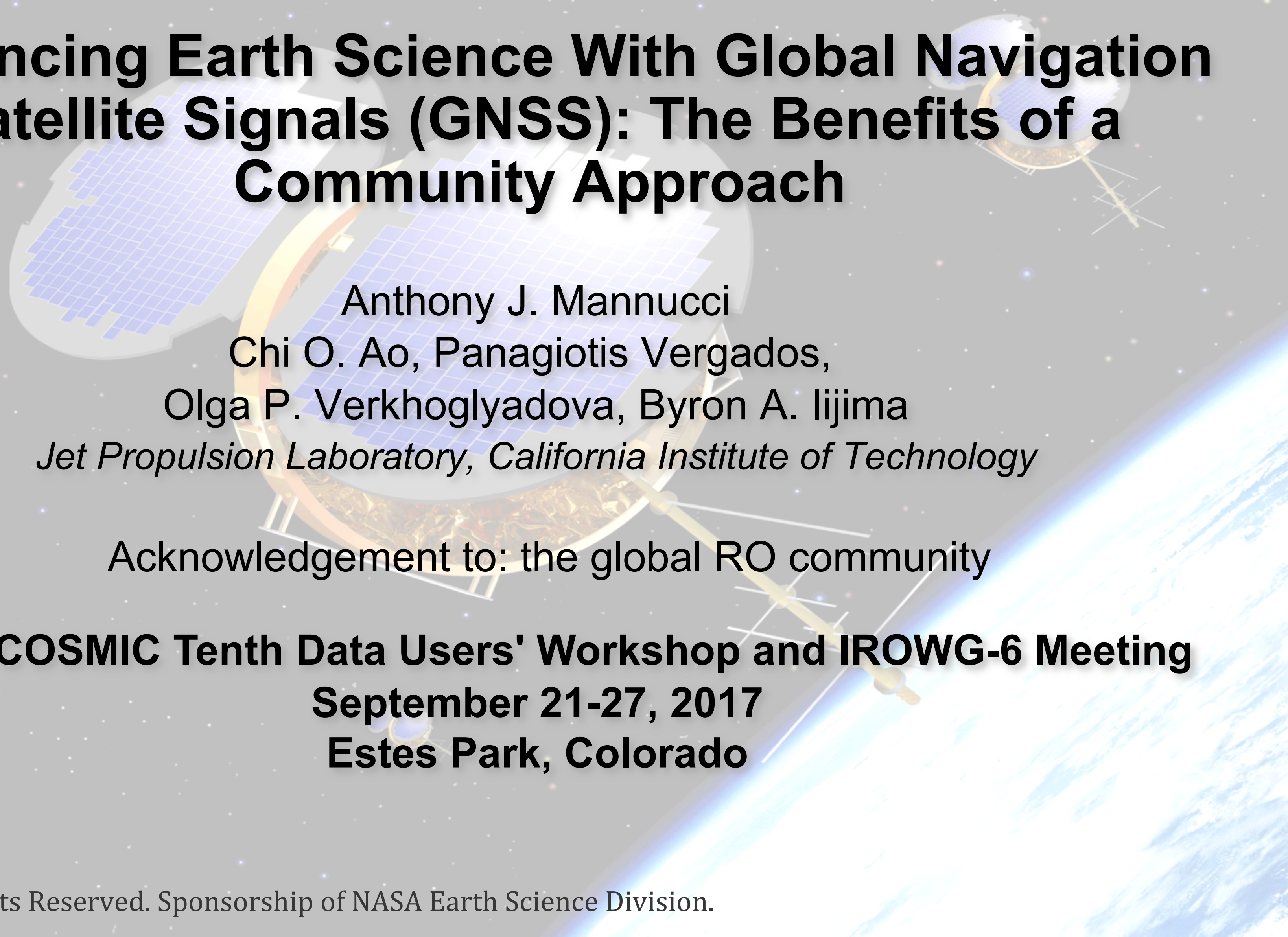
Advancing Earth Science With Global Navigation Satellite Signals (GNSS): The Benefits of a Community Approach



Anthony J. Mannucci
Chi O. Ao, Panagiotis Vergados,
Olga P. Verkhoglyadova, Byron A. Iijima
Jet Propulsion Laboratory, California Institute of Technology

Acknowledgement to: the global RO community

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Estes Park, Colorado

Overview of Today's Talk

- The "3G" Community Meeting
- CLARREO related activities
  - Instrument considerations
- Research satellites
- The commercial community
- The scientific community
- Future directions

Key Takeaway Points

- Diverse communities and approaches have brought benefits to our field
  - We should continue to embrace and benefit from diversity
- It takes decades to fully realize the value of a robust climate observing system
- We are still trying to understand inter-center differences that are larger than they should be

The “3G” Workshop of May 2014 GRUAN/GSICS/GNSS-RO

- **GRUAN-GNSS-RO comingling is now established**
  - **Jordy Tradowsky, Ben Ho, Rob Kursinski…**
- **GRUAN has led the way in uncertainty estimation and we are now catching up**
  - **Uncertainty terminology and approach has been particularly valuable**
  - **Do we all speak the same language yet?**
- **Radiosonde bias determination using RO is now established**
- **GSICS coordination is not established to my knowledge, but grass-roots efforts exist**
  - **Ben Ho (UCAR) is analyzing radiance biases**

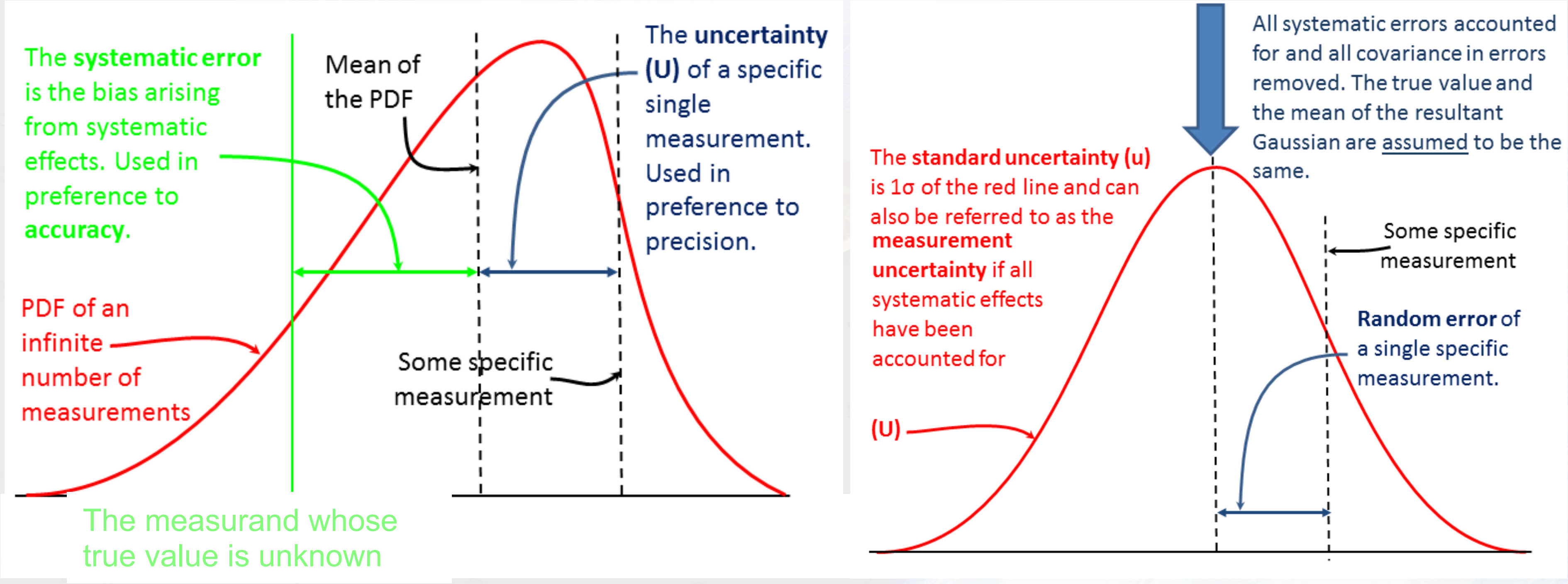
GSICS: Global Space-based Inter-Calibration System
GRUAN: GCOS Reference Upper-Air Network

The “3G” Workshop of 2014

- RO stability/accuracy has been beneficial to GRUAN
- One reference measurement helps all reference measurements
- Consider how this works for *retrievals* versus direct measurements

“GRUAN Measurement Uncertainty Terminology”

The measurand (e.g. refractivity) is subject to a probability density function



The **systematic error** is the bias arising from systematic effects. Used in preference to **accuracy.**

The **uncertainty (U)** of a specific single measurement. Used in preference to precision.

PDF of an infinite number of measurements

The measurand whose true value is unknown

The **standard uncertainty (u)** is 1σ of the red line and can also be referred to as the **measurement uncertainty** if all systematic effects have been accounted for

All systematic errors accounted for and all covariance in errors removed. The true value and the mean of the resultant Gaussian are <u>assumed</u> to be the same.

Random error of a single specific measurement.

Climate Absolute Radiance and Refractivity Observatory (CLARREO)

- A potential “game-changer” for RO
- RO enters the NASA mission process
- Recommended by the Decadal Survey for Earth Science (2007)
  - Highest priority tier
- “Virtually” cancelled due to cost (~$1B)
  - SI-traceability is very expensive in the NASA process
- A short-wave solar reflected path-finder remains for launch aboard the International Space Station

The Unrealized Benefits of CLARREO

- **Requirements flowdown from climate observing goals to RO instrument performance**
- **Resources to verify *very stringent*:**
  - **Instrument accuracy**
  - **Retrieval system accuracy**
- **Detailed analysis of sampling error for climate**

GNSS radio occultation
Systematic error <0.06% refractivity (k = 2) for 5–20 km
GPS and Galileo GNSS frequencies
5–20-km altitude range refractivity
>1000 occultations per day to control sampling noise

This is 2-sigma and for profile averages

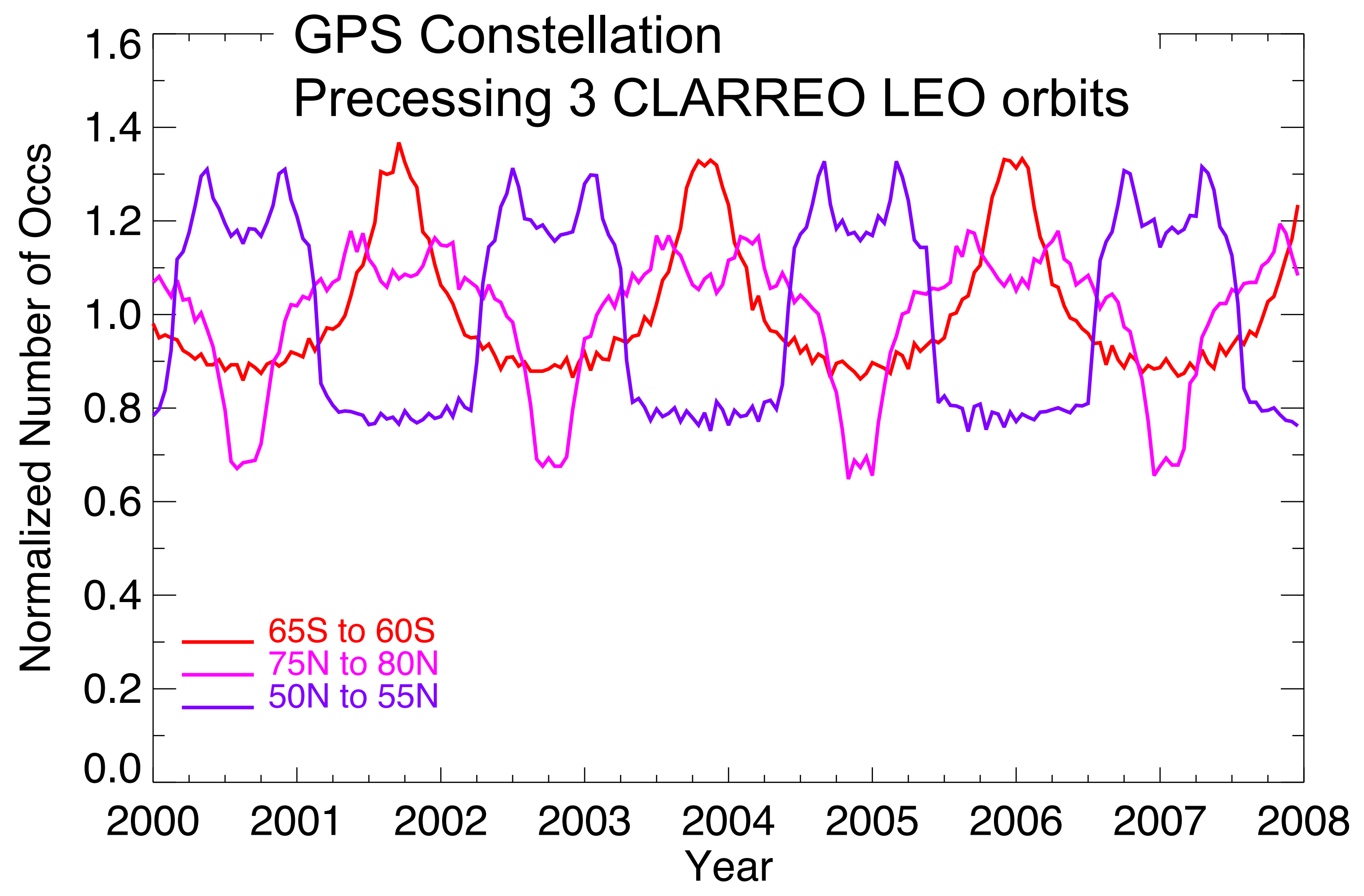
2 mHz Doppler unc

0.2 μrad bending unc

at 20 km altitude

Wielicki, B. A. et al. (2013), Achieving Climate Change Absolute Accuracy in Orbit, Bull. Amer. Meteor. Soc., 94(10), 1519–1539, doi:10.1175/BAMS-D-12-00149.1.

CLARREO Sampling For Climate



Sampling density in time in different latitude bands using just GPS transmitters and 3 CLARREO satellites

Temporally nonuniform sampling density occurs because of differential precession of the GPS and LEO orbits, which explains the periodicity of the temporal sampling pattern. In order to handle this problem, it is necessary to compose climatologies monthly before composing annual average climatologies.

CLARREO Requirements

- **Trend to observe -> measurement uncertainty**
- **Key concepts:**
  - Slope error assuming correlated noise
  - "Signal-to-noise" ratio of "detection" = s = 5
  - Trend we want to test: m_{est}
  - Formal error of trend δm

From a climate model →

$$s \equiv m_{est} / | \delta m |$$

$$\langle(\delta m)^2\rangle \simeq 12\,(\Delta t)^{-3}\,(\sigma_{\mathrm{var}}^2 \tau_{\mathrm{var}} + \sigma_{\mathrm{meas}}^2 \tau_{\mathrm{meas}})$$

Natural variability

Instrument

  - Natural variability is correlated and appears like measurement noise
  - Measurement noise is correlated according to mission life
  - Choose m_{est} (= 0.2K/decade) and *s*. Solve for δm

Leroy et al., "Climate Signal Detection Times and Constraints on Climate Benchmark Accuracy Requirements," J Clim 2008

The "Lost" CLARREO Meeting of 2010 Requirements Review

Presenters

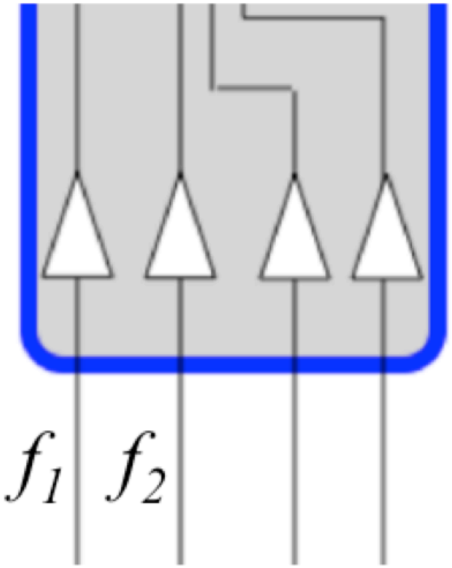
- Broad participation (US only requested)
  - Tony Mannucci (meeting organizer), Chi Ao, Byron Iijima, Larry Young, Tom Meehan, Garth Franklin, George Purcell, Feiqin Xie
  - Harvard University: Stephen Leroy
  - University of Arizona (via web telecon): Rob Kursinski
  - COSMIC Project at UCAR: Bill Schreiner and Chris Rocken
  - CLARREO project at LaRC (via web telecon): Bruce Wielicki (Science Team lead), Dave Young (Project Scientist), Jim Corliss (Deputy Chief Engineer)
- Discussed all the sources of systematic error we could think of
- Action item list at conclusion

CLARREO 2010 Meeting Highlights

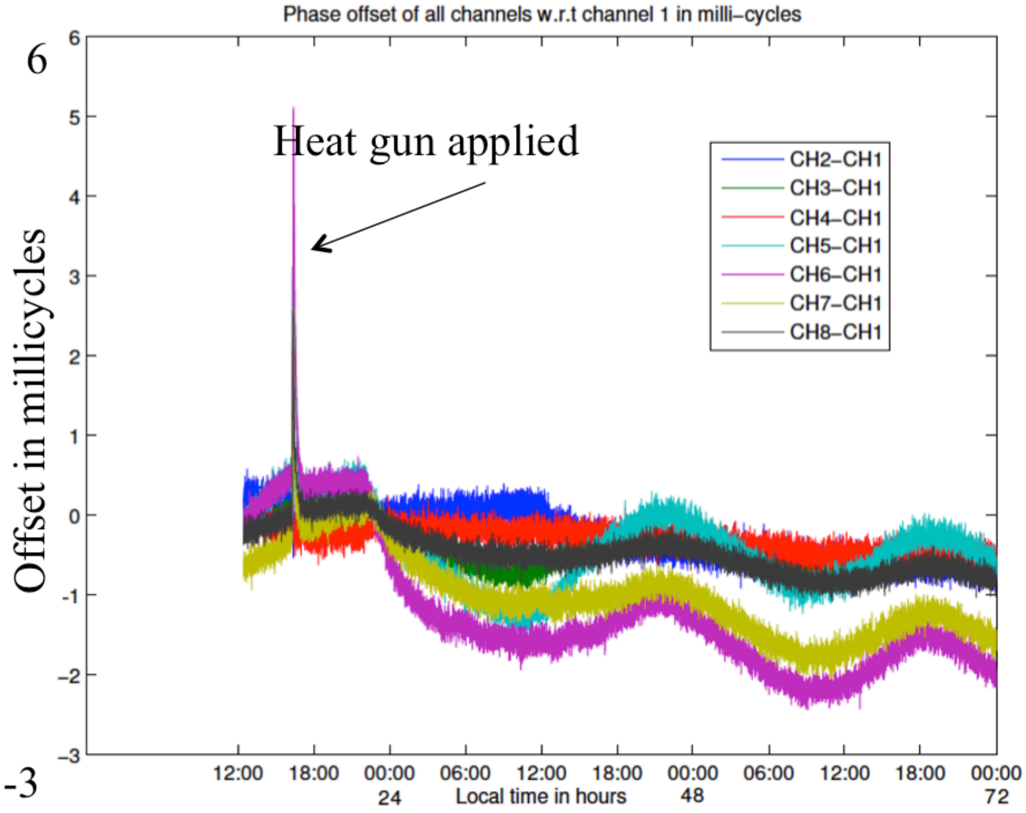
- Concern about correlated errors, e.g. between satellites or interannually, or between error sources
- The observatory shall carry a USO (10^{-13} over 1 second) to permit multiple paths to SI traceability to be carried out
- The science data system shall be capable of processing zero-difference, single and double-difference occultations
- The processing system will employ additional ionospheric correction algorithms beyond the current bending angle dual-frequency correction
- The observatory shall carry satellite laser ranging mirrors to provide multiple independent pathways to determining orbit error
- Multipath was a major CLARREO focus
  - Rocken had details

Building the CLARREO Instrument

- **Flowing down requirements to the instrument level**
- **Are there unaddressed requirements?**



Requirement	Occultation Duration	Max Drift (cycles)
0.1 mHz	100 s	0.01



Inter-channel drift may be reduced by using a clock differencing satellite (shown later)

Esterhuizen et al., ION Mtg 2009

Analyzing the Phase Extraction Step

Model phase *Residual*

$$\sin(\omega t + \phi(t))$$

Incoming signal

$$\sin(\omega t)\cos(\phi(t)) + \cos(\omega t)\sin(\phi(t))$$

Digital multiplication – "quadrature" – Q

$$\cos(\omega t)\cdot(\sin(\omega t)\cos(\phi(t)) + \cos(\omega t)\sin(\phi(t)))$$

$$Q = \frac{1}{2}\sin(\phi(t)) \boxed{+ \frac{1}{2}\cos(\phi(t))\sin(2\omega t) + \frac{1}{2}\cos^2(\omega t)\sin(\phi(t)) - \frac{1}{2}\sin^2(\omega t)\sin(\phi(t))}$$

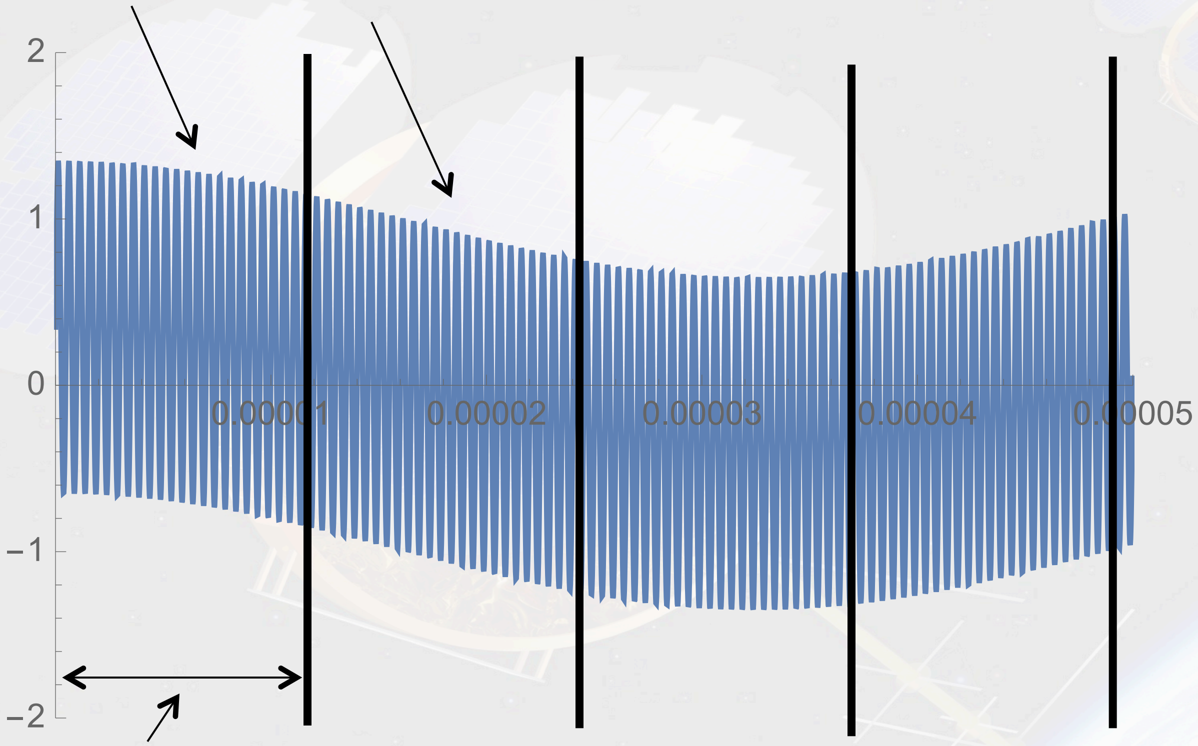
Digital multiplication – "in-phase" – I

$$\sin(\omega t)\cdot(\sin(\omega t)\cos(\phi(t)) + \cos(\omega t)\sin(\phi(t)))$$

$$I = \frac{1}{2}\cos(\phi(t)) \boxed{- \frac{1}{2}\cos^2(t\omega)\cos(\phi(t)) + \frac{1}{2}\cos(\phi(t))\sin^2(t\omega) + \frac{1}{2}\sin(2t\omega)\sin(\phi(t))}$$

"Sum and dump" then arctan: $\phi(t) = \tan^{-1}\left(\frac{Q}{\mathrm{I}}\right)$

Phase Extraction



One phase value extracted per interval

Sum and dump interval ~1-20 msec

- Desired: extract phase independently for each S&D interval
- Some receiver designs correlate extracted phase for several intervals

Concerns Regarding Phase Extraction

“Sum and dump” then arctan: $\phi(t) = \tan^{-1}\left(\frac{Q}{\mathrm{I}}\right)$

Q and I are the output of a low-pass filter:

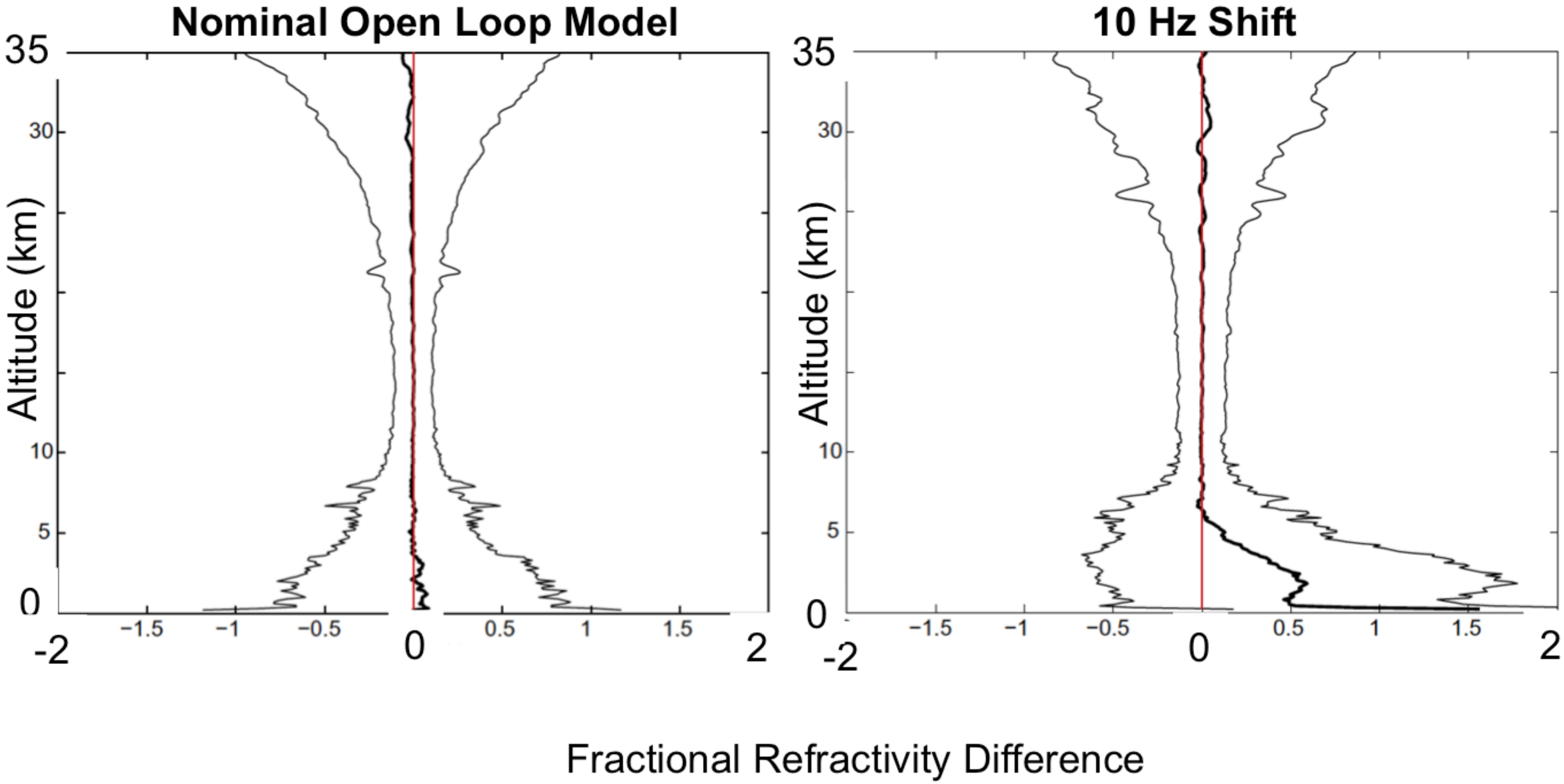
$$\bar{I} = \frac{1}{t_d}\int_0^{t_d} I(t)\, d\, t$$

$$\overline{Q} = \frac{1}{t_d}\int_0^{t_d} Q(t)\, d\, t$$

If the frequency model offset is within the Nyquist limit (e.g. ±25 Hz for 20 msec samples), then frequency error introduced by the low-pass filtering is << model offset

However, is frequency error introduced by the filtering always much less than the requirement of 0.1 mHz?

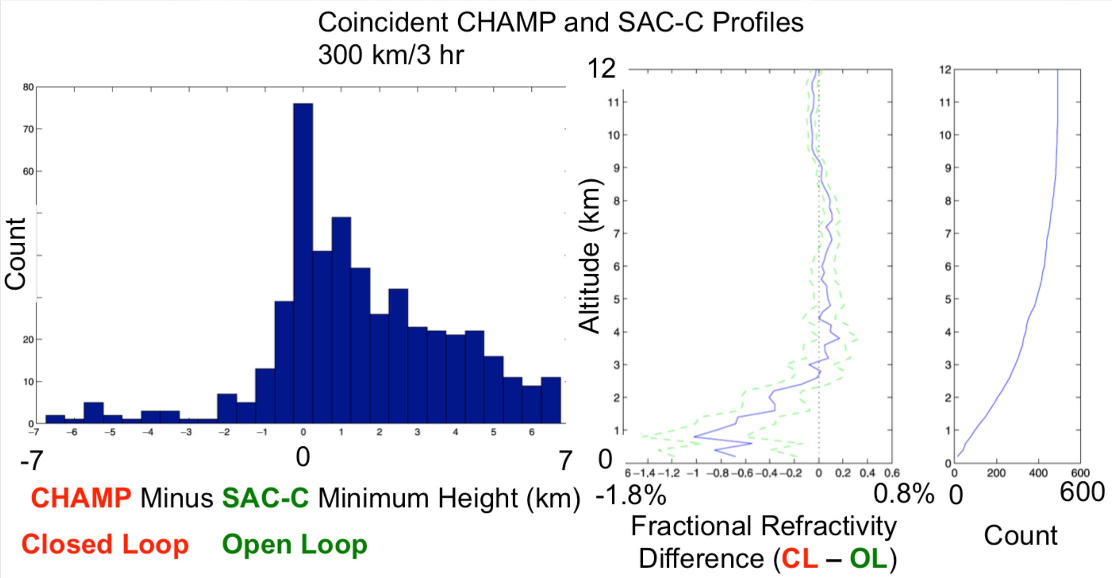
Case in Point?



Zus, F., L. Grunwaldt, S. Heise, G. Michalak, T. Schmidt, and J. Wickert (2014), Atmosphere sounding by GPS radio occultation: First results from TanDEM-X and comparison with TerraSAR-X, *Advances in Space Research*

Research Satellite Contributions

- **Open loop tracking was developed on SAC-C in orbit!**
  - **We continue to want experimental spaceborne platforms**
- **CHAMP established the benefits of multiple years of GNSS-RO data**
- **COSMIC/FORMOSAT-3 established operational benefit**



Ao, C. O., G. A. Hajj, T. K. Meehan, D. Dong, B. A. Iijima, A. J. Mannucci, and E. R. Kursinski (2009), Rising and setting GPS occultations by use of open-loop tracking, *J. Geophys. Res.*

None of these RO instruments followed a standard US process!

The Commercial Community

- The antithesis of the CLARREO approach
- Our challenge is to meet CLARREO-like requirements without explicit design
- Can we verify/falsify after launch?
- Are the sampling characteristics adequte for climate from commercial constellations?

The Scientific Community

- Climate modeling community: Obs4MIPS
  - Gridded products from RO
- Users needing high vertical resolution
  - Upper troposphere/lower stratosphere
  - Boundary layer
- Users interested in global change
- Users needing to calibrate instruments
- What will be the impact of GNSS-Reflections?

Recognition for our Community

- Lidia Cucurull – AMS Fellow
- John Labrecque (GPS receivers on CHAMP, SAC-C, Ørsted, Sunsat) – AGU's Edward A Flinn III award
- Jay Fein – Gratitude for getting us here. It is a remarkable achievement.

Future Directions

- NWP is still the “killer app”
  - Disadvantage: a single observing system has limited impact
  - Compare to GRACE: only way to measure time variable gravity (e.g. sub-surface water and glacier volumes)
- Science applications besides climate are still somewhat limited compared to “facility” instruments
- We should foster platforms for experimentation
- Will GNSS-R have the largest future impact?
  - Will proliferation of scatterometry applications drive future constellations?
  - Altimetry eventually (post-SWOT)

Summary and Conclusions

- We have benefitted from diverse communities and approaches
  - From top-down requirements missions to “guerilla tactics”
- We benefit from diverse processing systems and a diversity of instruments
  - RO-CLIM, GRAS, CHAMP, IGOR/COSMIC
  - “Multiple paths to SI-traceability”
- We should continue to engage with other observing systems
- The scientific benefits we enable bring multiple challenges
  - Climate has a long time scale
  - Weather is crowded with observing systems

BACKUP