GNSSRO at NSF:
A personal view from the CLD program

Successes, Challenges, and Opportunities

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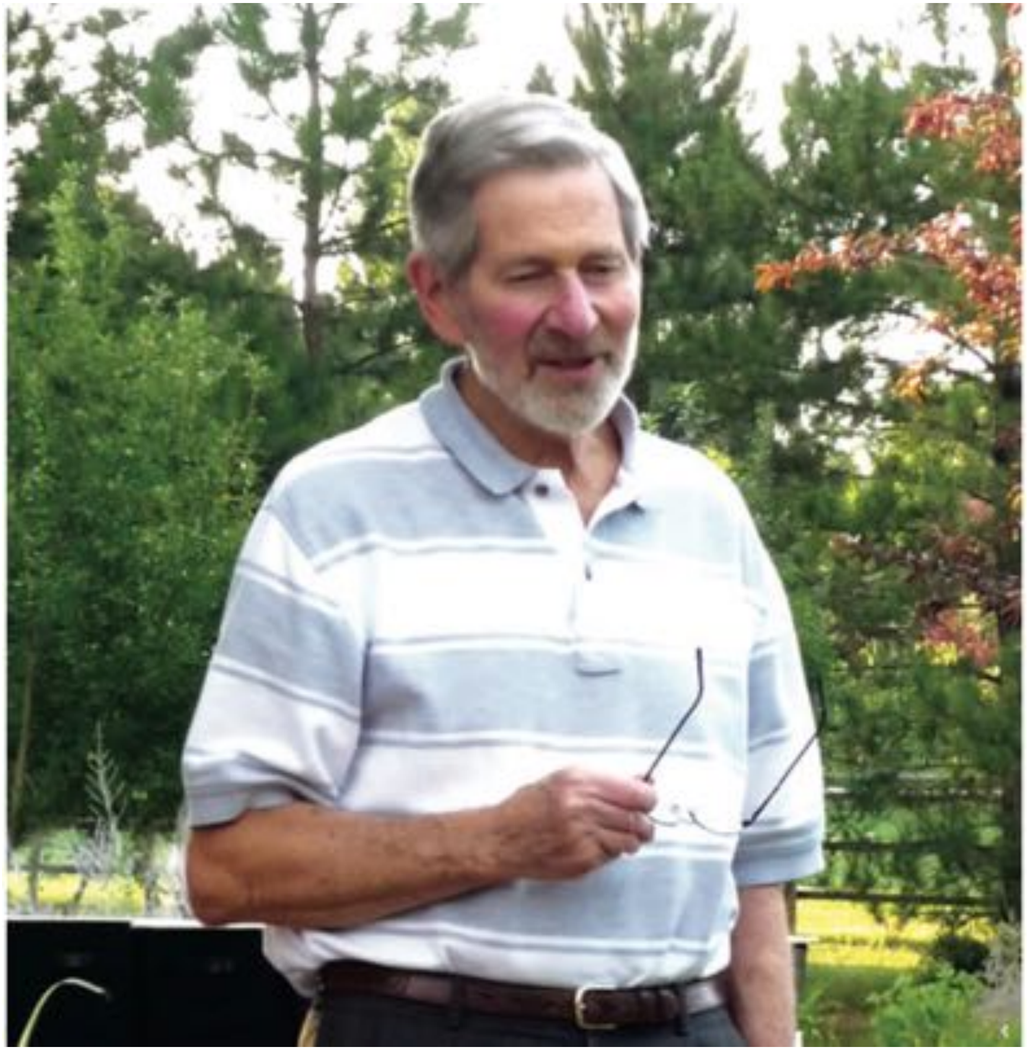
Thanks to Rick Anthes

How RO came to NSF



Jay S. Fein

Jay ran a $20M/year program, yet he put together a $100M satellite constellation. How?

A small subset of the skills:

1. Listening
2. Leading Upward
3. Persistence
4. Risk tolerance

These skills are critical for carrying out NSF's mission of supporting bottom-up, community-driven science.

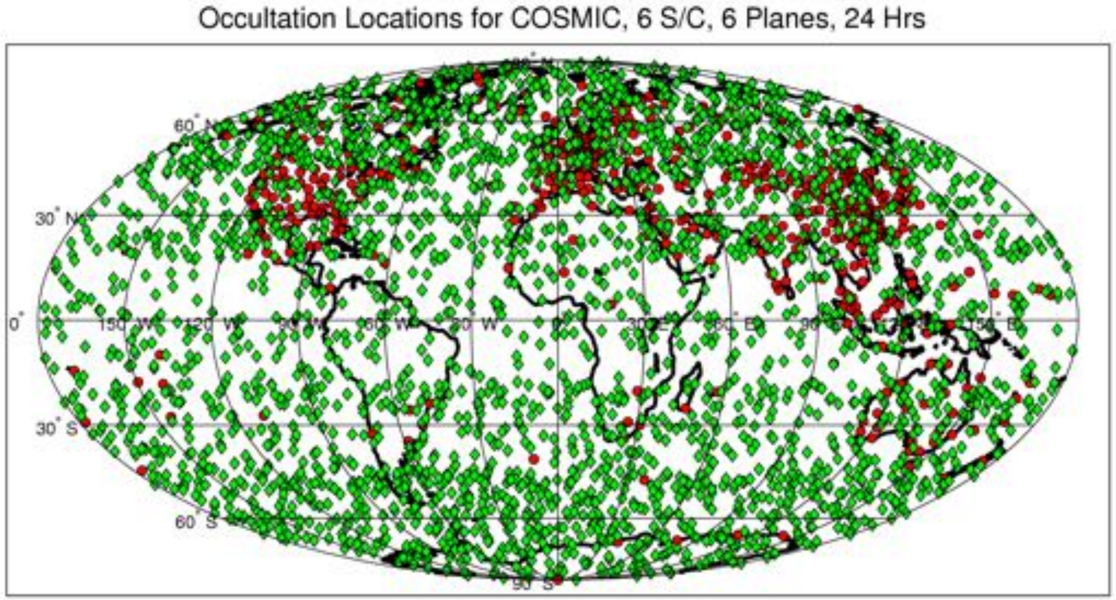
How RO came to NSF

For jay to convince his management to go for COSMIC/Formosat3 he had to convince them that this is an NSF-like activity. How?

Two NSF buzzwords apply:

- Potentially Transformative
- Broader Impacts

The transformative potential of RO is impressive both for basic science research and operational prediction.

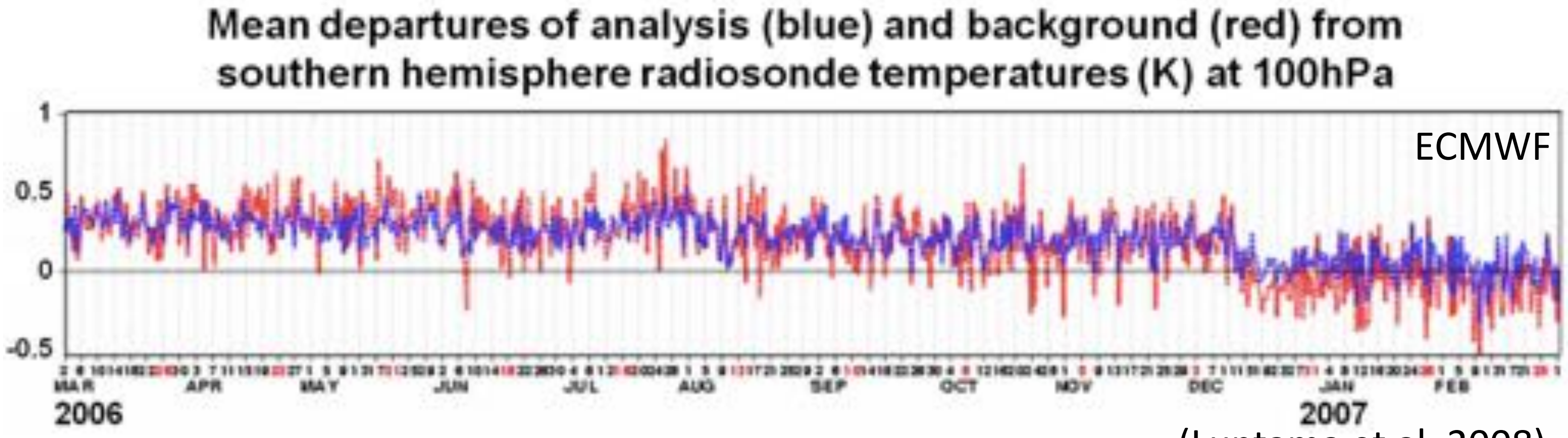


- **Global coverage**
- **Profiles ionosphere, stratosphere and troposphere**
- **High accuracy (equivalent to <0.5 K; average accuracy <0.1 K)**
- **High vertical resolution (0.1 km near surface – 1 km tropopause)**
- **Only system from space to profile atmospheric boundary layer (ABL)**
- **All weather-minimally affected by aerosols, clouds or precipitation**
- **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**
- **etc**

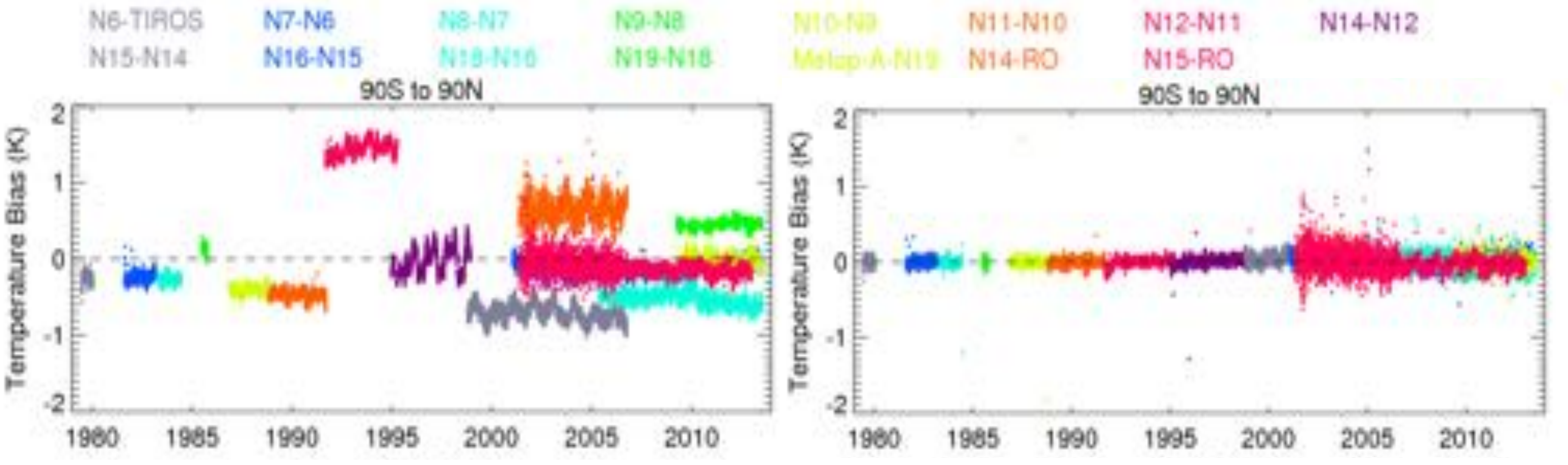
"World's most accurate, precise, and stable thermometer from space" (Anthes, see GK's talk)

The potentially transformative nature of SI-traceable observations from space is abundantly clear.

Virtually all atmospheric science research benefits from calibration effect of RO observations.



(Luntama et al. 2008)



(Ho, 2014).

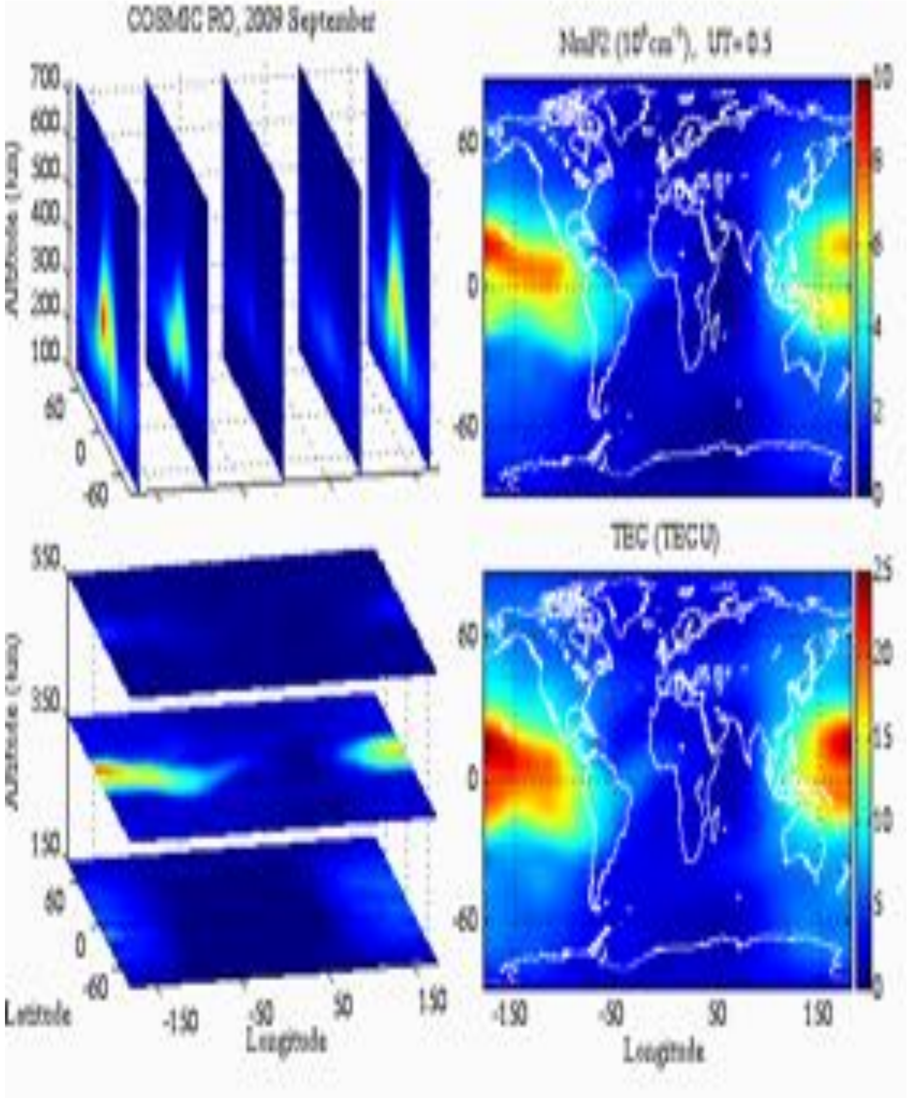
3-D Electron Density Reanalysis

The application of RO to ionospheric data assimilation and analysis is potentially even more transformative, as ionospheric analysis is in a much earlier stage of development.

Much of NSF's emphasis as been on ground-based observations, thus RO fills in the larger scales.

We are fortunate that COSMIC coincided with a quiet sun period.

OK, but what's this got to do with Space Weather?



[*Yue et al*, 2012]

RO is very helpful for making the case that there's more to Space Weather than CMEs.

Yue et al. 2014

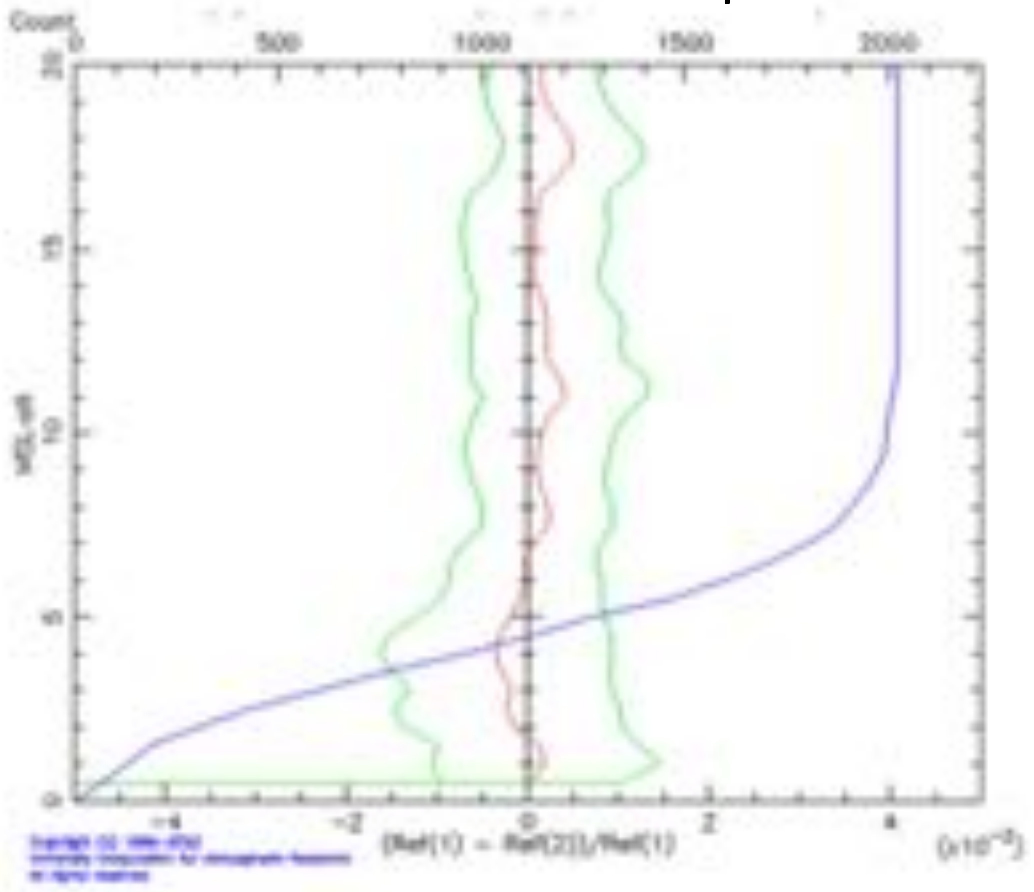
Congratulations Sergey!

THE VERNER E. SUOMI AWARD, January 2017
"For exceptional theoretical and practical contributions to the science and application of radio occultation observations of Earth's atmosphere"

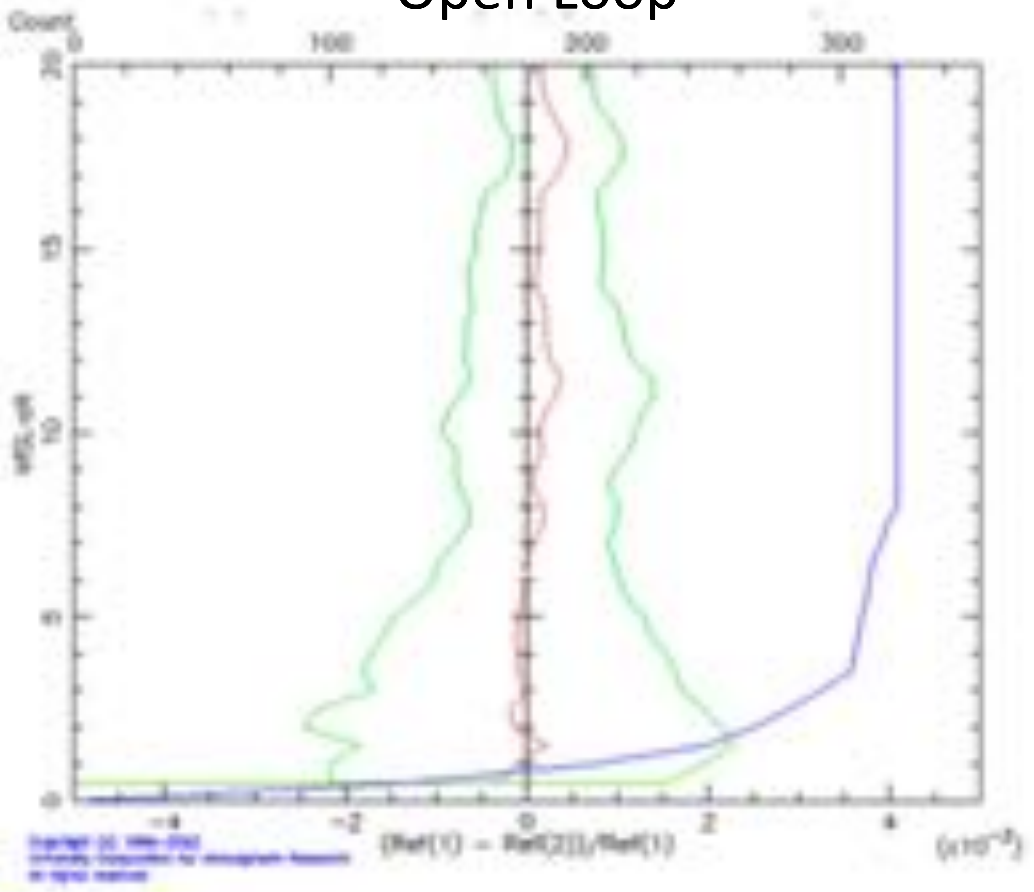
Well-deserved recognition both for Sergey and for the transformative power of RO

Open Loop Tracking

Phase Locked Loop



Open Loop



Transformative for profiling the boundary layer

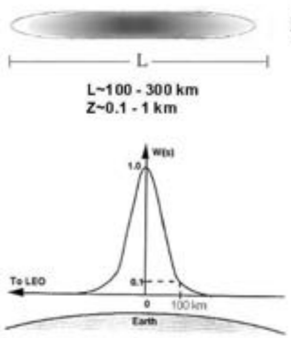
Can NSF Claim Success?

Yes, but RO is not as widely known within the research community as it could be.

Some obstacles to more widespread awareness and exploitation:

- It's in the reanalysis products so it's already in use (e.g. TRMM is better known because it can't be assimilated)
- Bending angles and refractivity are unfamiliar observables
- Risk/learning curve/effort associated with new (ungridded) observations
- Time series isn't quite long enough for some applications
- SI traceability of RO-derived water vapor isn't well understood
- Lack of formal instruction (compared to passive RT methods)
- Need to combine two essentially separate disciplines

Observed Atmospheric Volume



We're working on it

The UCAR COSMIC group (jointly funded by NSF and NASA) has worked to promote use and awareness of RO in a variety of ways including workshops (including this one), hosted visitors (Therese Rieckh, Jeremiah Sjoberg and Shay Gilpin presenting here), colloquia, and educational materials developed with COMET.

We also supported travel of US scientists to the ICGPSRO meetings sponsored by NSPO. Good papers have come out of this, but still adoption is a slow process.

This is critical as it's not about the satellites you launch but the science you do with them. (M. Freilich. NASA/ESD)

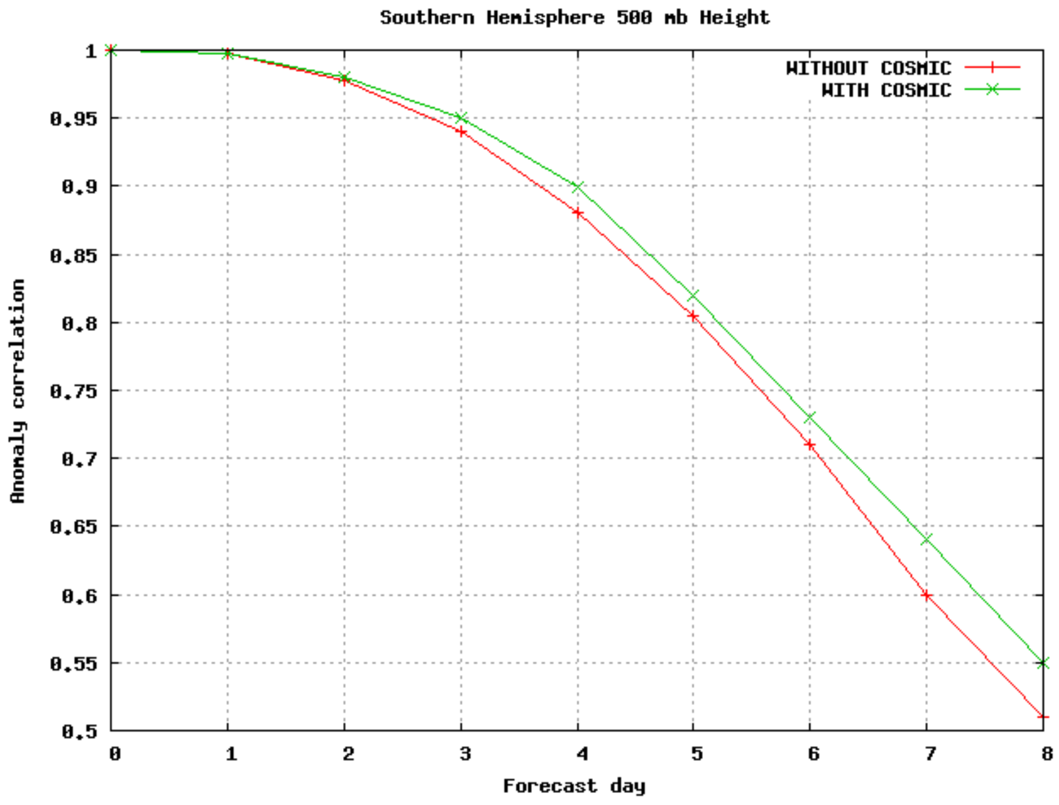
3rd ICGPSRO, Taipei 2016

Broader Impacts

The conversation around RO tends to focus exclusively on operational forecasting.

But for NSF this falls in the somewhat open-ended category of Broader Impacts.

This raises the issue of how NSF relates to the other agencies in the research/operations enterprise.



Cucurull 2010 (WAF)

8 hours of gain in forecast skill at day 4

NSF in the Research/Operations Ecosystem

NSF has two key and closely related attributes:

Agility

NSF in the Research/Operations Ecosystem

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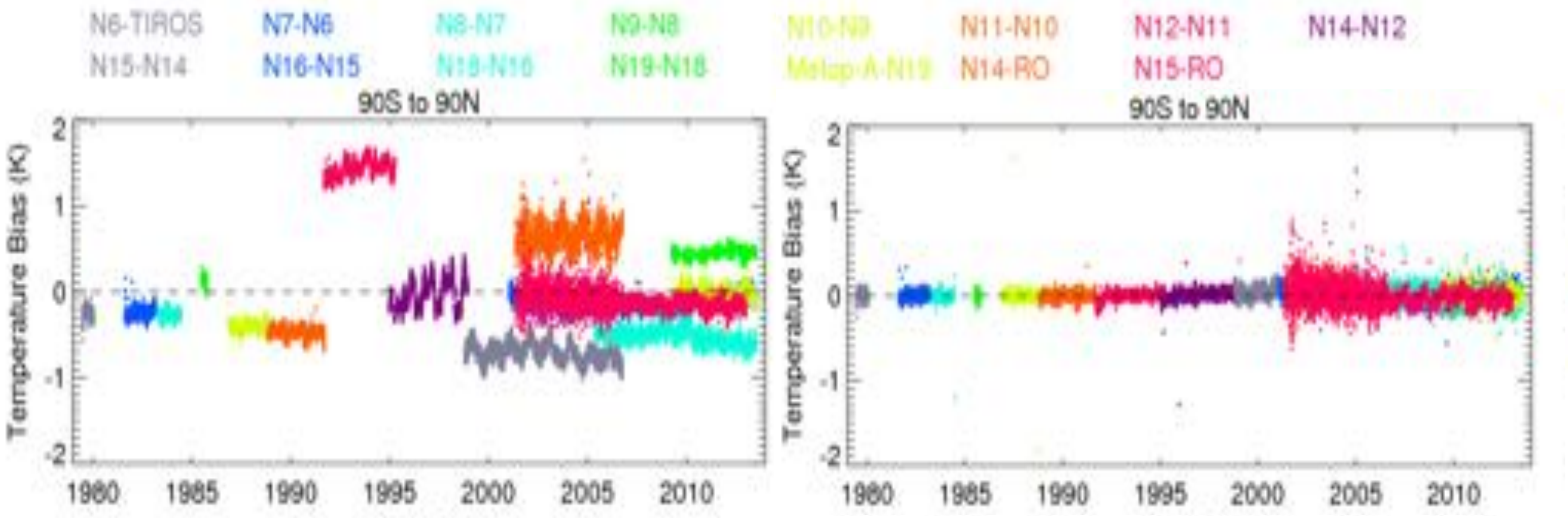
Agility

Poverty

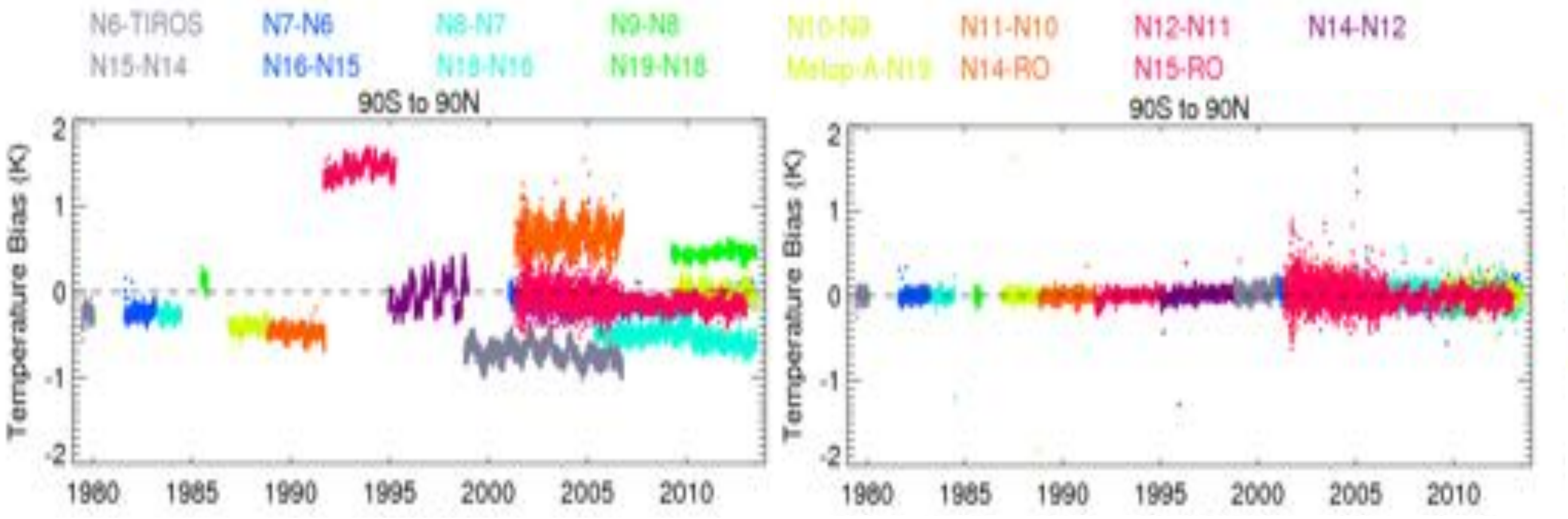
NSF in the Research/Operations Ecosystem



NSF

Q: How much does this slide cost?

NSF in the Research/Operations Ecosystem



NSF

Q: How much does this slide cost?
A: More $$ than I have

The reason we can do good science with our limited budget is that the raw materials are freely available.

This is the key “requirement” for us.

NSF in the Research/Operations Ecosystem

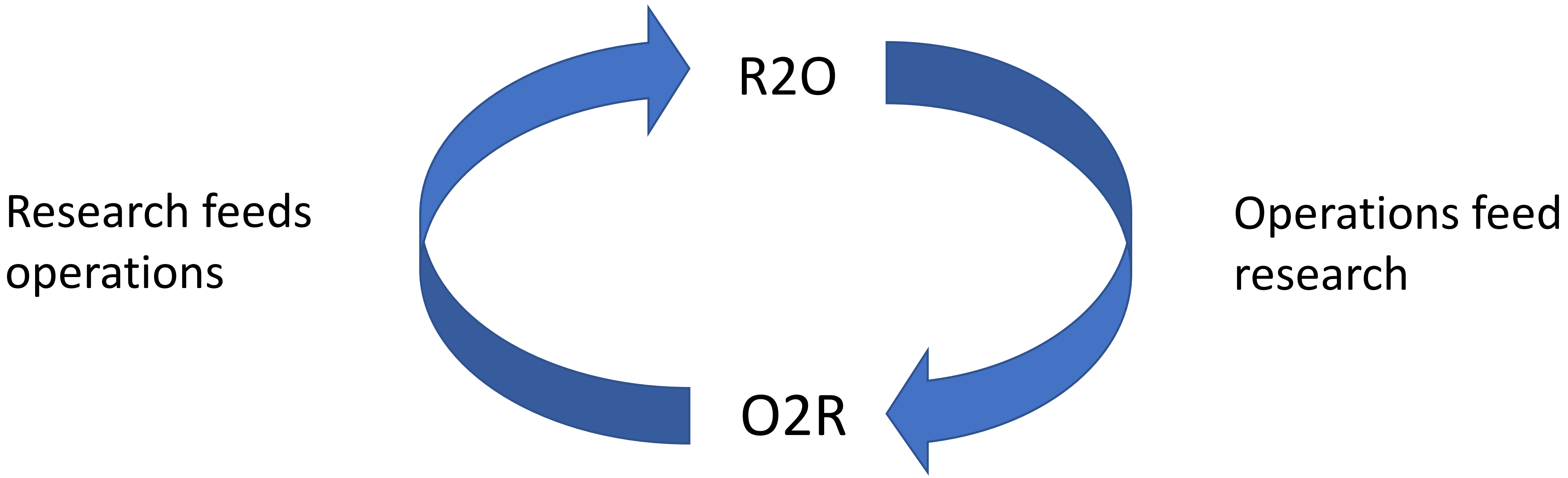
Our limited funds and basic science mission necessitate a handoff to operational agencies with larger budgets.

This handoff is generally called R2O.

The hand-off is not easy or quick (e.g. COSMIC-2/F7).

But: the R2O handoff is not the end of the story.

The R2O2R Cycle*

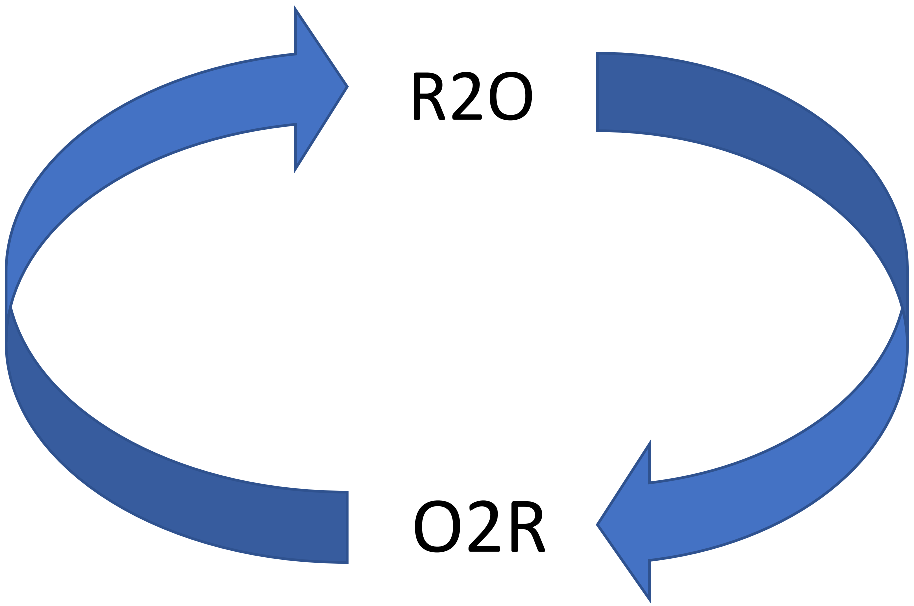


On the operational side there are "requirements". What are the "requirements" of the research community? Fortunately the needs of the research community are not that different from those of the operational world. Shared needs include:

- Continuity
- Global coverage
- Raw data, instrument characteristics and other metadata

* Note: not all basic research feeds operations

The R2O2R Cycle



Research feeds operations

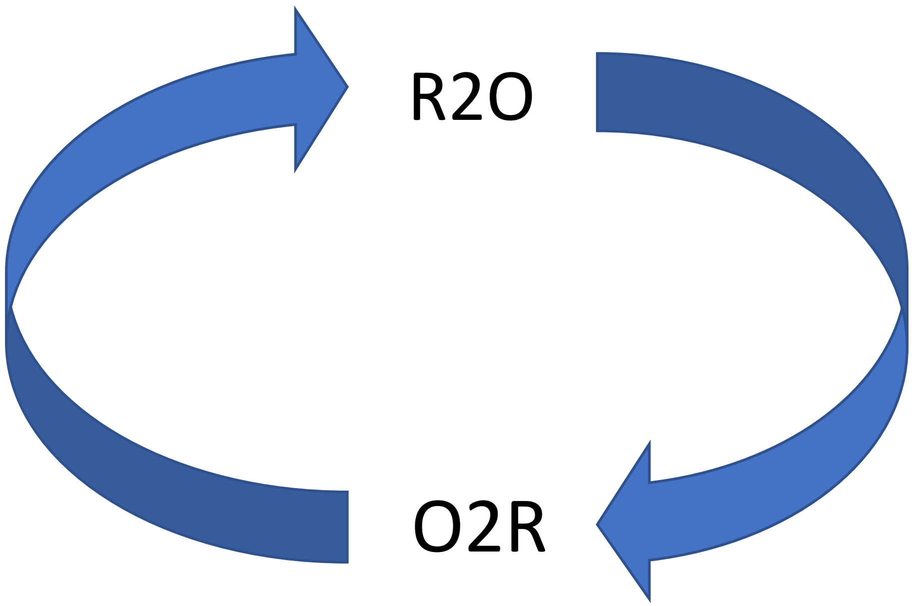
Operations feed research

Some differences between research and operational needs:

- Near-real time not essential
- Post-processing and reprocessing
- Free and open access to the world (not just government centers or agencies)
- Long-term archival, hosting, and service (free data isn't free)
- Intercalibration from mission to mission

Are the research needs being considered?

Research feeds operations



Operations feed research

Two places to look for the latest RO recommendations and requirements:

- IROWG minutes and recommendations
- The NOAA Commercial Weather Data Pilot (CWDP)

Fortunately, both are represented in this meeting.

How well do their deliberations reflect the needs of the research community?

CWDP Round 1 Lessons Learned

While Round 1 is still underway, NOAA is already incorporating lessons learned into planning for Round 2 and beyond.

- Having data in advance is critical to prepare for data processing
- Vendors must be a
- Need verification a
- More work is neede ... nd NOAA/NOAA's CWDP partners du
- NOAA must be able to state specific requirements
- Parts of the commercial sector would prefer that NOAA purchase processed data products rather than lower level data

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Not very compatible with research needs

But: may not work for operations either

Round 1/Round 2 Comparison

Requirement	Round #1	Round #2
Data latency	Minimum monthly deliveries required.	Minimum weekly deliveries required; options for vendors to demonstrate low-latency downlink and processing.
Data Rights and Sharing	[illegible]	analysis and retention, and and international partners.
Radio Occultation data	[illegible]	5 months total consecutive 500km² surface areas,
Ionospheric data	[illegible]	tal Electron Content (TEC); y, S4 and σΦ derived product files.
Concurrent RO/POD/Attitude data	Attitude data required, and closed-loop POD corresponding to RO dataset.	POD and attitude data concurrent with RO data required; minimum 50% POD duty-cycle and 60 minute arcs required.
GNSS Tracking data	No requirement on tracking data quality. Dual-frequency required.	Requires 4 GNSS satellites in Field of View during POD, 95% of the time.
Derived bending angles and profiles	Not requested.	Requested as an option. Onboard clock steering information required, to ensure accurate angle/profile derivation.

What about access to metadata?

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A good start.

Do we have a complete list of necessary metadata?

Round 1/Round 2 Comparison

Requirement	Round #1	Round #2
Data latency	Minimum monthly deliveries required.	Minimum weekly deliveries required; options for vendors to demonstrate low-latency downlink and processing.
Data Rights and Sharing	Only within entities performing specific CWDP analysis.	Rights for non-operational analysis and retention, and sharing with U.S. agencies and international partners.
Radio Occultatior		tal consecutive face areas,
Ionospheric data		Content (TEC); derived product
Concurrent RO/POD/Attitude		RO data required; minute arcs
GNSS Tracking da		ew during POD,
Derived bending angles and profil		steering te angle/profile

Data sharing is required, which is good.

But: researchers need open access to data outside of federal agencies (although not in NRT).

Also, costs of serving and archiving should be incorporated in data buy.

IROWG-5 Recommendations, May 2017

The Backbone Paradigm

- "IROWG recommends … **a backbone of instruments**, technologically **state-of-the-art**, and **labelled** as **essential** … This backbone should … provide the highest level of performance, and become a reference asset. … Operational missions (like the planned COSMIC-2 equatorial and polar constellations) are required as a backbone to ensure continuity."

Operationally, the backbone is critical for calibration, continuity, and evaluating commercial data for purchase.

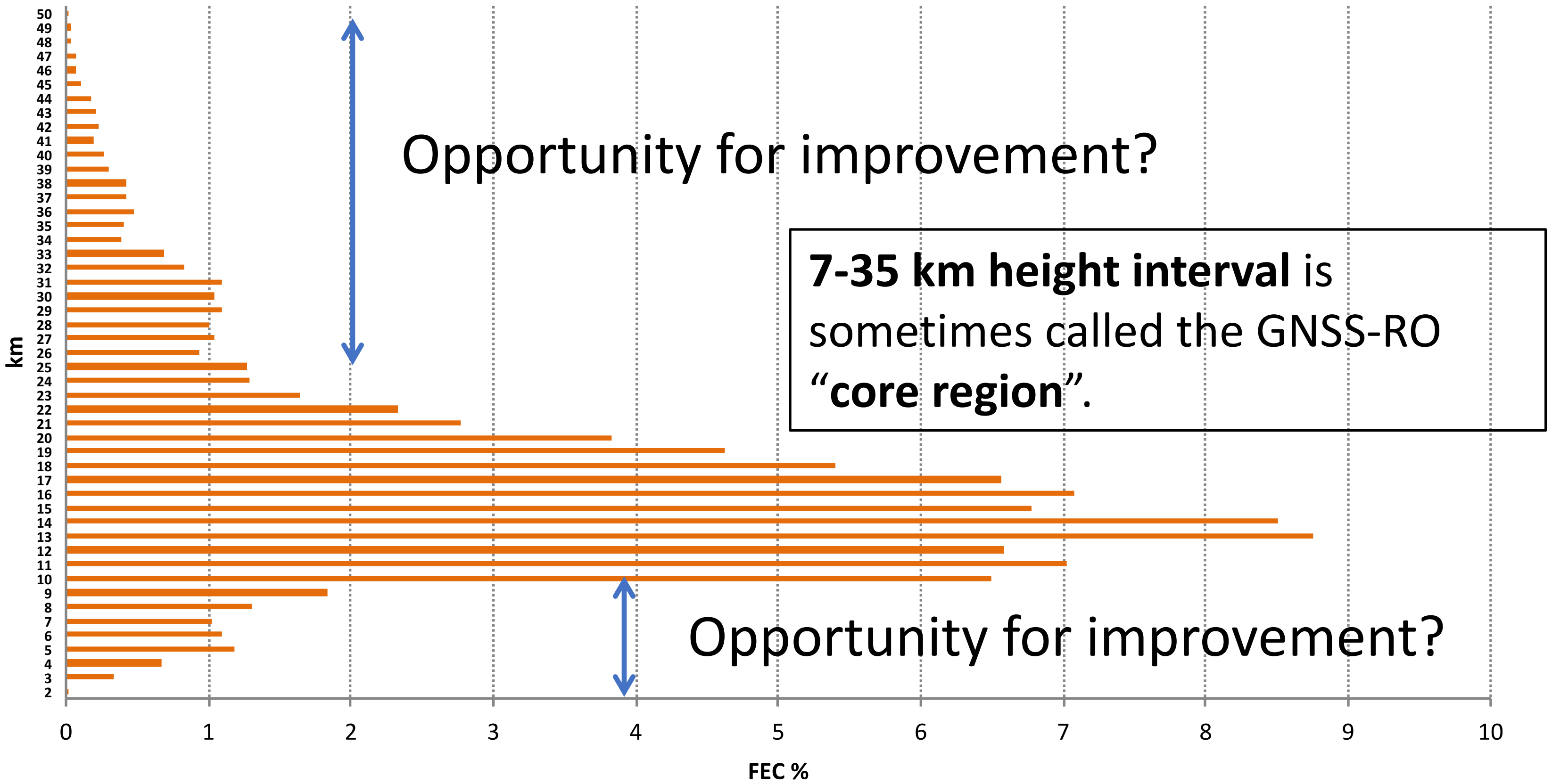
For research, the backbone provides continuity and the high performance receivers enable basic science research, thus providing for long-term advancements in science and (potentially profitable) technology.

Exploring the Opportunity Regions with Backbone Receivers

The core region may be the commercial sweet spot (where the PV is)

High-gain receivers may be the best way to explore the "oppportunity" regions.

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



Harnisch, Healy, Bauer, English,Yen, 2013

Commercial value may result from such research.

IROWG-5 Recommendations, May 2017

IROWG also recommends free availability and access to metadata:

- “IROWG recommends that a supplementary set of instruments provide further data, perhaps commercial, **not necessarily** labelled essential. **IROWG strongly recommends that this supplementary data are nevertheless as freely available as possible**.“

- “Regardless of the operational availability, it is important that there is a clear characterization of the properties (accuracy, error properties) of this dataset.”

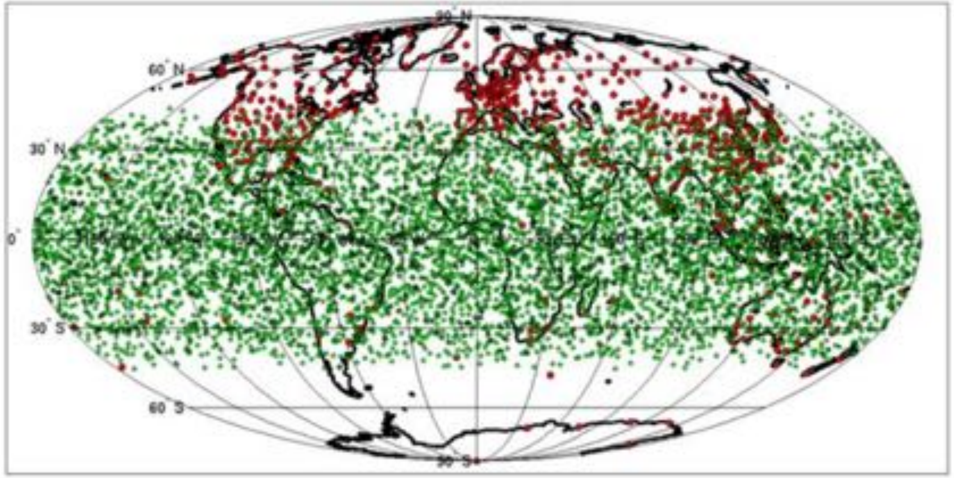
If these two recommendations are followed, the R2O2R loop can be conducted as a private-public partnership, to the benefit of the private sector.

Some Conclusions

- Jay's hard work and persistence have had tremendous payoff in terms of Transformative Science.
- GNSSRO has already had transformative effects, but more work is needed to establish continuity and promote research applications.
- NSF relies on operational agencies for the raw materials, including satellite data, that make basic science research affordable. This is a critical component of the R2O2R cycle.
- The CWDP requirements are generally favorable for research needs, but continued attention to these needs is highly desirable.
- The IROWG backbone paradigm is a good start, but continued consideration of research needs is again critical.

Up Next: C2A

We look forward to the launch of the COSMIC-2/Formosat-7 tropical constellation.



Timing is excellent given the high level of research interest in tropical phenomena like tropical cyclones, the MJO, TTL, QBO, and convective processes.

Questions?