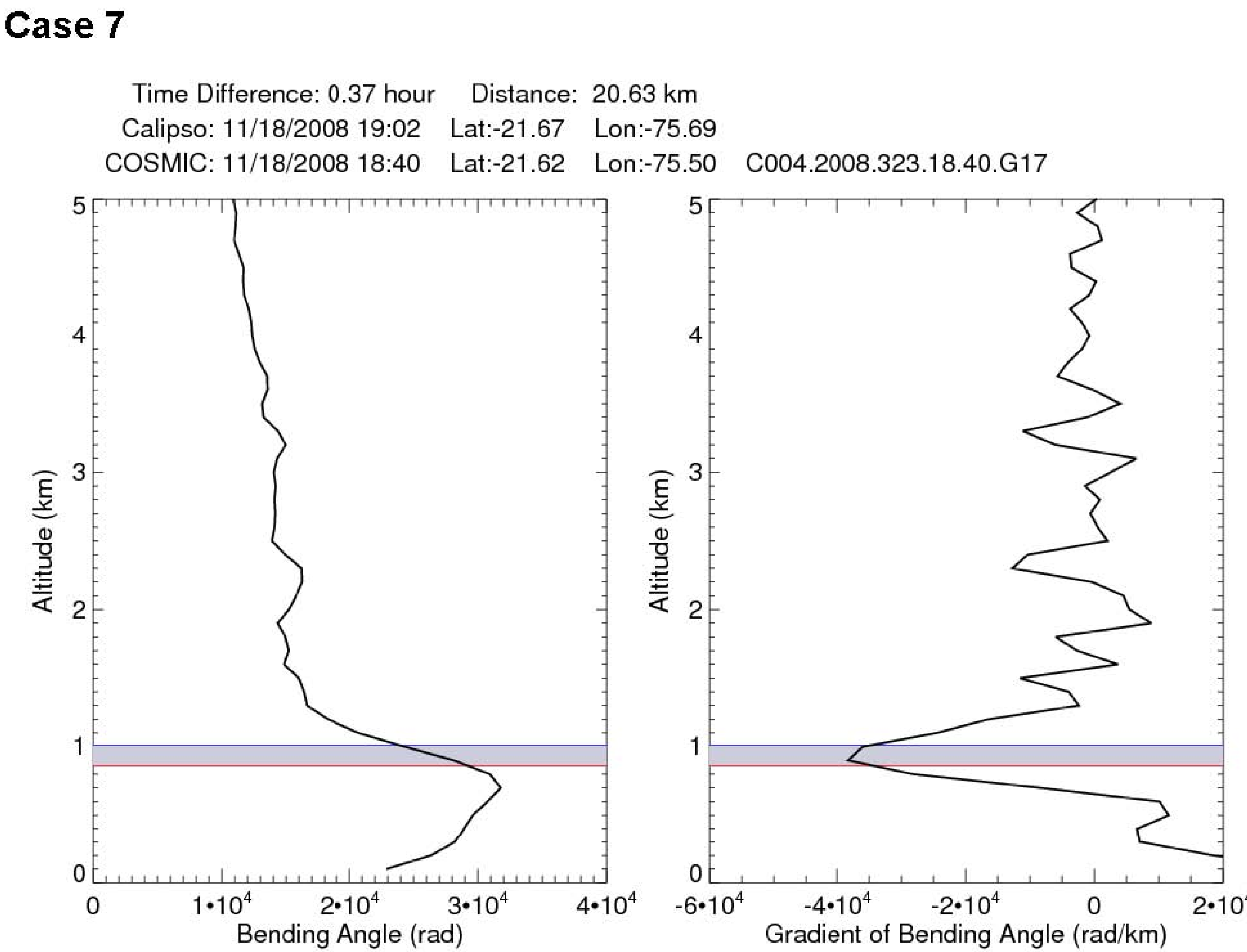
Global Map of sharpness parameter

N'_{min}/RMS N



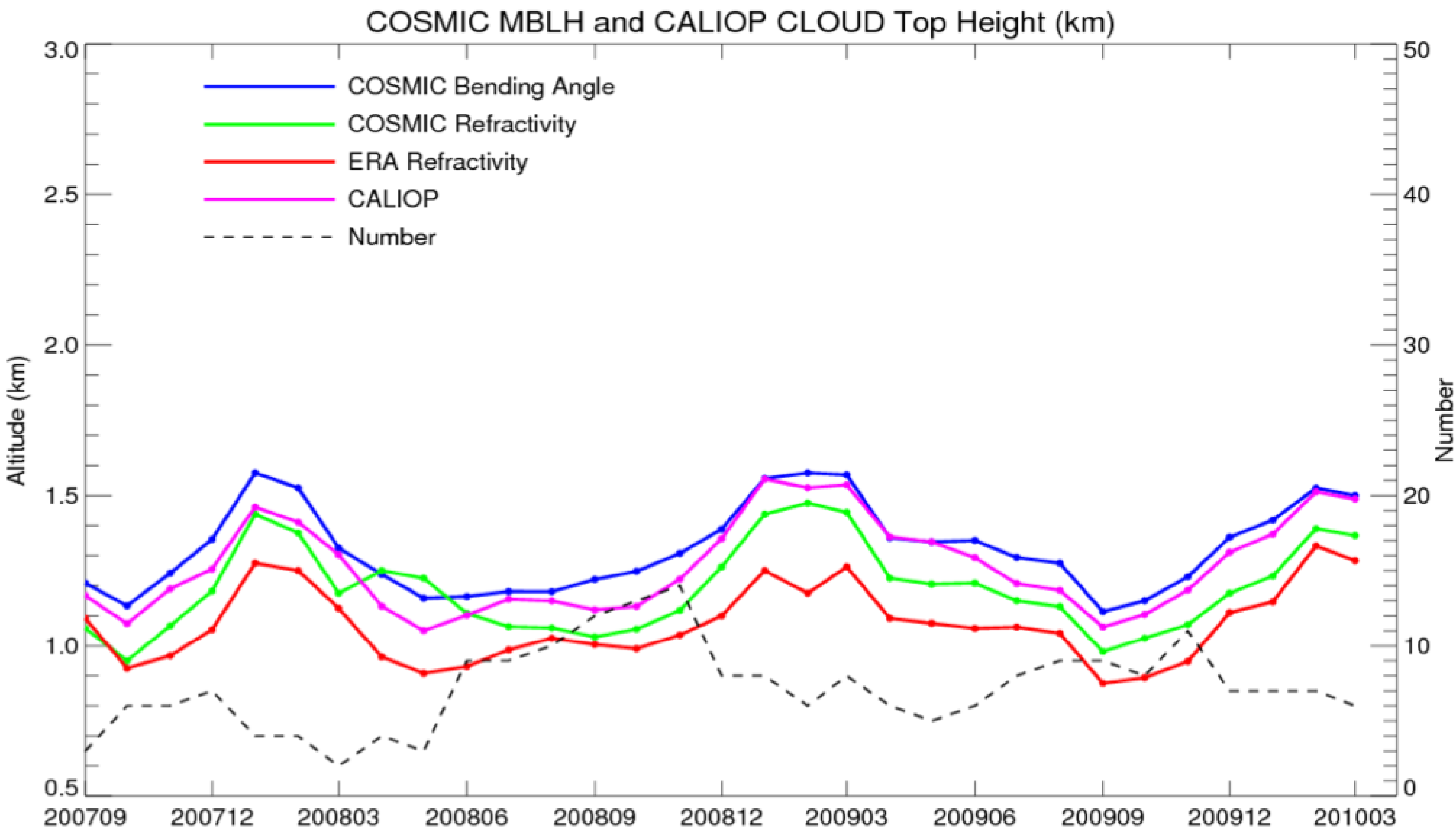
Chi Ao et al. JGR 2012

Comparison between CALIPSO Cloud Top Height and COSMIC PBLH Over VOCALS region (off west coast South America)



Ho et al., 2015, J. of Climate

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



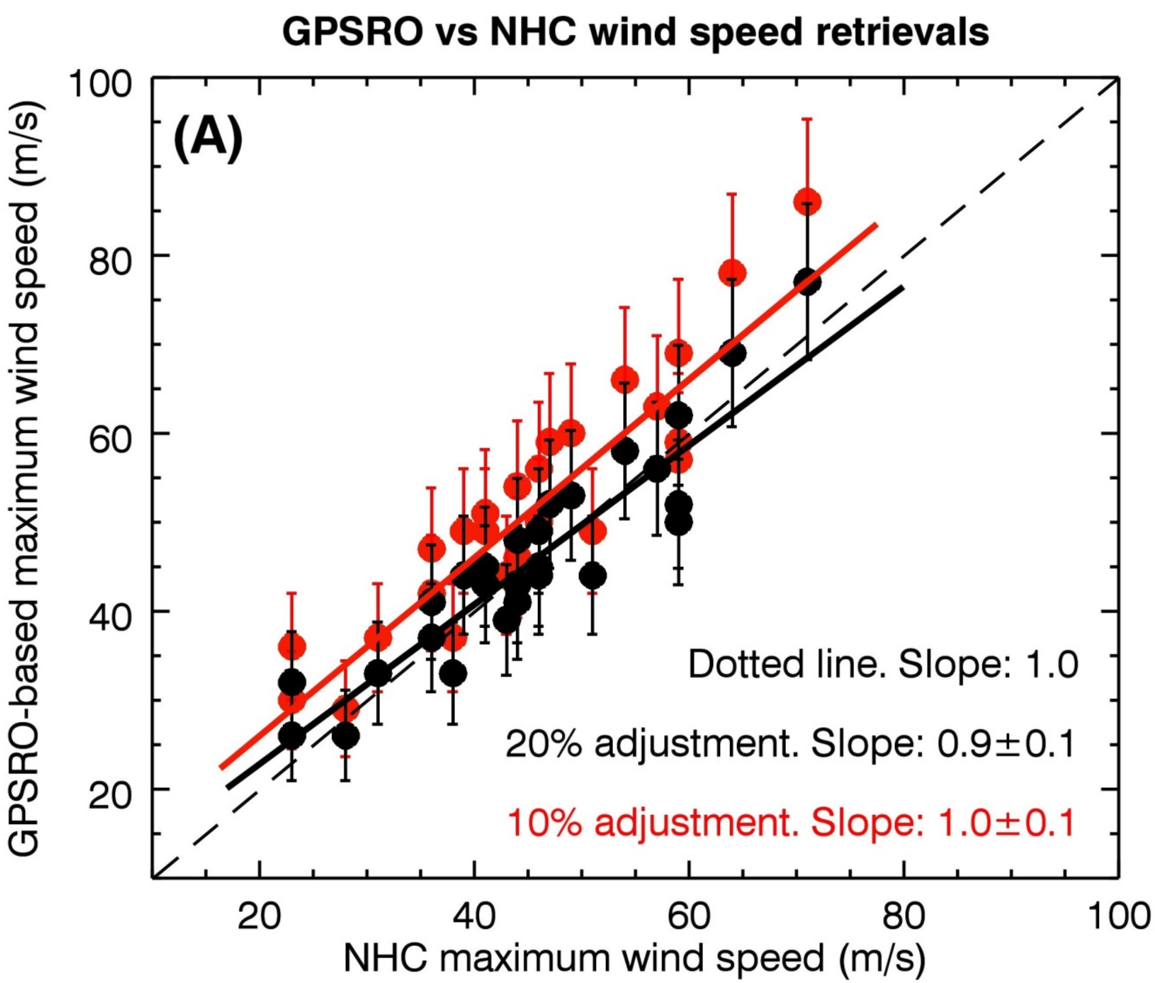
Ho et al., 2015, J. of Climate

RO and tropical cyclones

- Tropical cyclone observation and prediction:
  - Water vapor: Important for convective development, genesis, intensity, track and precipitation forecasts
  - Temperature: Important for large-scale circulations and track forecasts
  - Can estimate intensity of TC using RO
- COSMIC-1 has demonstrated significant impact in TC forecasts; COSMIC-2 with 5X number of higher quality observations will be significantly better

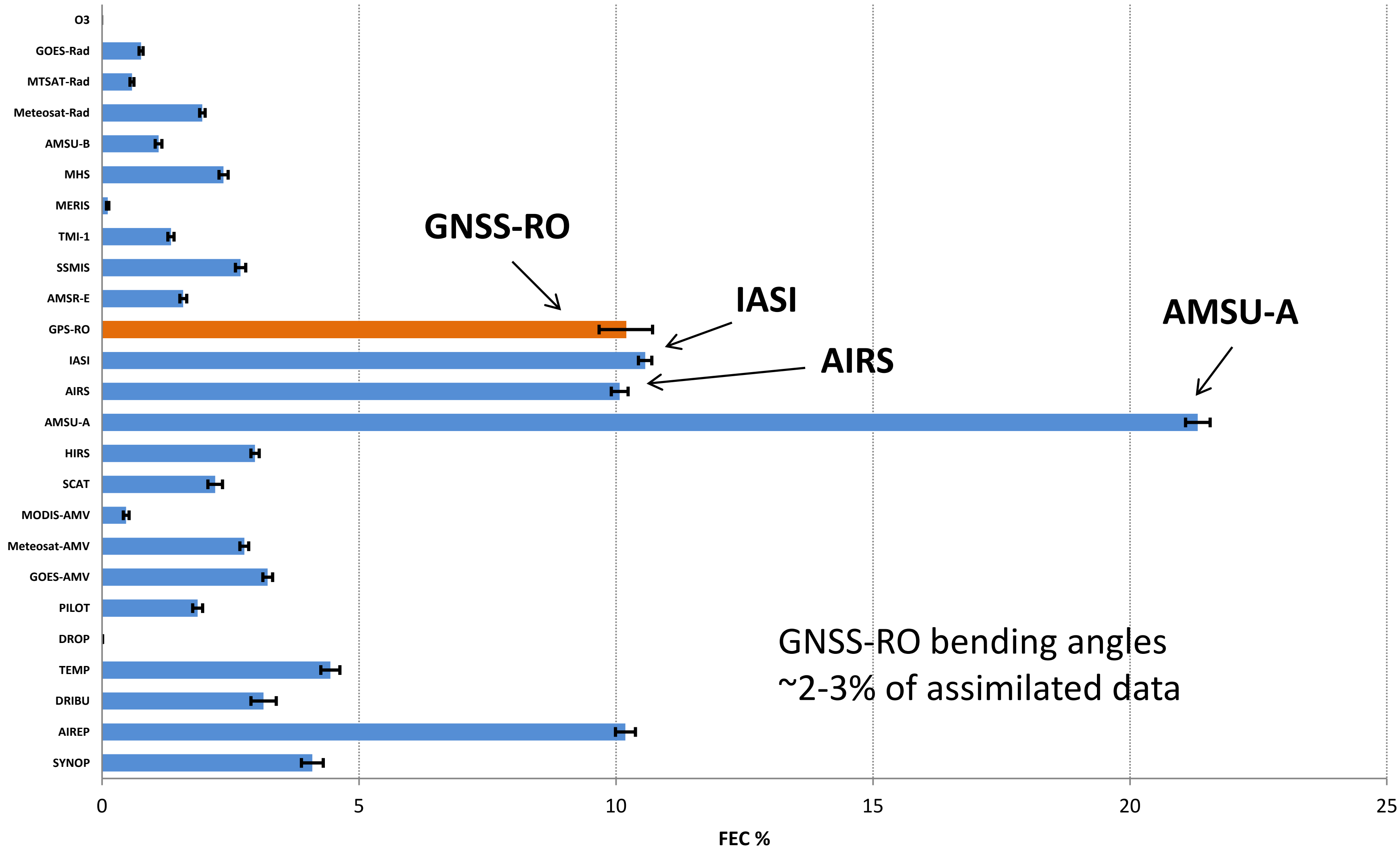
Tropical cyclone intensity from RO

Outflow temperatures in the eyewall region of 27 hurricanes in 2004–2011 were obtained from RO. With ocean surface temperatures, it was possible to estimate hurricane intensities using a simplified hurricane model.



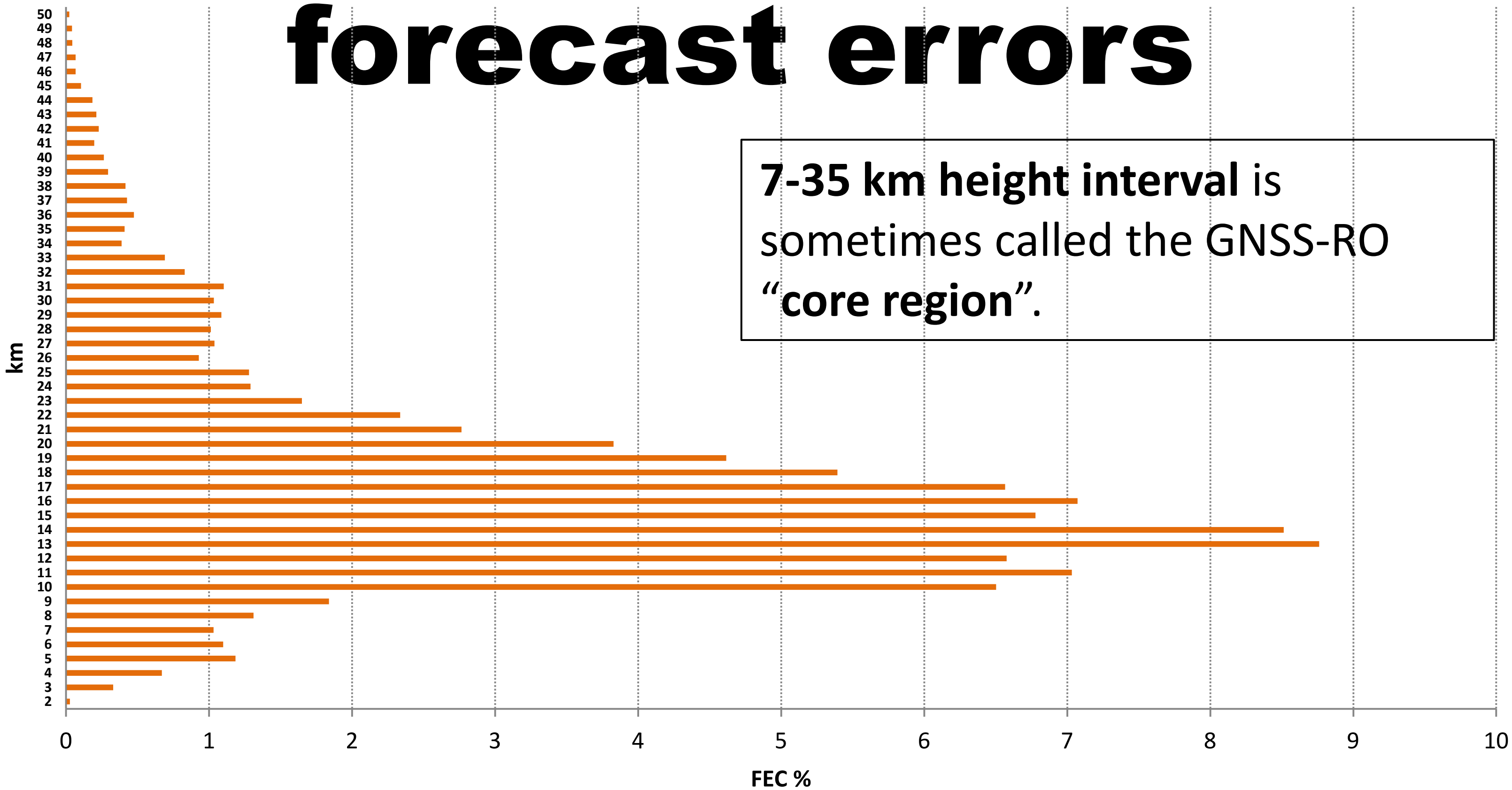
Observational tests of hurricane intensity estimations using GPS radio occultations. Vergados, Luo, Emanuel, and Mannucci, 2014, *JGR*

RO has major impact on global weather prediction
Among top five observing systems in impact



ECMWF System (June 2011)

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



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

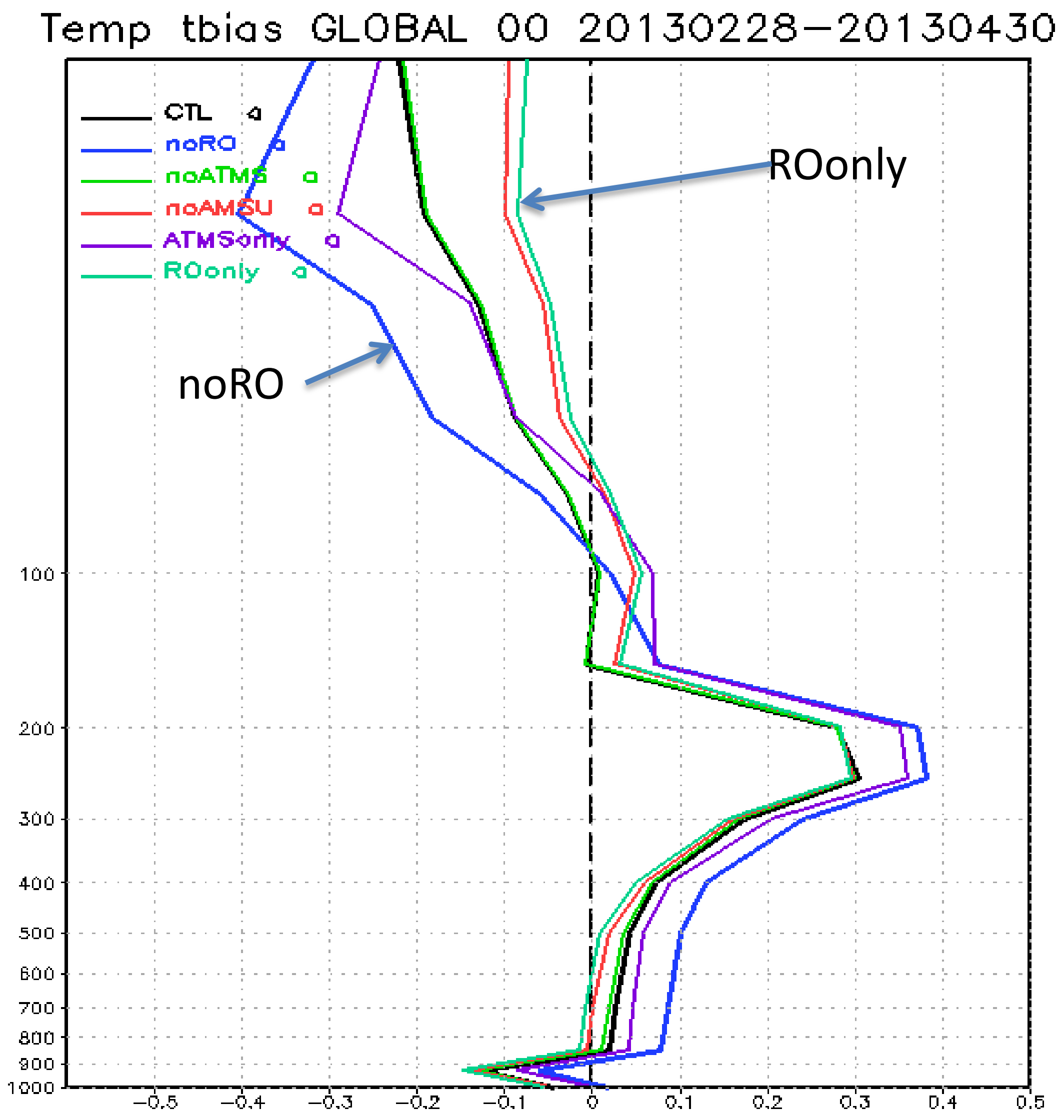
Remark: Agrees with early 1D-Var information content studies.

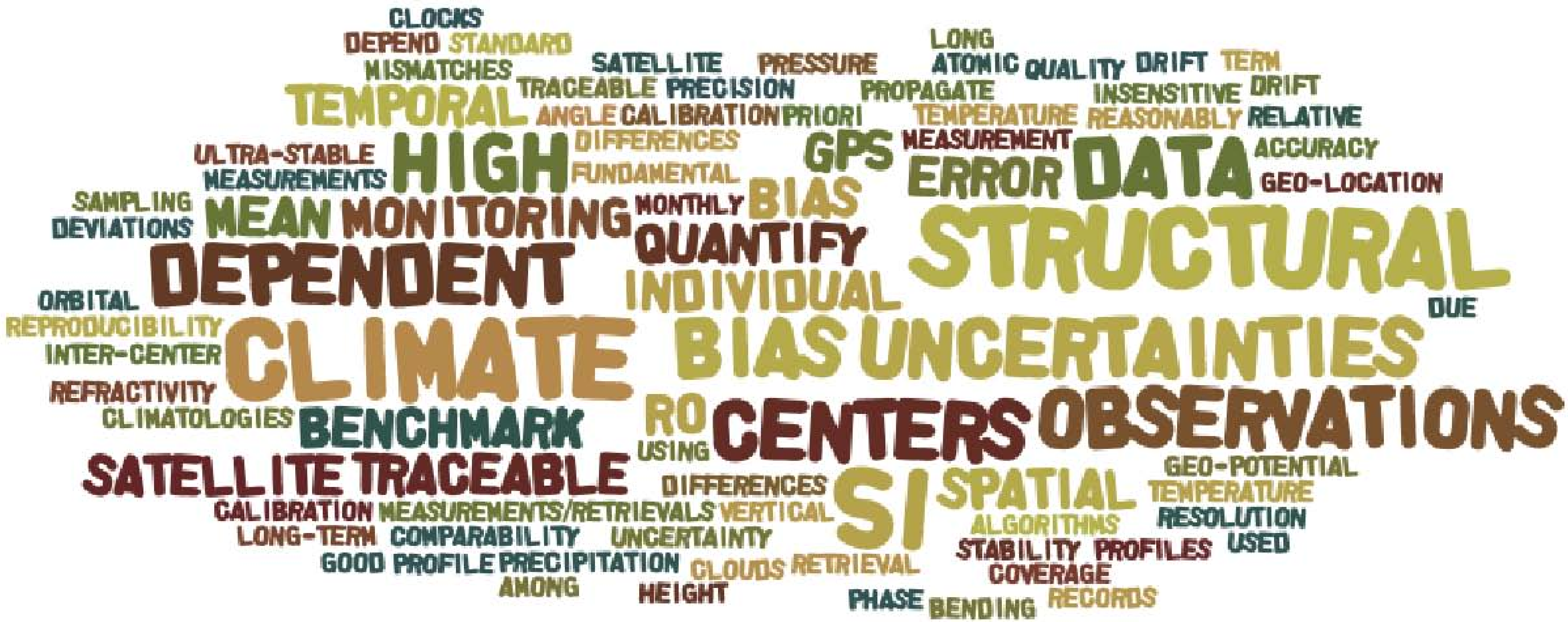
Florian Harnisch, Sean Healy, Peter Bauer, Steve English, Nick Yen, 2013

RO, IR, and Microwave are complementary

- Three systems provide independent information on temperature and water vapor
- RO can be used to calibrate and validate IR and microwave retrievals
- RO “anchors” NWP and reduces bias corrections needed for IR and microwave observations in NWP models
- Therefore balanced system of IR, MW and RO is most efficient and cost effective

Global temperature biases of analyses relative to radiosondes in six experiments (Cucurull and Anthes, 2015)




CLOCKS
DEPEND STANDARD
MISMATCHES
SATELLITE
PRESSURE
LONG
ATOMIC QUALITY DRIFT TERM
TEMPORAL
TRACEABLE PRECISION
PROPAGATE
INSENSITIVE DRIFT
ANGLE CALIBRATION PRIORI
TEMPERATURE REASONABLY RELATIVE
HIGH
DIFFERENCES
GPS
MEASUREMENT
DATA
ACCURACY
ULTRA-STABLE
MEASUREMENTS
FUNDAMENTAL
ERROR
GEO-LOCATION
SAMPLING
DEVIATIONS
MEAN MONITORING
MONTHLY BIAS
STRUCTURAL
QUANTIFY
DEPENDENT
INDIVIDUAL
ORBITAL
DUE
REPRODUCIBILITY
CLIMATE
BIAS UNCERTAINTIES
INTER-CENTER
REFRACTIVITY
CLIMATOLOGIES
BENCHMARK
RO
CENTERS
OBSERVATIONS
USING
SATELLITE TRACEABLE
GEO-POTENTIAL
DIFFERENCES
SI
SPATIAL
TEMPERATURE
CALIBRATION MEASUREMENTS/RETRIEVALS VERTICAL
ALGORITHMS
RESOLUTION
LONG-TERM COMPARABILITY UNCERTAINTY
STABILITY PROFILES USED
GOOD PROFILE PRECIPITATION
CLOUDS RETRIEVAL
COVERAGE
AMONG
HEIGHT
PHASE BENDING RECORDS

wege entstehen, indem wir sie gehen
paths emerge in that we walk them

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Atmospheric Remote Sensing and Climate System Research Group
ARSCliSys

Climate Monitoring & Change Detection with GPS Radio Occultation

A.K. Steiner

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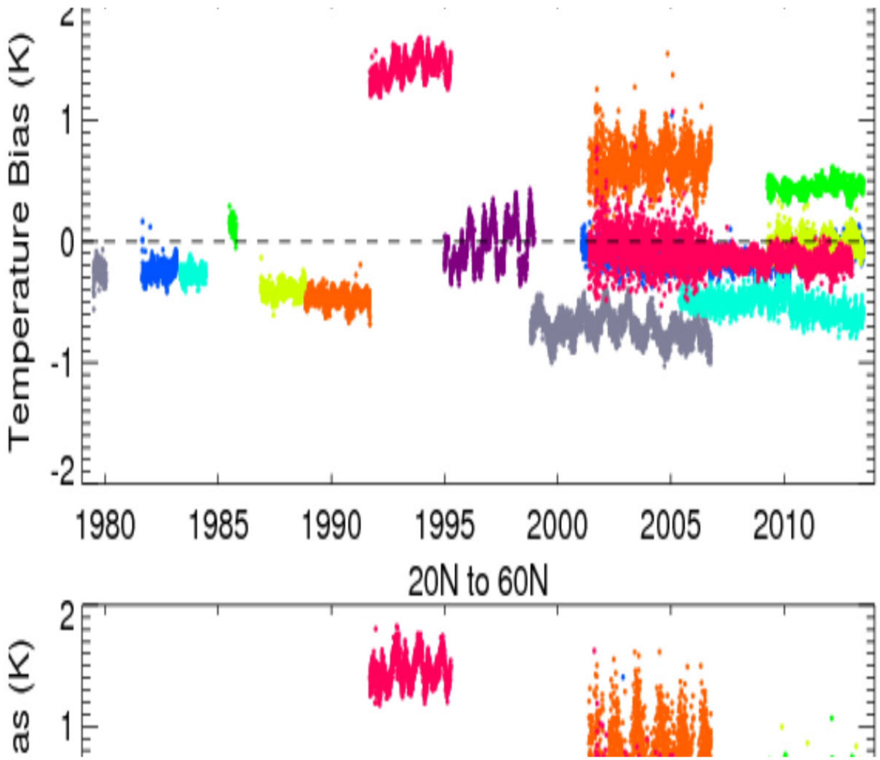
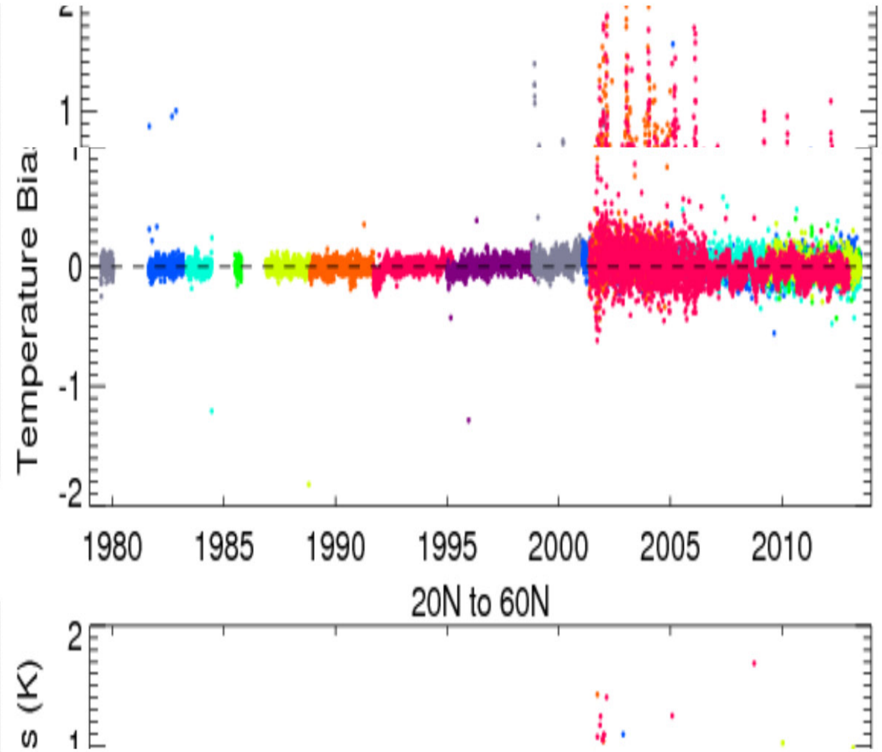
Thanks to all colleagues of the ARSCliSys research group/WEGC and to all colleagues worldwide who contributed to work discussed here.

2nd International Conference on GPS Radio Occultation - ICGPSRO, May 14-16, 2013, Taipei, Taiwan

Calibration of MSU/AMSU with RO Measurements



Temperature biases in MSU/AMSU satellites before calibration with RO.

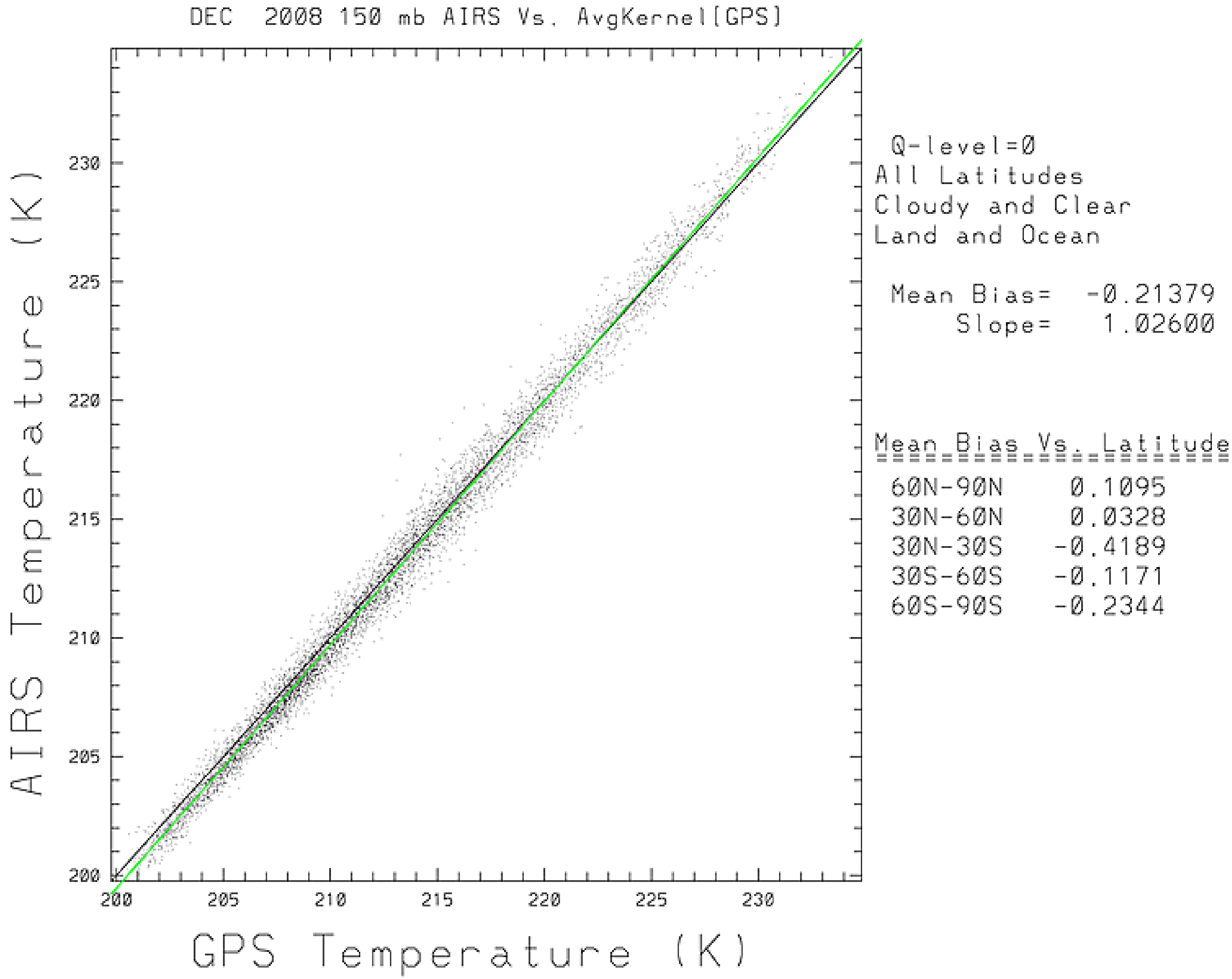


Temperature biases after calibration with RO data from 2001 to 2013.

AIRS vs. COSMIC Temperature (K)

Corr ~ 1.0

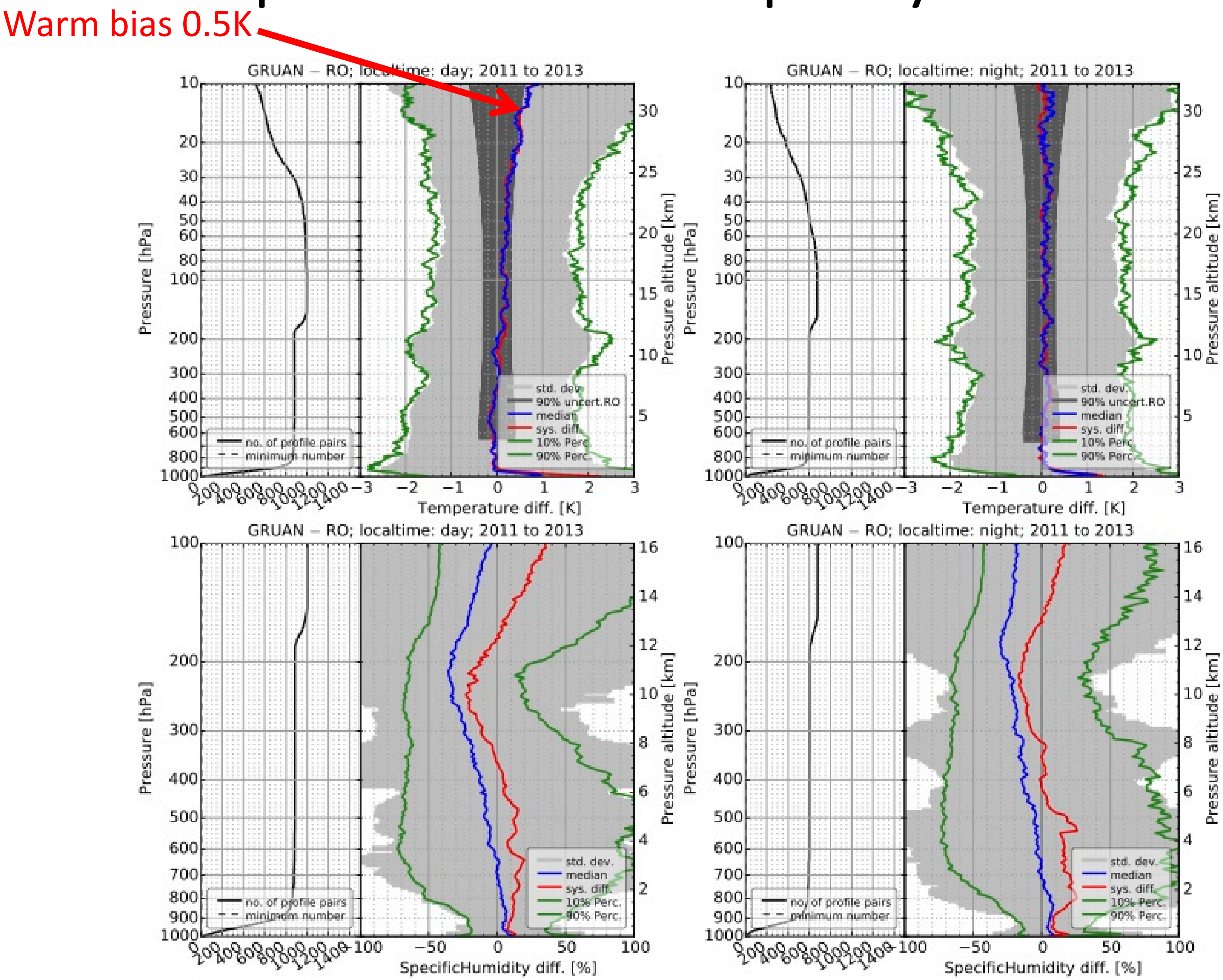
We can use the defined slope and offset to calibrate AIRS temperatures



Ben Ho, 2014

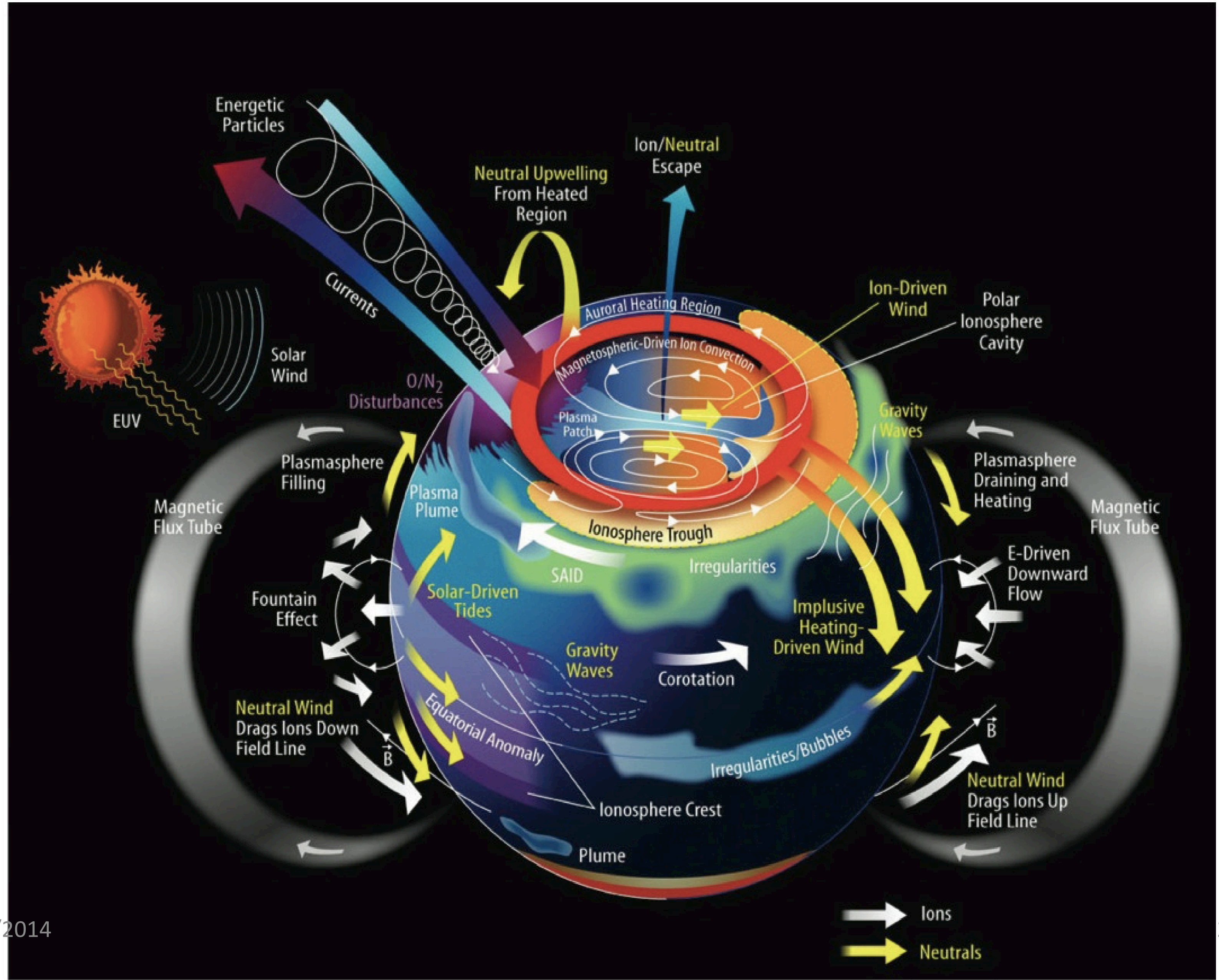
Agreement here is very good, validating AIRS retrieval algorithms and calibration

RO compared to climate-quality radiosondes

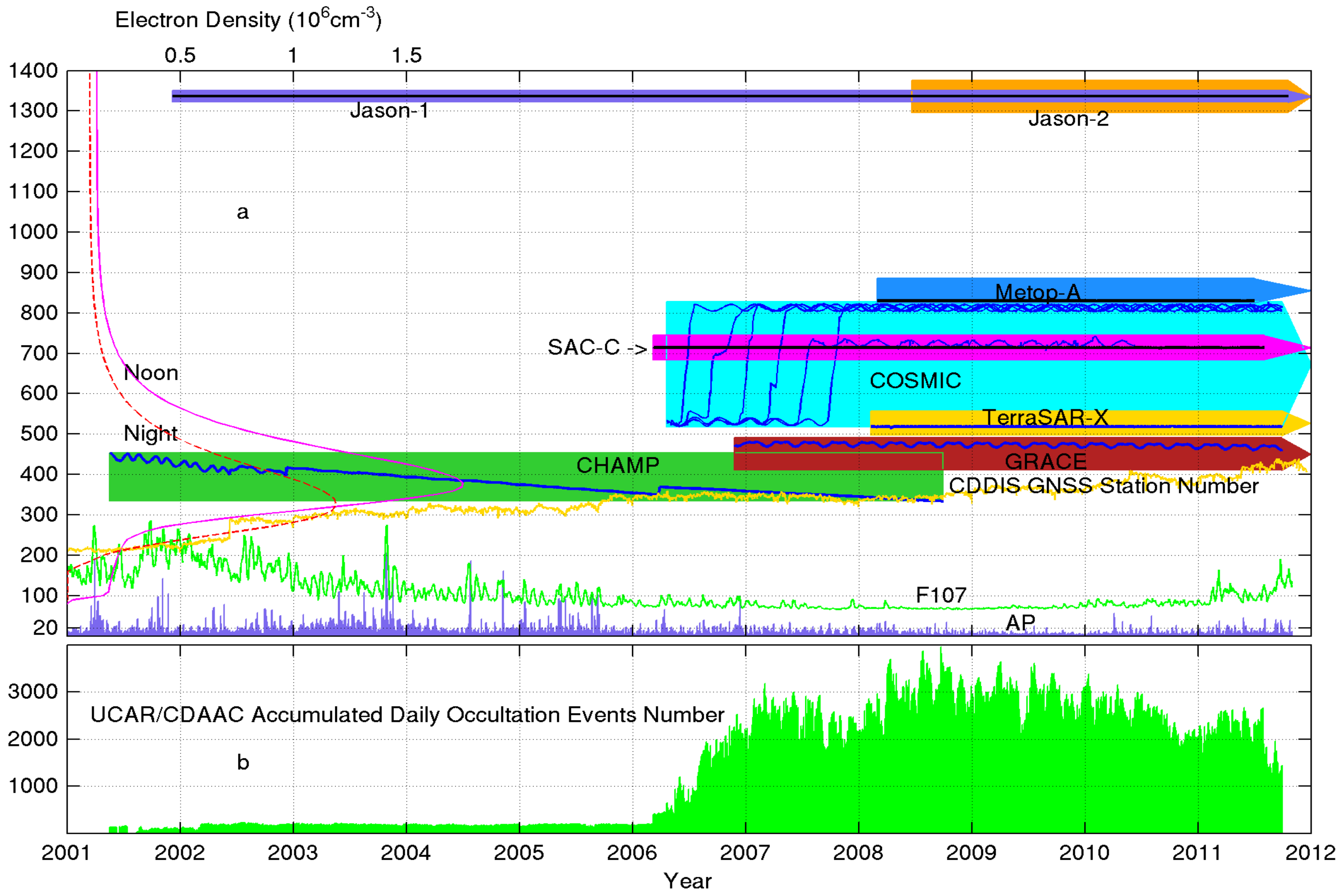


Ladstädter, Steiner, Schwärz and Kirchengast, 2015 AMT

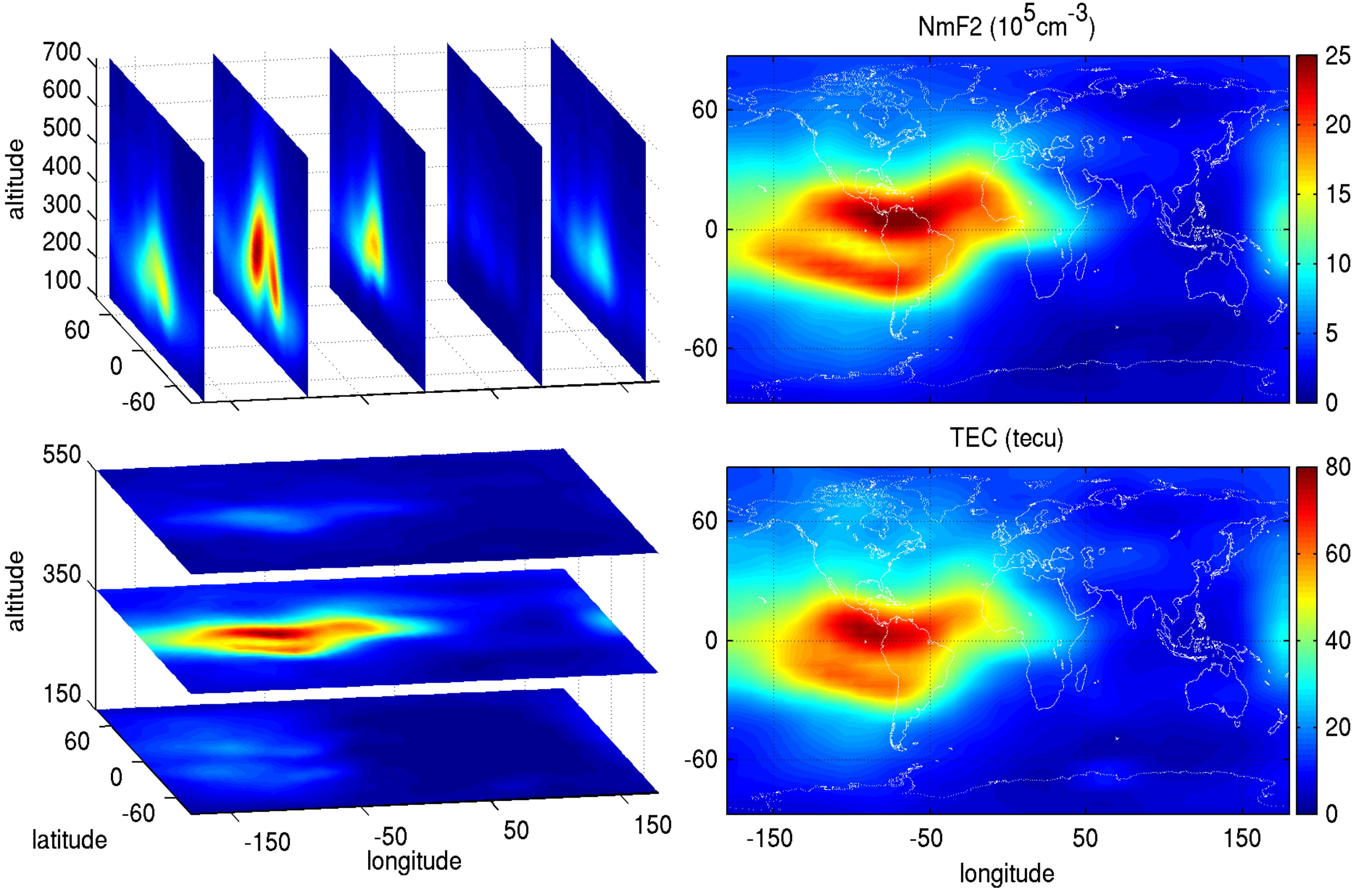
Ionospheric (Space) Weather

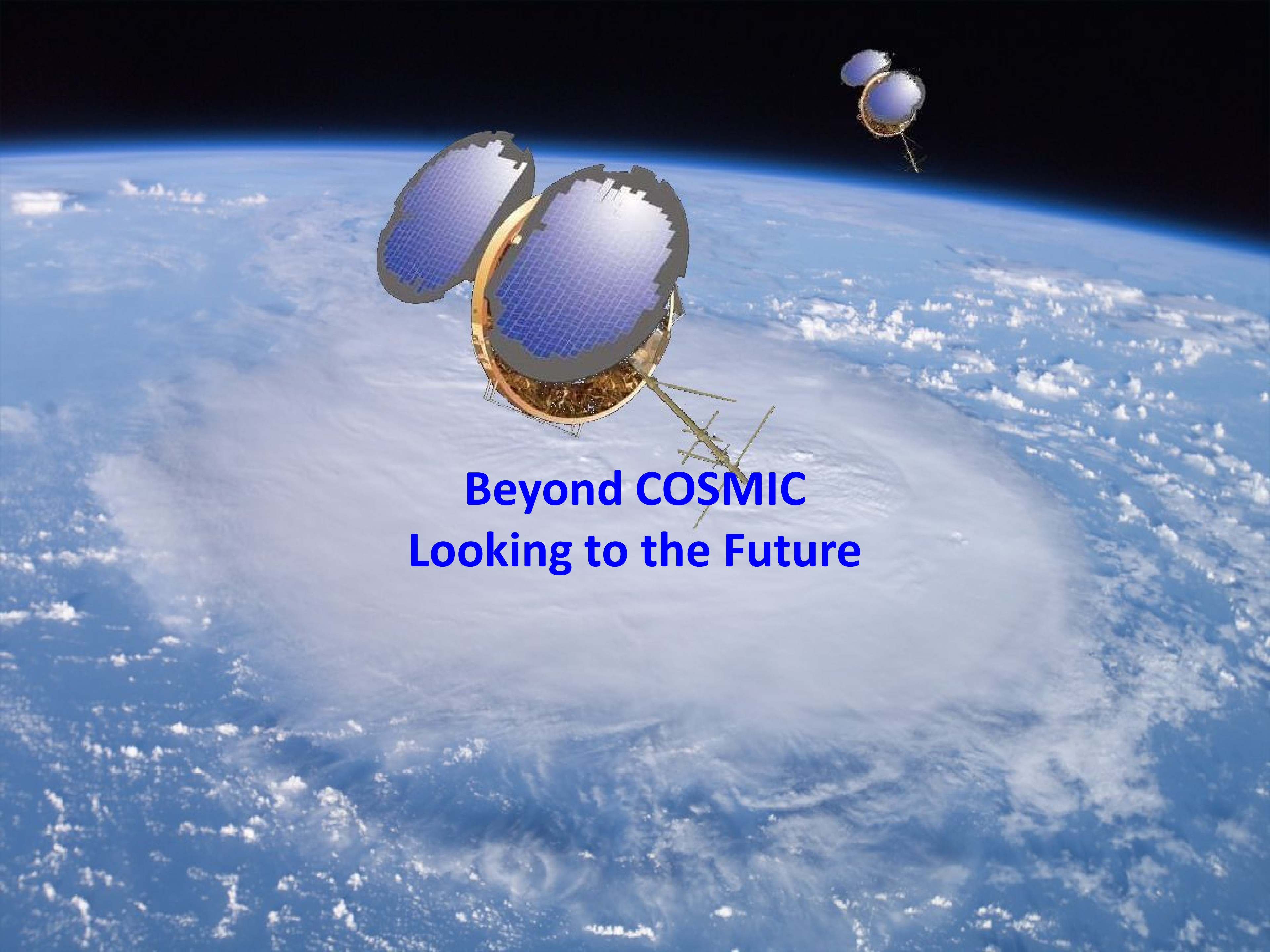


Global 3-D ionospheric electron density reanalysis based on multi-source data assimilation (Xinan Yue at al. JGR 2012)



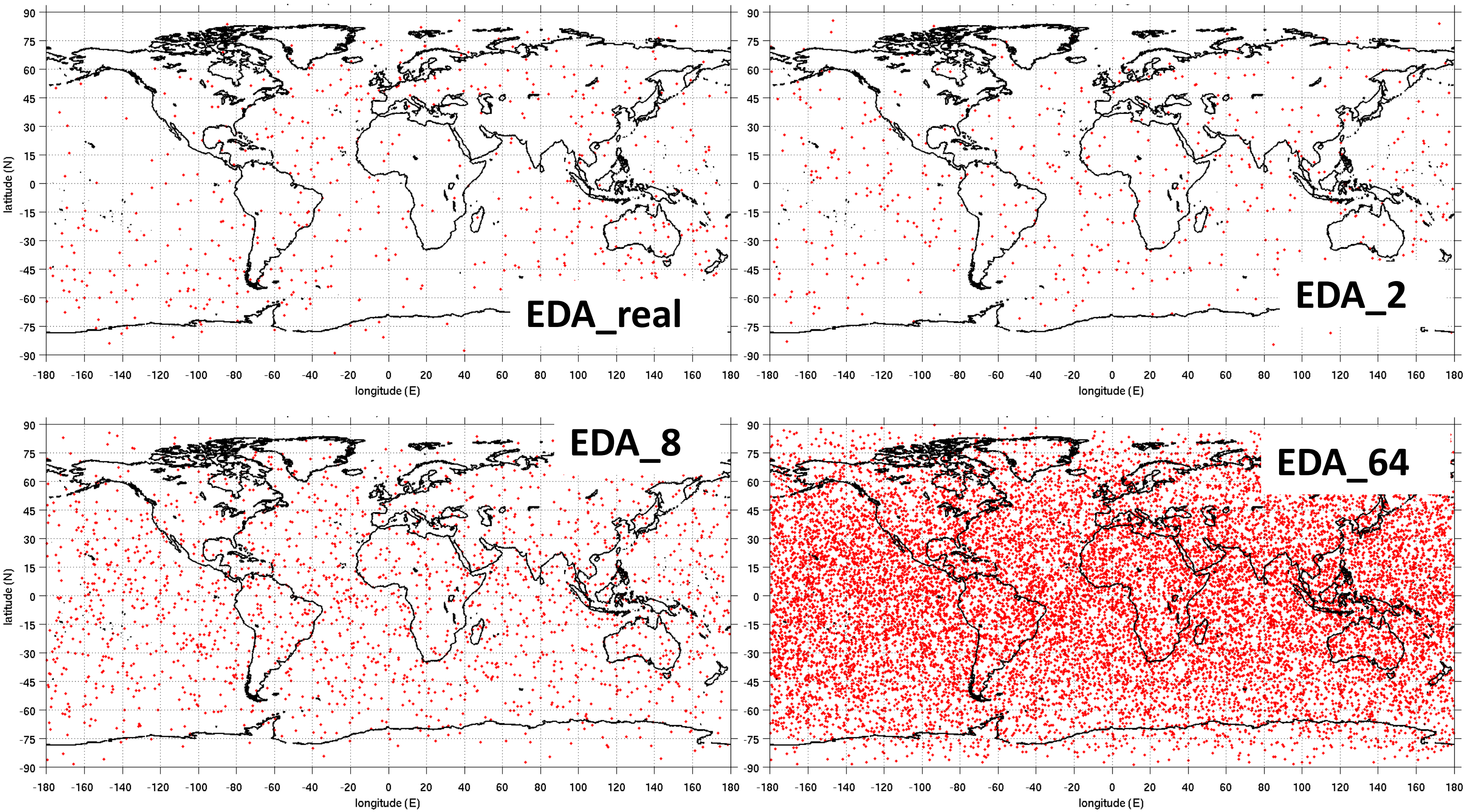
• Reanalysis results : Global 3-D electron density example




Beyond COSMIC
Looking to the Future

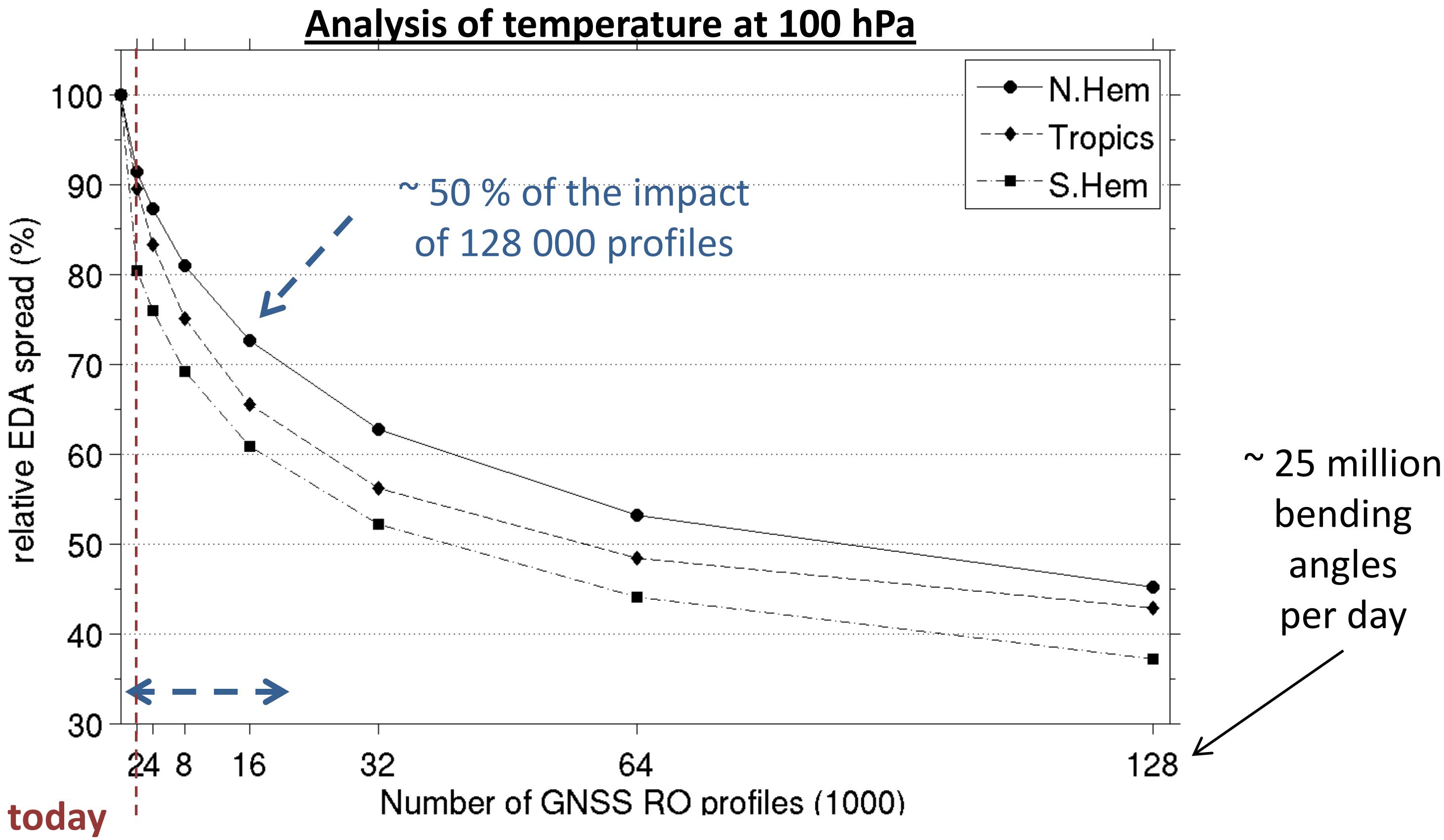
How many RO are needed?

6-hourly observation coverage



Harnisch, Healy, Baur, English, 2013: Mon. Wea. Rev.

A lot!

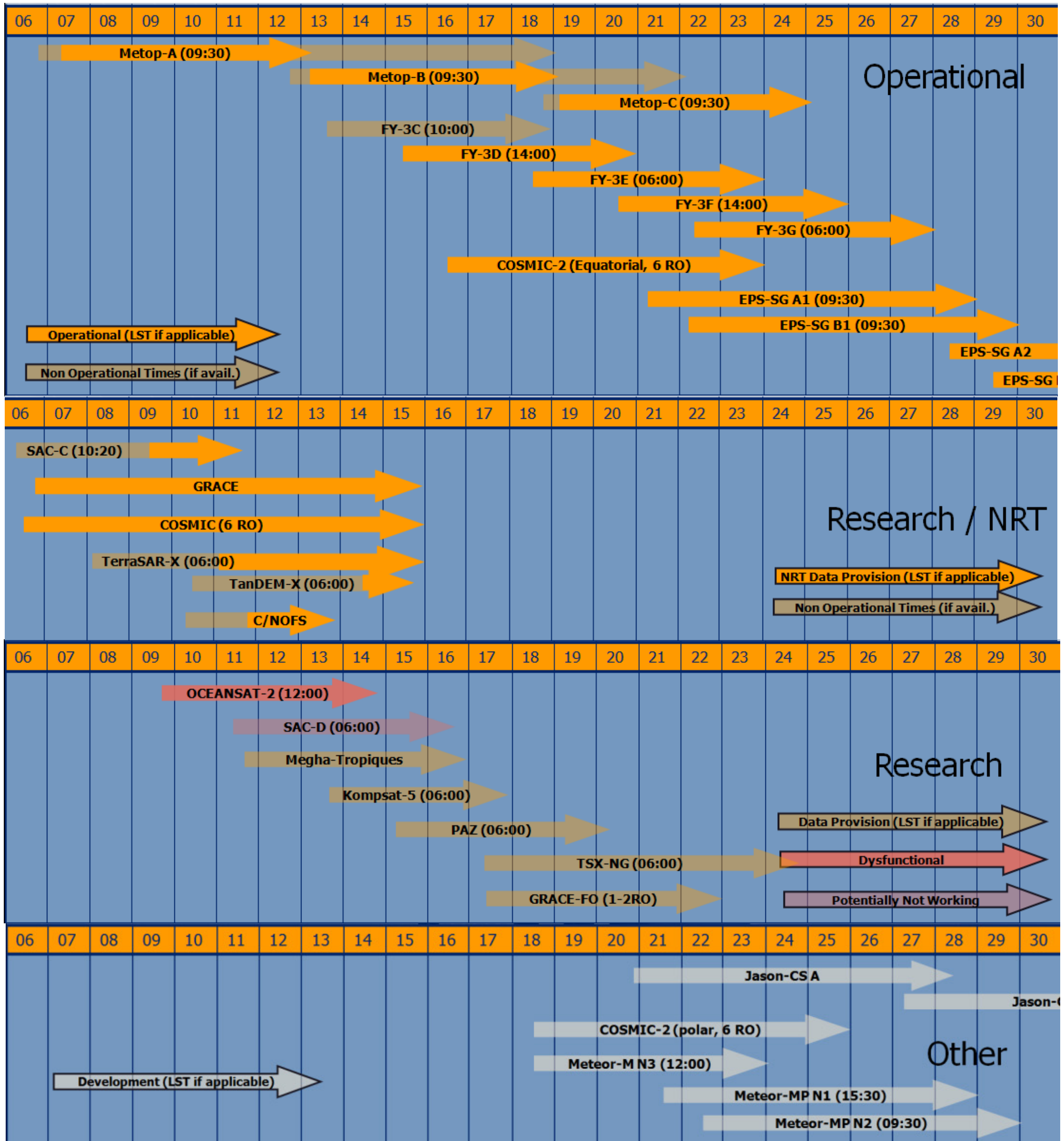


- **Large improvements up to 16000 profiles per day**
- **Even with 32000 – 128000 profiles still improvements possible**

→ no evidence of a zero impact up to 128000 profiles.

Harnisch, Healy, Baur, English, 2013: Mon. Wea. Rev.

Future RO missions



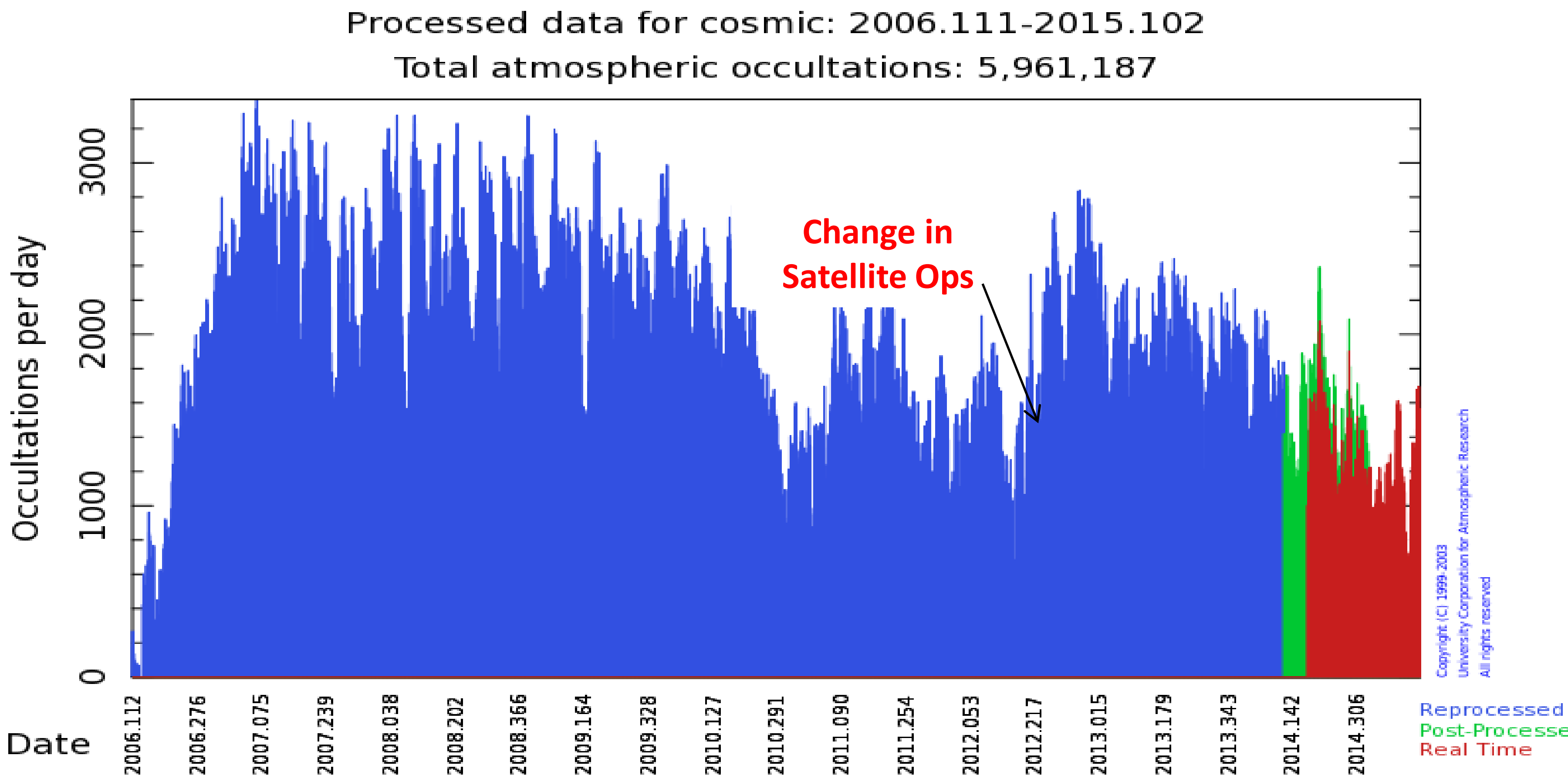
Future is tenuous at best

- Best case:
- By January 2017
  - Metop-B
  - COSMIC-2 Equatorial
  - FY-3D
- By January 2020
  - Metop-C
  - COSMIC-2 Equatorial
  - COSMIC-2 Polar
  - FY-3D
  - FY-3E
  - Meteor-M N3

Source: Axel von Engeln, March 2015


Hey Dude, what do we do about this gap?
What gap?
RO GAP
COSMIC-2

> 5.9 Million COSMIC Profiles
4/21/06 – 4/12/2015



COSMIC: Four of six currently operating nine years after launch (design life: 2-3 yr)

- FM#3 dead since August 2010
- FM#4 not operating since Jan 11, 2015

COSMIC continues to provide 1,000-2,000 GPS radio occultation soundings per day

Focusing on the Wrong Gap!

Impending gap in RO observations more important than possible gap in IR or MW soundings (shown by two recent studies).

RO has much larger impact per sounding than IR or MW

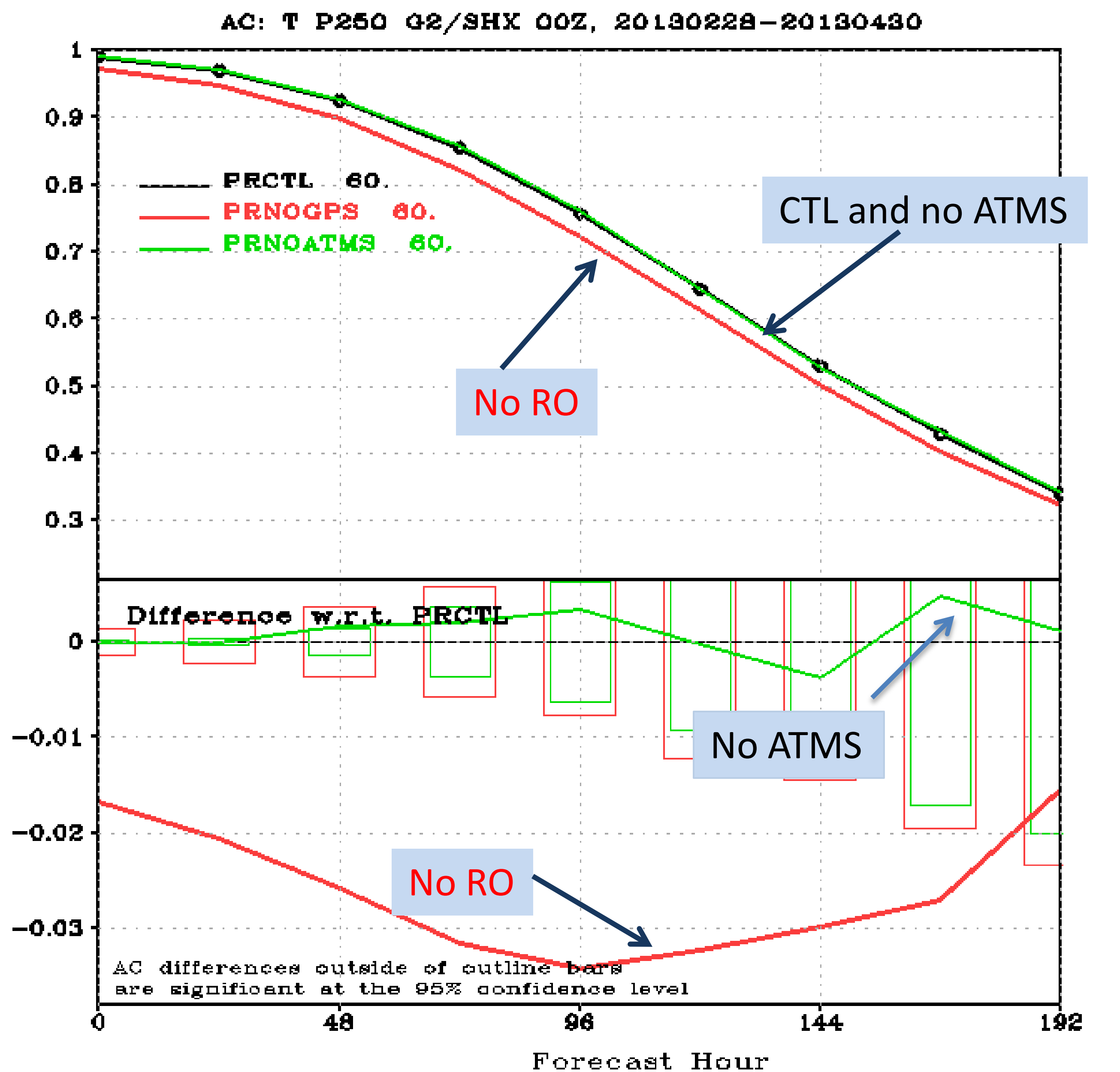
There are many more IR and MW soundings than RO (more than 100 times as many), so loss of afternoon ATMS and CrIS soundings makes small impact relative to loss of RO soundings

Complementarity of RO, IR and MW means that a balanced system is the most important aspect of the sounding system to maintain.

And besides all of the above, RO are climate benchmark observations and contribute strongly to space weather, which IR and MW do not-a ‘free’ added bonus!

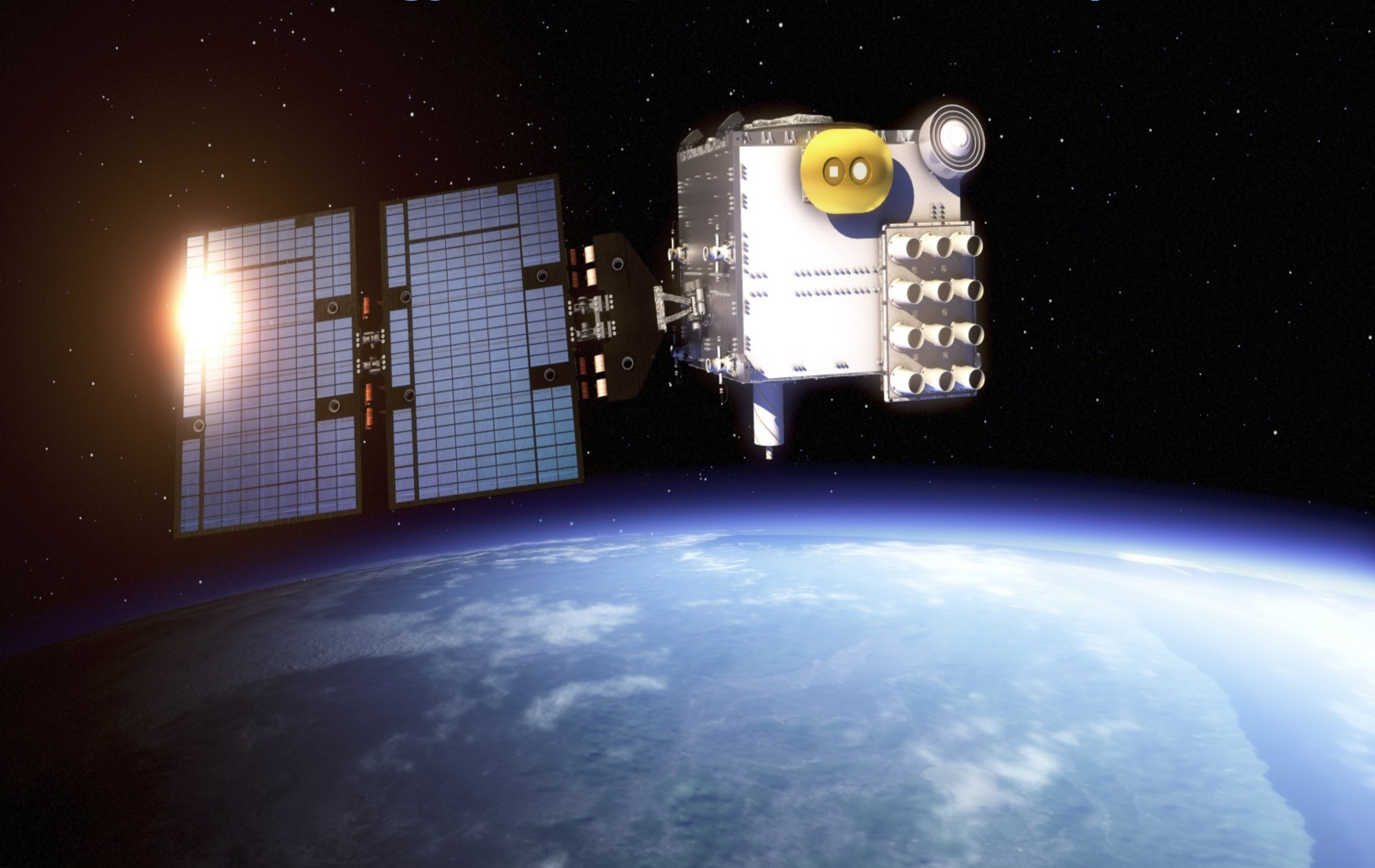
EXAMPLE

Impact of losing RO much greater than impact of losing ATMS



Impact of Loss of Microwave and Radio Occultation Observations in Operational NWP in Support of the US Data Gap Mitigation Activities. Cucurull and Anthes, 2015, *Weather and Forecasting*

COSMIC-2 (Constellation Observing System for Meteorology, Ionosphere and Climate)



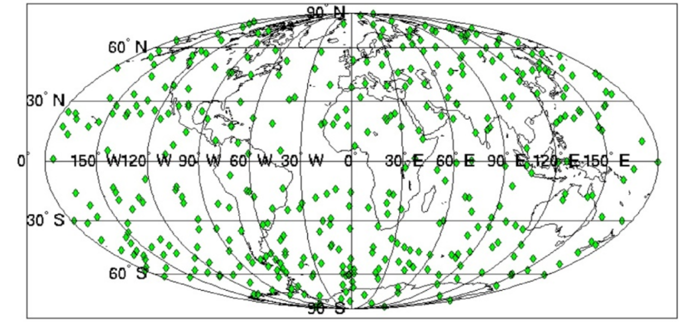
COSMIC-2 Summary

- 12 satellites with improved receivers and antennas
  - 6 launched into Equatorial orbit early 2016
  - 6 launched into polar orbit 2019 or 2020
- System will provide 10,000+ worldwide atmospheric and 10-12,000 ionospheric soundings per day
- Total cost (10 years) ~$420M
  - Taiwan ~$210M
  - Air Force ~$140M
  - NOAA ~$70M
- First launch completely funded; second launch requires additional U.S. funding to keep Taiwan funding

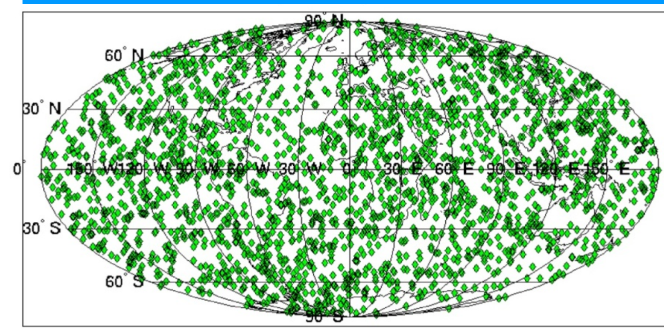
COSMIC-2

- Improved receiver and better antenna will improve data quality
- Many more soundings---10,000/day
- Greater impact on weather forecasts
- Improve hurricane track forecasts by 25-50%
- Continue climate benchmark observations without gap
- Significant improvement in space weather observing and prediction
- Improved data latency (avg 45min)

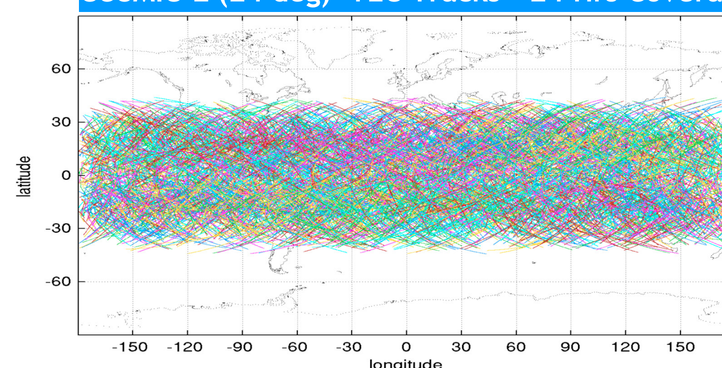
COSMIC Occultations-3 Hrs Coverage



COSMIC-2 Occultations - 3 Hrs Coverage

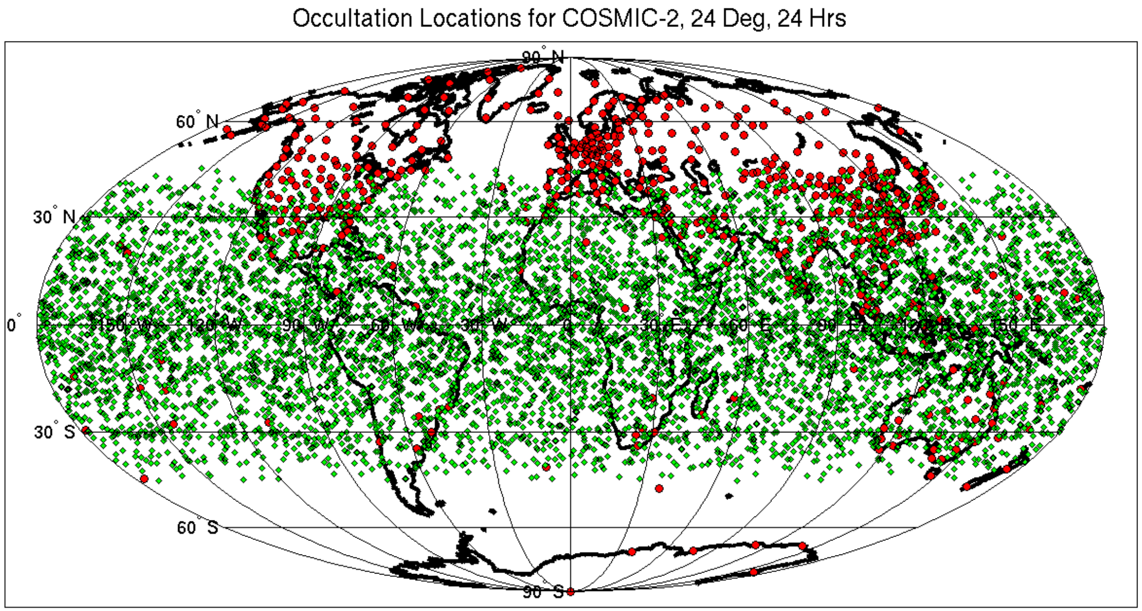


COSMIC-2 (24 deg) TEC Tracks - 24 Hrs Coverage

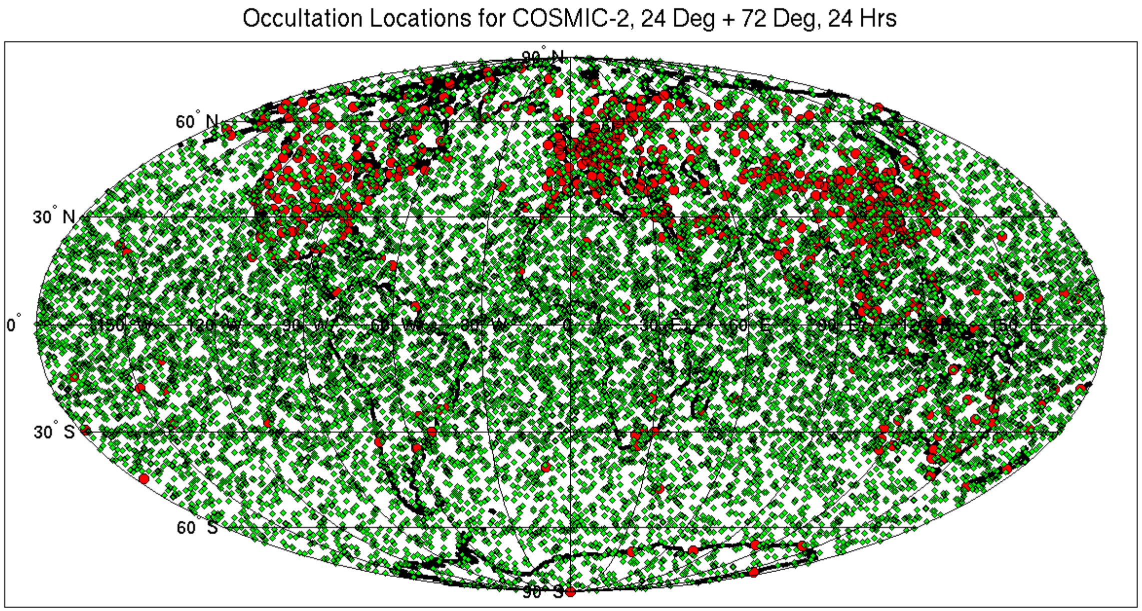


Importance of C-2 Second Launch

1st Launch 2016



With 2nd launch
2018 or 2019



Summary

- Radio Occultation is a proven high-impact and low-cost global observing system
- Only observing system to give information on ionosphere, stratosphere and troposphere simultaneously
- Significant positive impact on weather forecasts at all major international weather centers
- Contributes to weather, climate and space weather
- Impending RO gap—need full COSMIC-2 and more RO constellations (private sector role?)

Acknowledgments

- NSF
- Taiwan's NSPO
- NASA/JPL, NOAA, USAF, ONR, NRL
- Broad Reach Engineering
- Other RO Missions, CHAMP, SAC-C, GRACE, TerraSAR-X, C/NOFS, Metop-A/GRAS

UCAR NSF NASA USAF NOAA NSPO ONR