The Value of GNSS Radio Occultation Observations and the Optimal Implementation of GNSS Missions

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Overview of Today's Talk

- GNSS RO for climate
- GNSS RO for water vapor
- Changes afoot at NASA: Decadal Survey for Earth Science #2
- A broader view of GNSS remote sensing
- Summary

Radio Occultation as a Climate Benchmark

- Traceable to the international definition of the "second" (s)
- Kursinski et al., 1997: "exhaustive" error analysis (36-page JGR paper) was a good start
- Covers: Clock error, local multipath, orbit error, residual ionospheric delay, refractivity constants, upper altitude boundary, horizontal structure, water vapor

Not covered:

- Smoothing algorithms
- Small-scale ionospheric structure ("burst of noise")

K97

Covered, but not getting much attention:

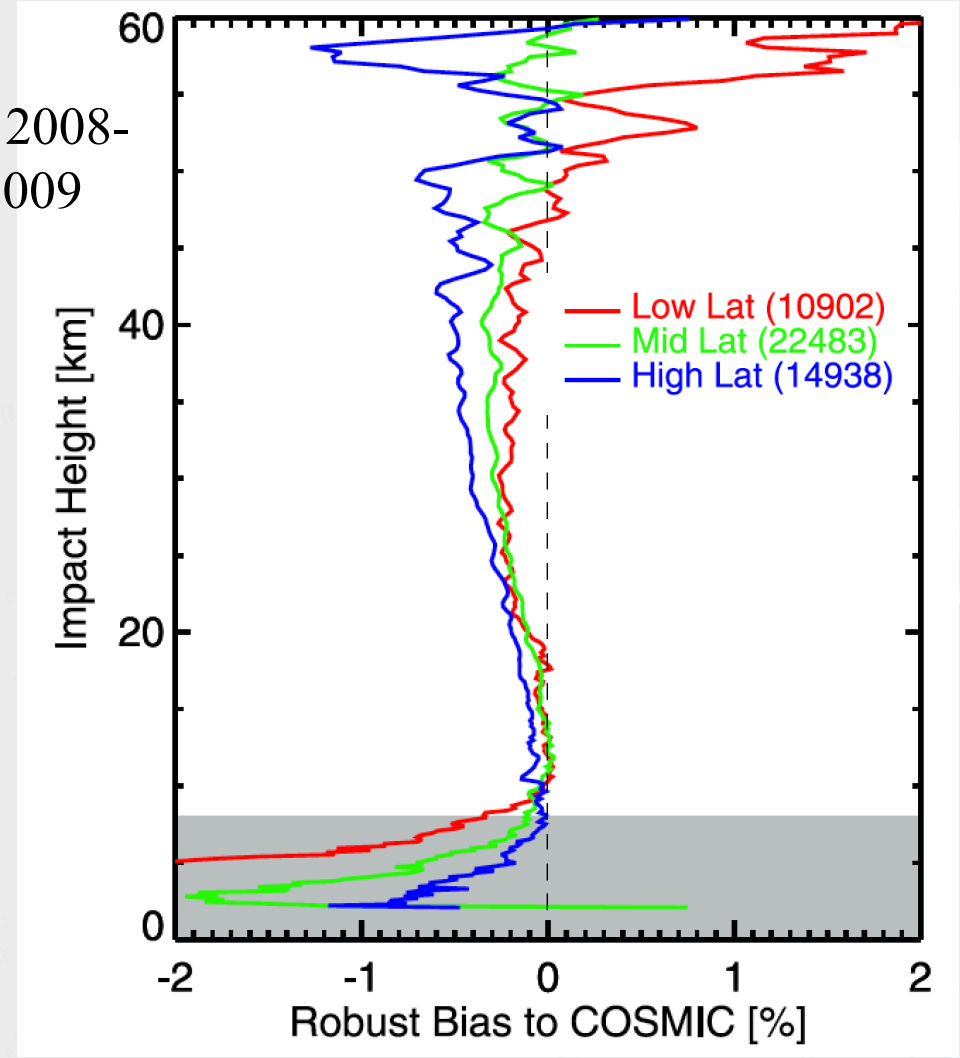
- Horizontal structure

K97

Smoothing Algorithm – Bending Angle

Bending angle, collocated COSMIC-GRAS

Nov 2008-
Jul 2009

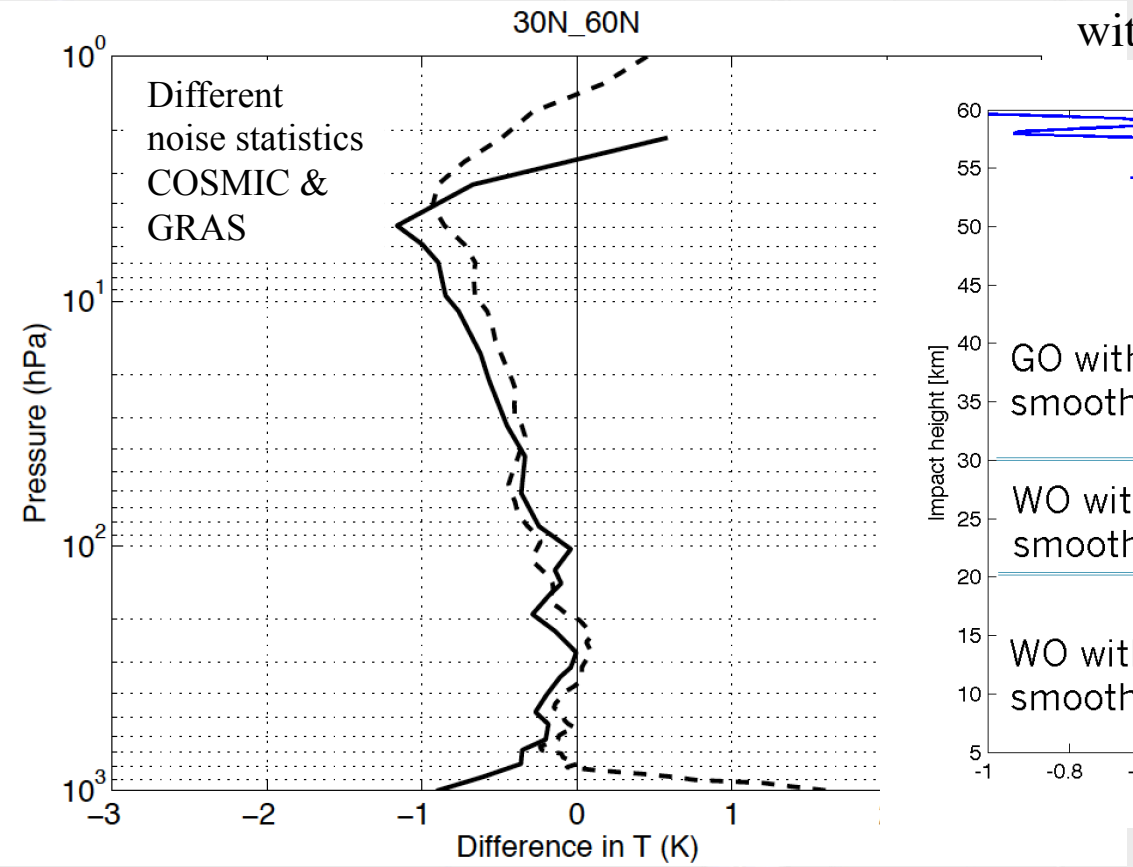


"Further investigations by the GRAS and the COSMIC teams identified the COSMIC phase smoothing as a likely cause. GRAS processing uses a Savitzky-Golay filter while COSMIC uses a Gaussian filter (S. Sokolovskiy, COSMIC team, personal communication, 2009). Processing of COSMIC data at EUMETSAT has shown that the Gaussian filter introduces similar biases. The COSMIC team is currently in the process of updating their operational setup, which should bring the two RO instruments into even better agreement."

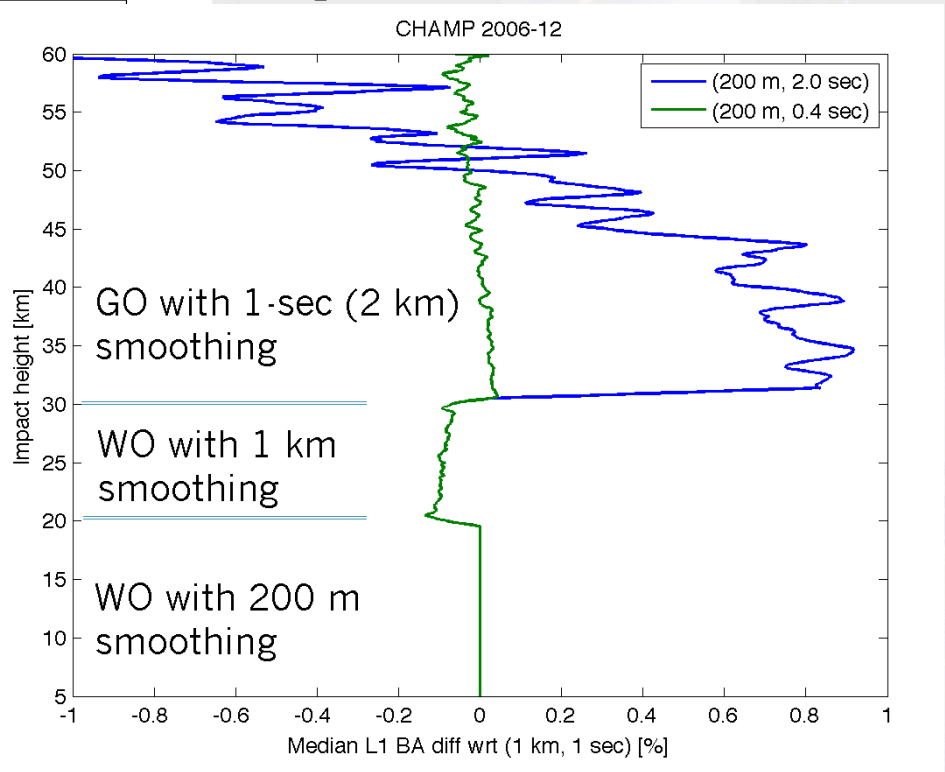
von Engeln, A., S. Healy, C. Marquardt, Y. Andres, and F. Sancho (2009), Validation of operational GRAS radio occultation data, Geophys. Res. Lett., 36, L17809, doi:10.1029/2009GL039968.

Be More Careful: Smoothing Algorithms

(IASI – COSMIC) – (IASI – GRAS)



Median bending angle fractional difference with respect to 1km-1sec smoothed

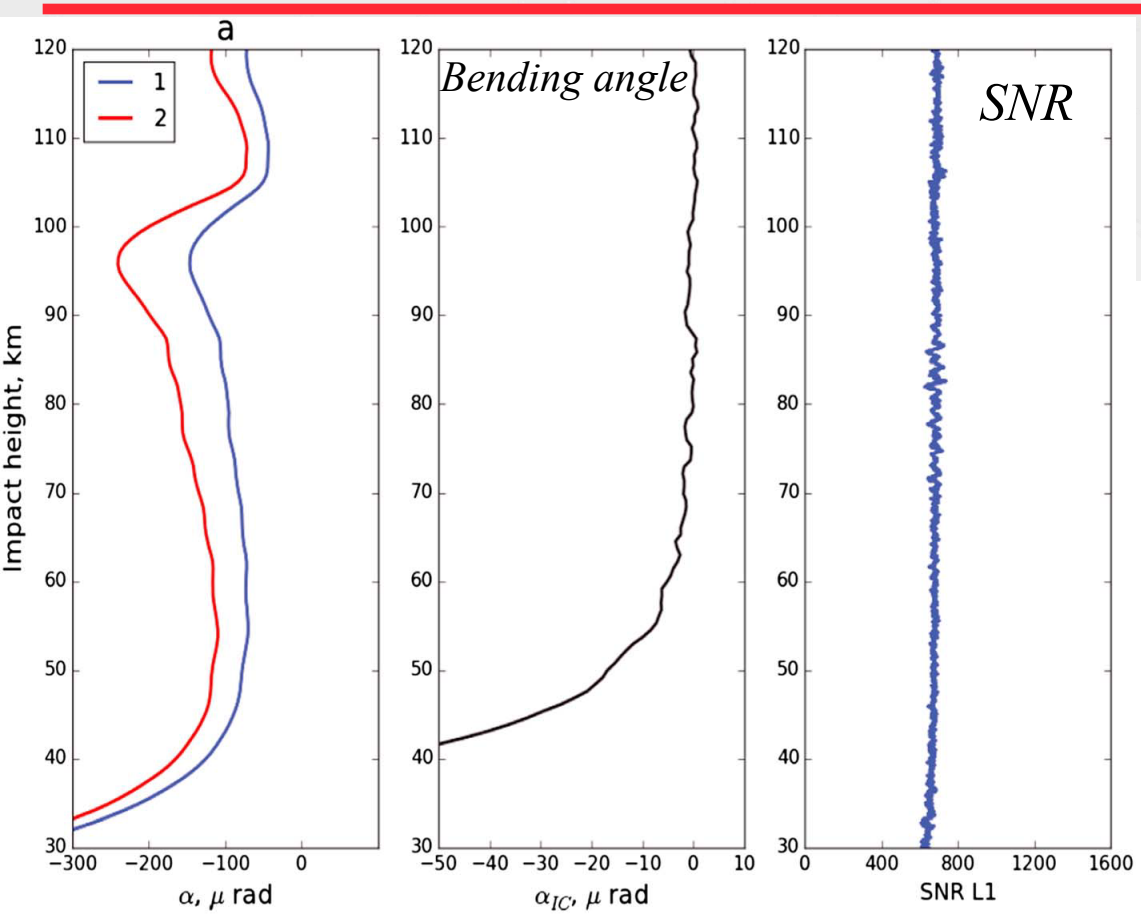


Feltz, M., R. Knuteson, S. Ackerman, and H. Revercomb (2014), Application of GPS radio occultation to the assessment of temperature profile retrievals from microwave and infrared sounders, Atmos. Meas. Tech., 7(11), 3751–3762, doi: 10.5194/amt-7-3751-2014.

Answer: cubic smoothing versus quadratic

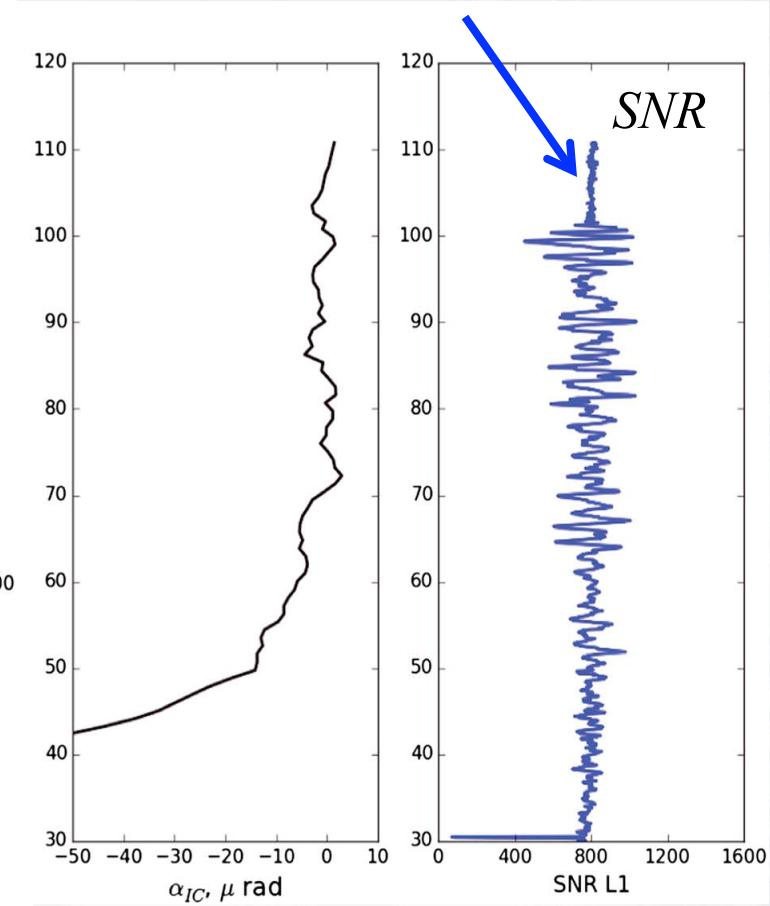
Chi Ao, JPL

Small-Scale Ionospheric Structure



No small scale structure

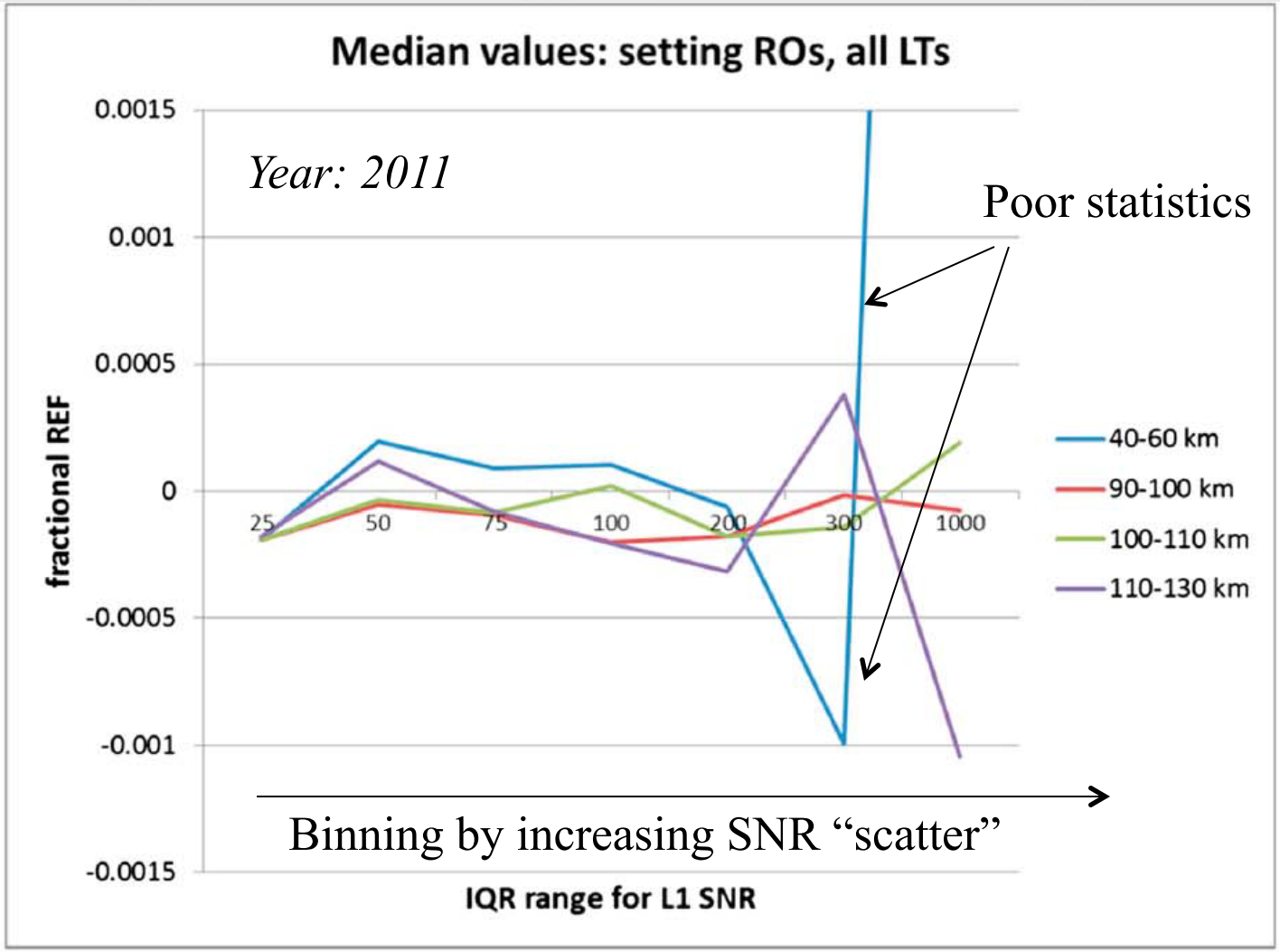
Increased amplitude fluctuation due to small-scale ionospheric structures ("scintillation")



Verkhoglyadova, O. P., A. J. Mannucci, C. O. Ao, B. A. Iijima, and E. R. Kursinski (2015), Effect of small-scale ionospheric variability on GNSS radio occultation data quality, J. Geophys. Res. Space Physics, 120(9), 7937–7951, doi:10.1002/2015JA021055.

Small-Scale Ionospheric Structure

Fractional refractivity difference with ECMWF



Whereas ECMWF may have a bias, its bias will vary independently of ionospheric small scale structure

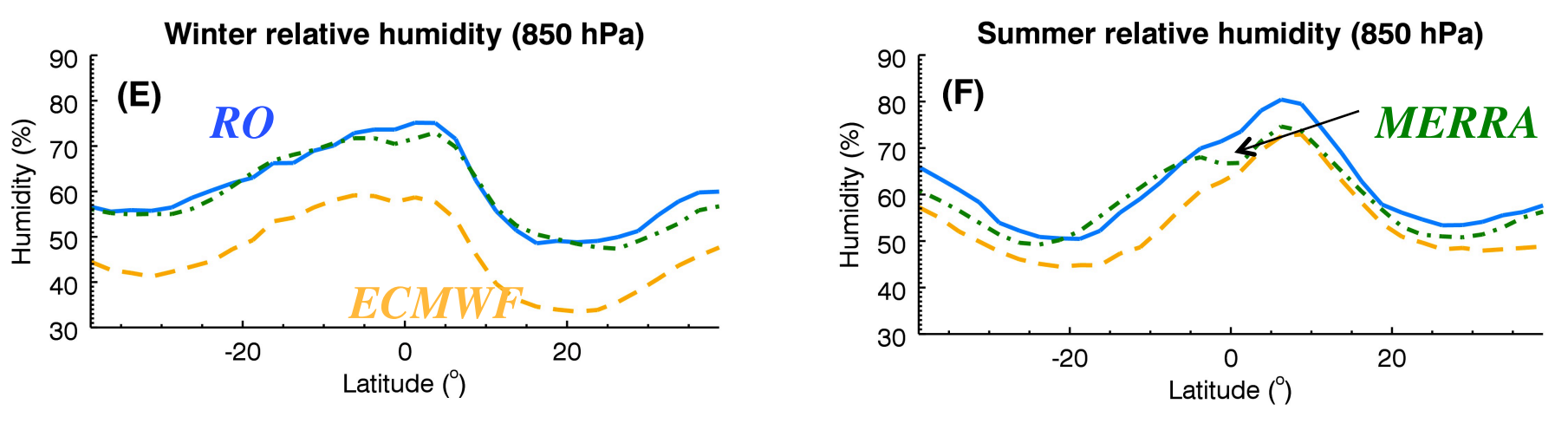
No evidence yet that small scale structure biases the retrievals

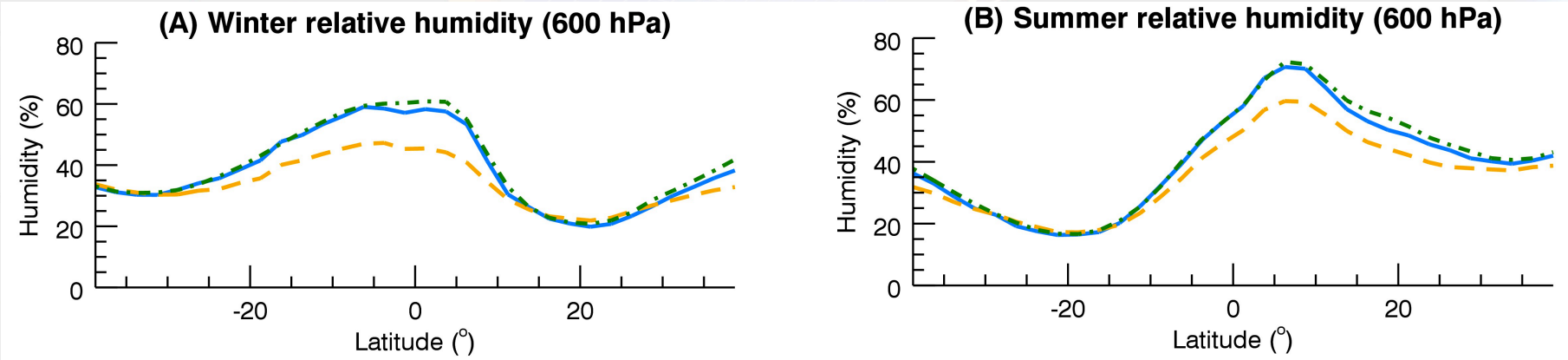
Follow-on work: different phases of the solar cycle

Tropical Relative Humidity

- Jiang et al. (2012): "We find more than half of the models show improvements from CMIP3 to CMIP5 in simulating column-integrated cloud amount, while changes in water vapor simulation are insignificant."
- Representing deep convection properly remains a challenge (Stratton and Stirling, 2012)
- GNSS RO provides unique observations of lower-to-mid troposphere water vapor
- Water vapor traces changes in the Hadley circulation and is strongly affected by deep convection

Zonal Mean Relative Humidity: Tropics 2007-2009





Winter DJF Summer JJA

Vergados, P., A. J. Mannucci, C. O. Ao, J. H. Jiang, H. Su (2015), On the comparisons of tropical relative humidity in the lower and middle troposphere among COSMIC radio occultations and MERRA and ECMWF data sets, Atmos. Meas. Tech., 8(4), 1789–1797, doi:10.5194/amt-8-1789-2015.

Tropical Relative Humidity: Conclusions

- MERRA and GPS-RO generally in excellent agreement
  - No assimilation of RO in MERRA
- At higher altitudes (not shown) MERRA is too wet by 10%-15%
  - 300, 400 hPa
- ECMWF systematically drier, to varying amounts
  - Disagreement reduced at higher altitudes
- ECMWF underestimates the moisture budget of the ascending branch of the Hadley Cell circulation
  - Convective shortfall?
- Stronger convection clearly observed in NH summer vs winter (not shown) – more water aloft, strongly peaked – captured better by MERRA
- The middle troposphere over the regions of dry air subsidence is most sensitive to seasonal oscillations.

The Future of GNSS Remote Sensing: Decadal Survey 2017

- "The process of distributing resources for science does not follow the scientific method"
- Decadal Survey chartered by NASA, NOAA, USGS
- Statement of task: Develop a prioritized list of top-level science and application objectives to guide space-based Earth observations
- Recently released: "Continuity of NASA Earth Observations From Space" (also National Research Council)
- The committee was formed at the request of NASA Earth Science Division (ESD) to assist in the determination of when a measurement(s) or data set(s) initiated by ESD should be collected for extended periods
- It is clear that the "value framework" in the continuity report is having a measure impact

A Value Framework?

- Concern expressed repeatedly by the DS chair: implementing the top priorities must be done with a concept of "value" in mind
- The cost of implementation is a factor to be considered because high cost for any one priority may mean fewer science questions can be addressed overall
- "You can no longer take over the whole box if we let you in the box"

Describing the Value Framework

- **Basis: "Quantifiable Earth science objective"**
  - **Identify the land carbon sink and quantify this globally to ±1.0 Pg C per year aggregating from the 1° × 1° scale.**
  - **Determine the rate of global mean sea level rise to ±1 mm per year per decade (1σ).**

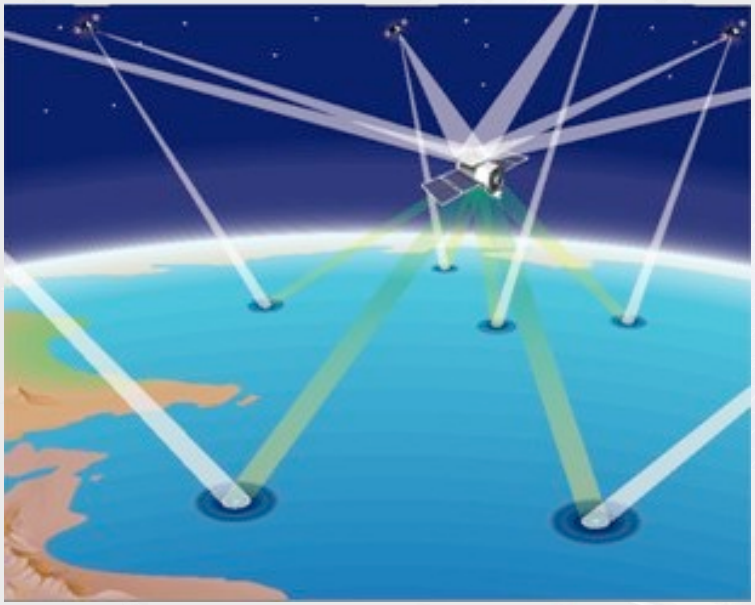
Value = (Benefit x Affordability)

Benefit = I x U x Q x S

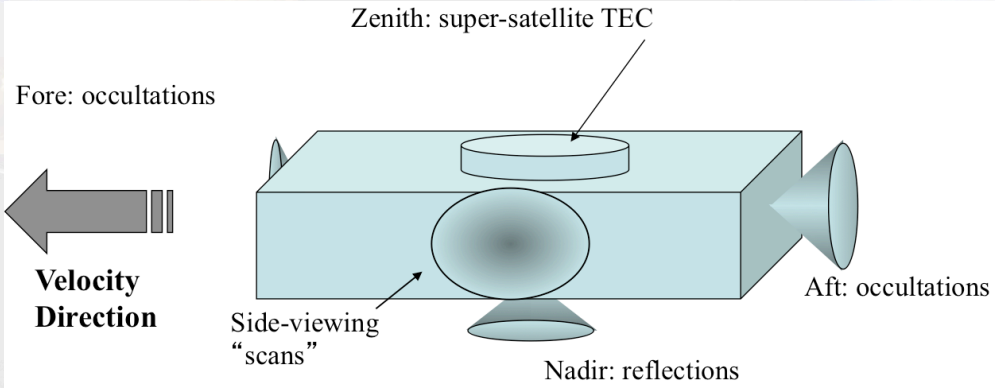
- **Importance: how important is the QSO?**
- **Utility: what is the contribution of the geophysical variable to meeting the QSO**
- **Quality: combined standard uncertainty, repeatability, time and space sampling, and data systems and delivery for climate variables**
- **Success probability: e.g. mission class (B, C, D)**

Implications for the GNSS Community

- **Low cost is now an explicit asset, not a liability**



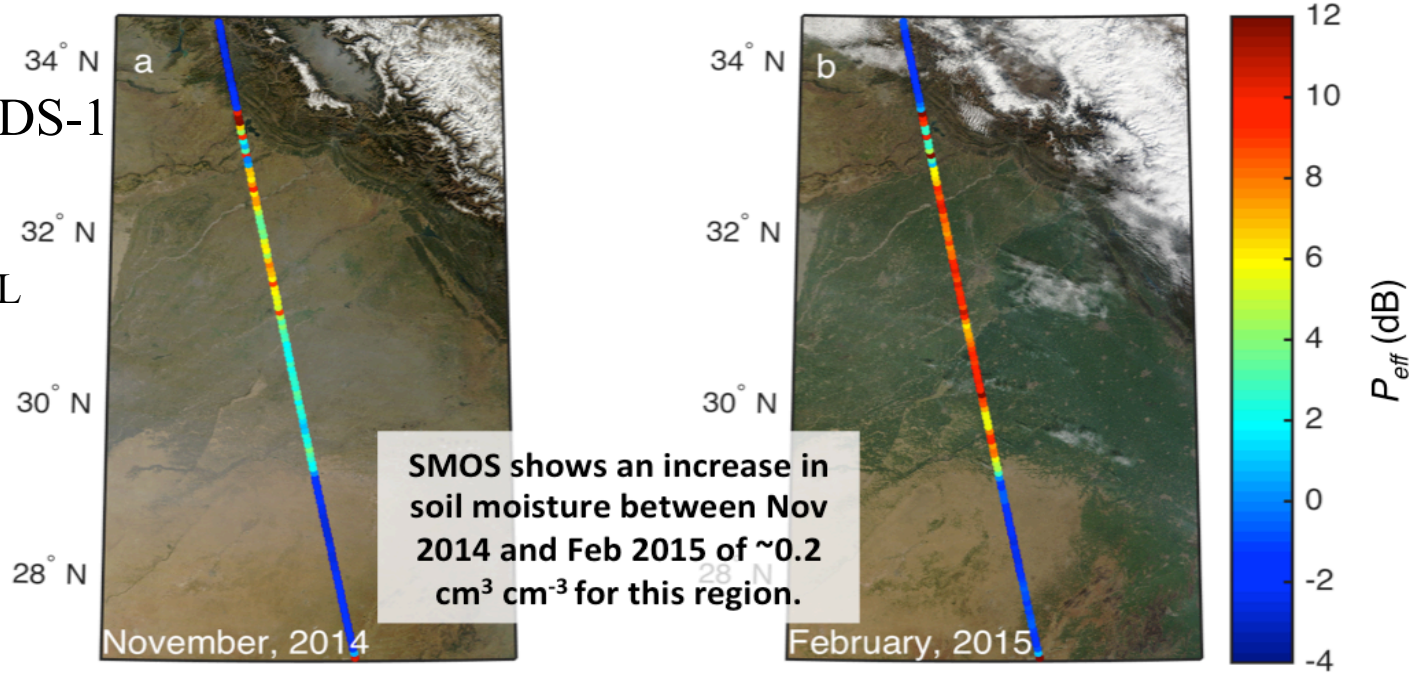
- **RO + Reflections is *low hanging fruit***
- **The additional cost of including both capabilities on a constellation is exceedingly modest**



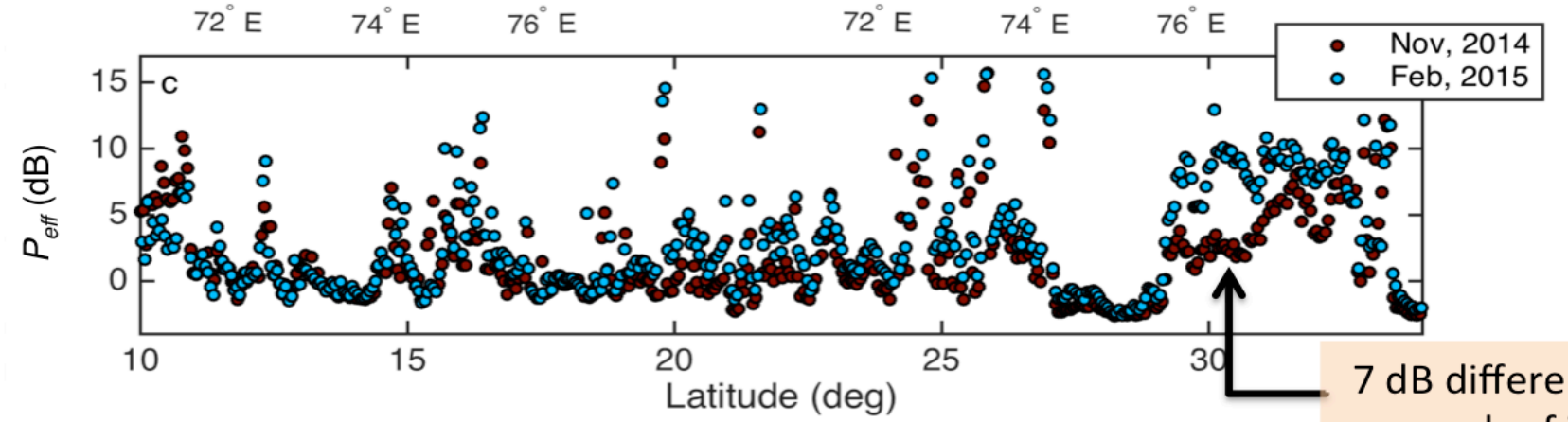
- **GNSS-R must address high-prioirity Earth science objectives or it won't matter**

Data from TDS-1

Analysis:
Clara Chew, JPL



SMOS shows an increase in soil moisture between Nov 2014 and Feb 2015 of ~0.2 $cm^3\ cm^{-3}$ for this region.



7 dB difference, much of it probably caused by soil moisture differences.

Above are two repeating ground tracks that passed over a heavily-irrigated region in India. Note that the tracks are very similar except between 29-33 degrees latitude, which is the region that is irrigated during the winter growing season. The winter growing season runs from Nov to April.

Summary

- **Our understanding of GNSS retrieval biases, though robust, continues to improve, as it should**
- **GNSS retrievals are largely independent of analyses, providing an excellent tool to assess reanalyses or other data for long-term change**
- **GNSS remote sensing, in its broadest sense, is well suited to have a major influence on the current Decadal Survey, if we can show strong ties to *important* Earth science objectives**
  - **Particularly in concert with other observations**
- **Contribute to the Request for Information from the Decadal Survey (ESAS 2017)**

Did I neglect to mention space science?