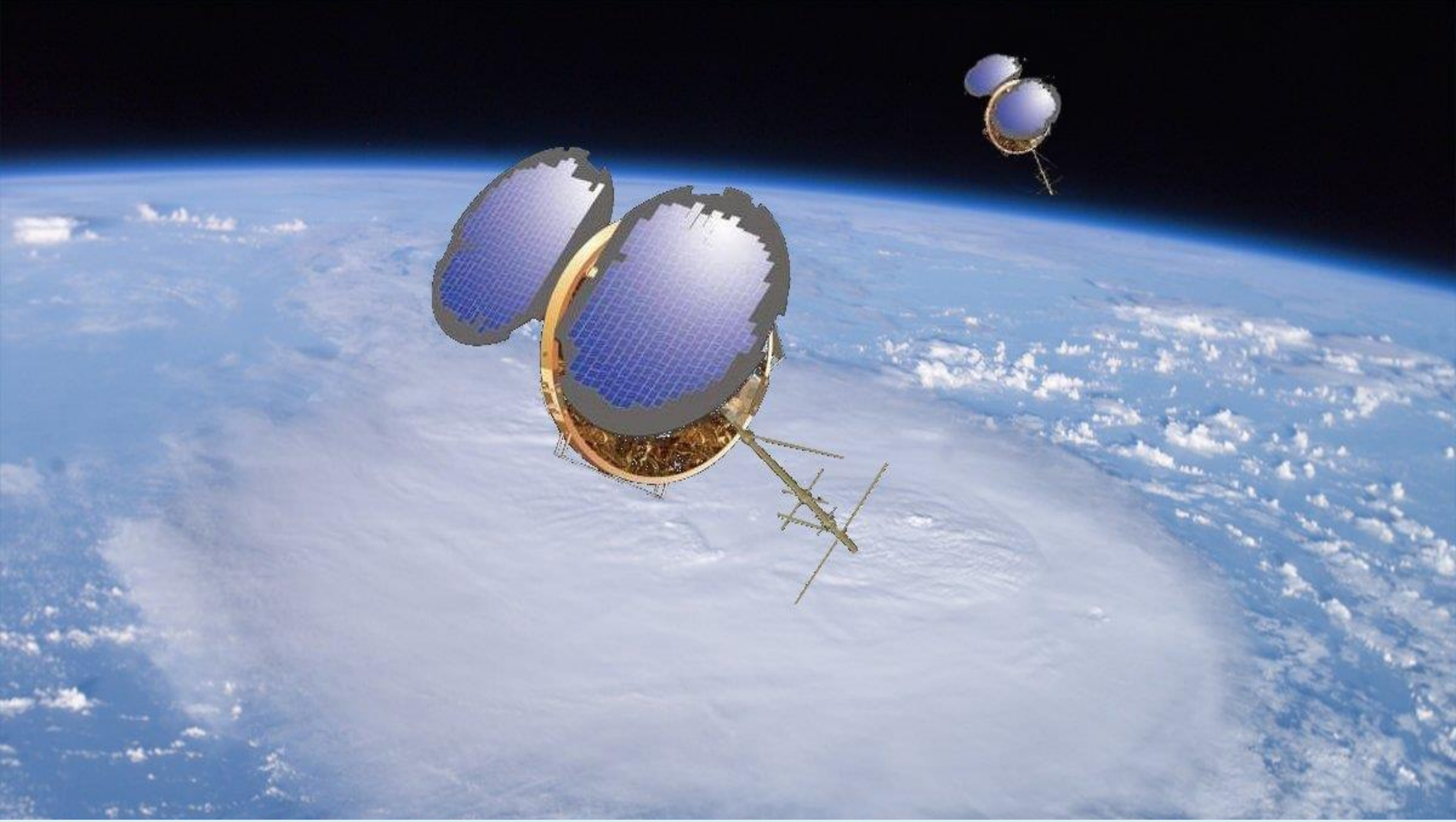


Radio Occultation as a Gap Filler for Infrared and Microwave Sounders

Richard Anthes

Presentation to Joshua Leiling and Shawn Ward, GAO

RICHARD ANTHES is President Emeritus of the University Corporation for Atmospheric Research.

He is Past President of the American Meteorological Society and was Chairman of the National Research Council's first Decadal Survey of Earth Science and Applications from Space (2007)

Anthes has chaired or participated in over 40 national committees and has published more than 100 articles and books in the areas of tropical cyclones, meteorology, and remote sensing using the radio occultation technique. He is a Fellow of the AMS and the AGU and has won the AMS' Meisinger and Charney Awards.

Overall Conclusions

Radio occultation observations will mitigate against any gaps in ATMS or CrIS observations, <u>while adding significant value at the same time.</u>

Extending the life of COSMIC and fully implementing COSMIC-2 will provide these observations through at least 2025 at extremely low additional cost (~$100M) to the U.S.

And even more importantly……(next slide)

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

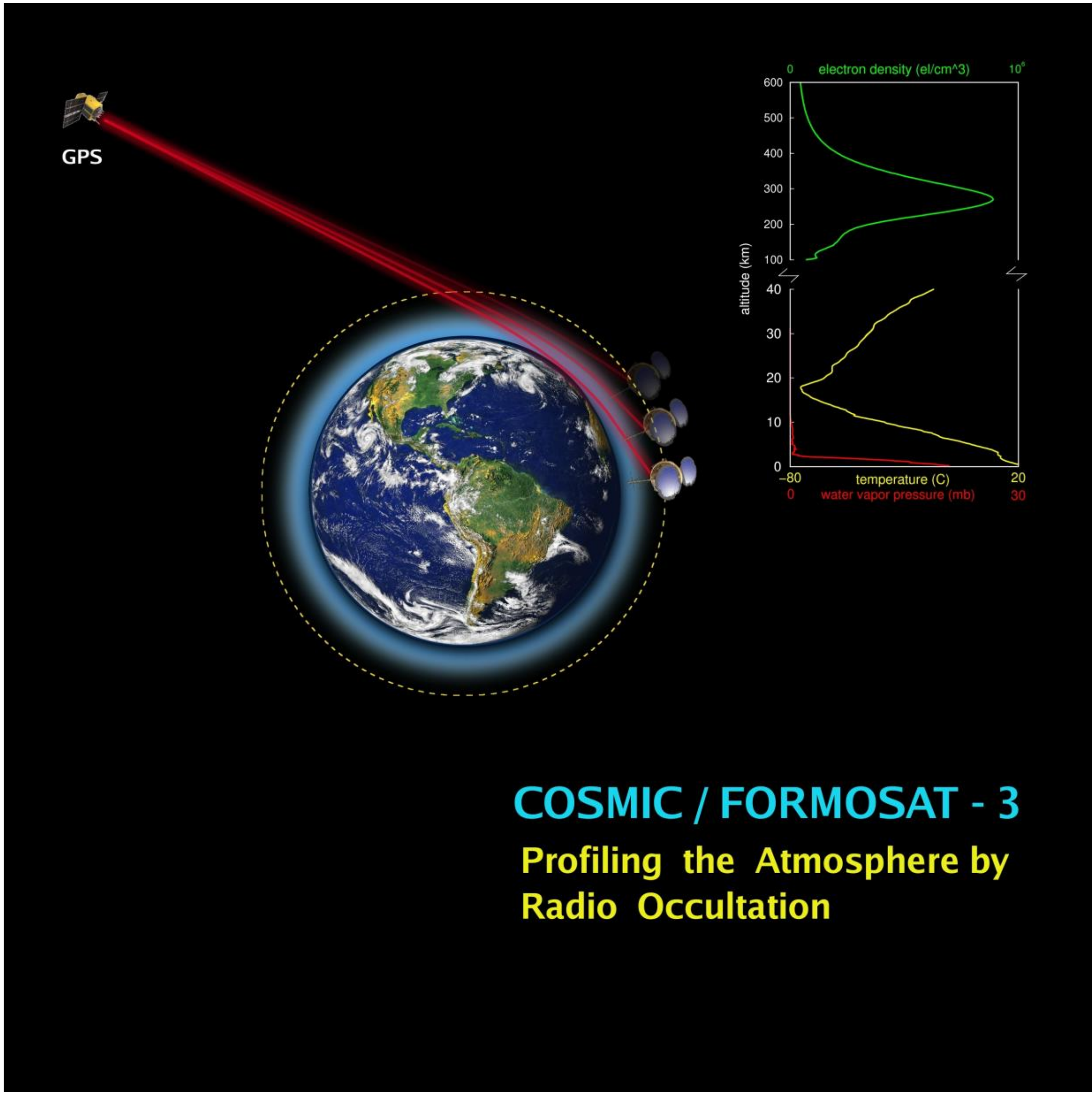
Complementarity of RO, IR and MW means that a balanced system is the most important aspect of the sounding system to maintain.

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!

Radio Occultation

As a satellite in low-Earth orbit carrying a radio receiver passes behind Earth (is occulted by Earth), the radio waves from a GPS satellite pass through the atmosphere and are slowed and bent along the way.

The amount of bending depends on the temperature and water vapor in the lower atmosphere and the electron density in the ionosphere.



Scientific Uses of Radio Occultation Data

- **Weather**
  - Improve global weather analyses, particularly over data void regions such as the oceans, tropics, and polar regions
  - Improve skill of numerical weather prediction models
  - 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

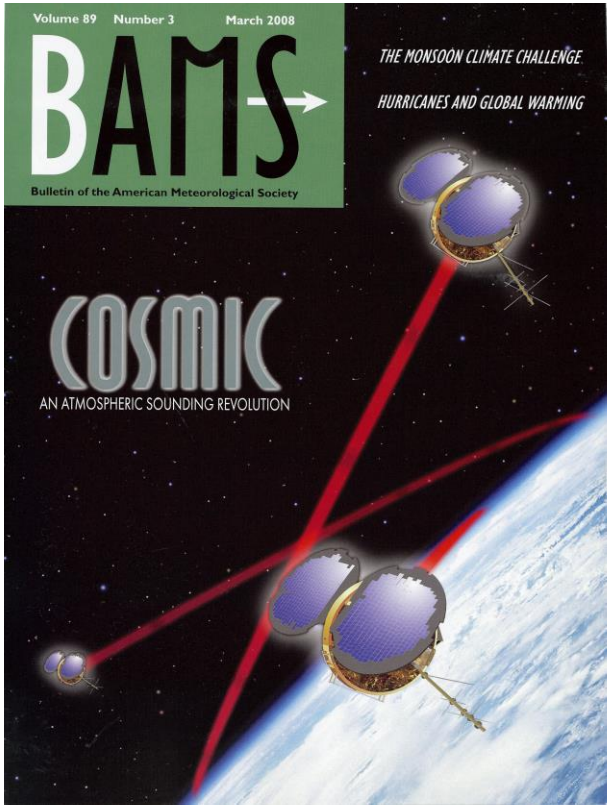
Characteristics of RO Data

- **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**
- **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.

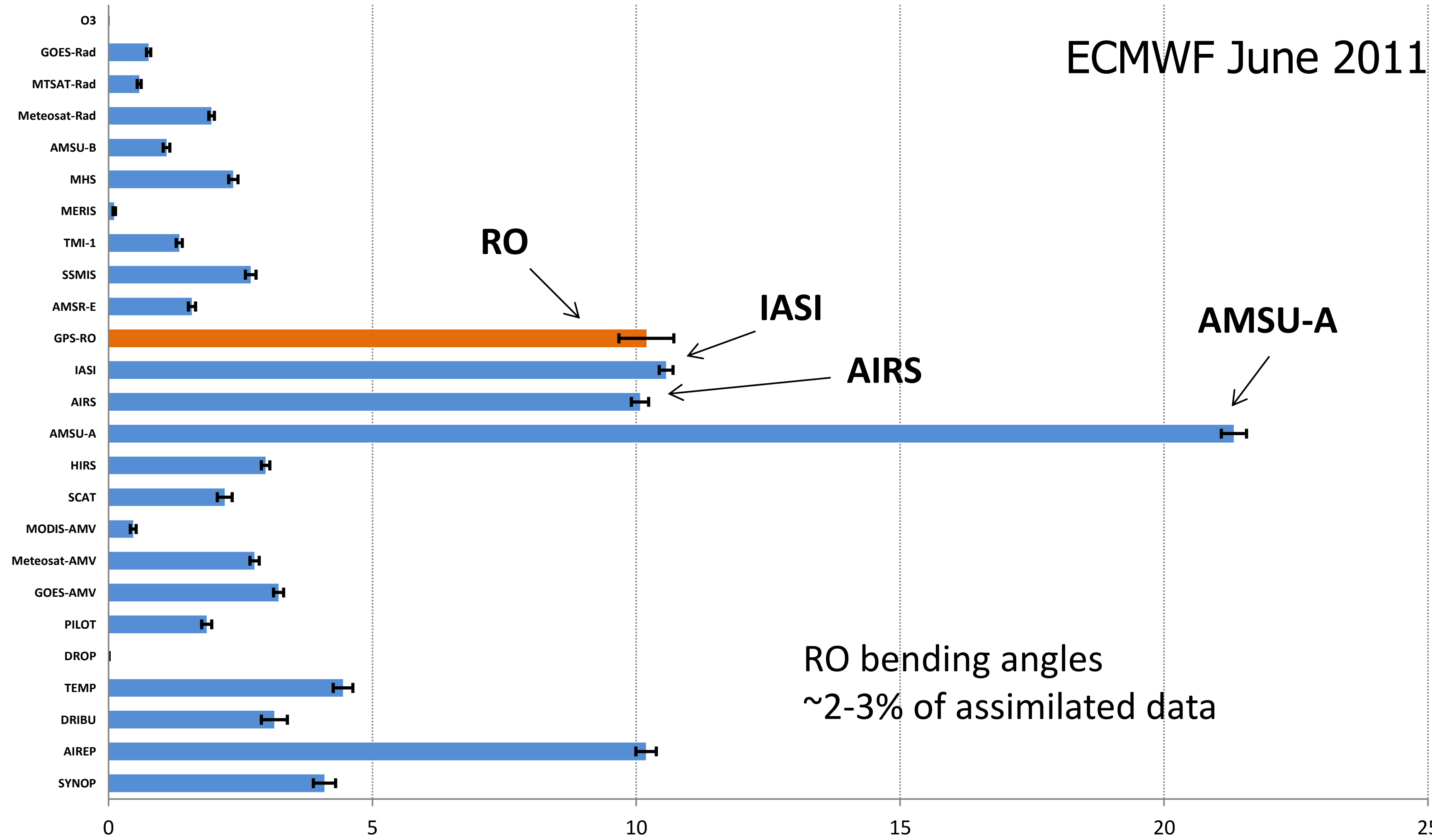
COSMIC

- 6 Satellites launched in April 2006
- Global observations of:
  - Pressure, Temperature, Humidity
  - Refractivity
  - Ionospheric Electron Density
- Large impact on weather prediction
- Taiwan paid $80M; U.S. $20M
- Constellation has operated eight years, more than 5 years beyond expected lifetime, and is gradually degrading, increasing risk of gap in RO



Bulletin American Meteorological Society March 2008

Contributions to forecast accuracy by observing systems



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

Recent ECMWF Summary of Impact of RO Observations (mostly COSMIC)

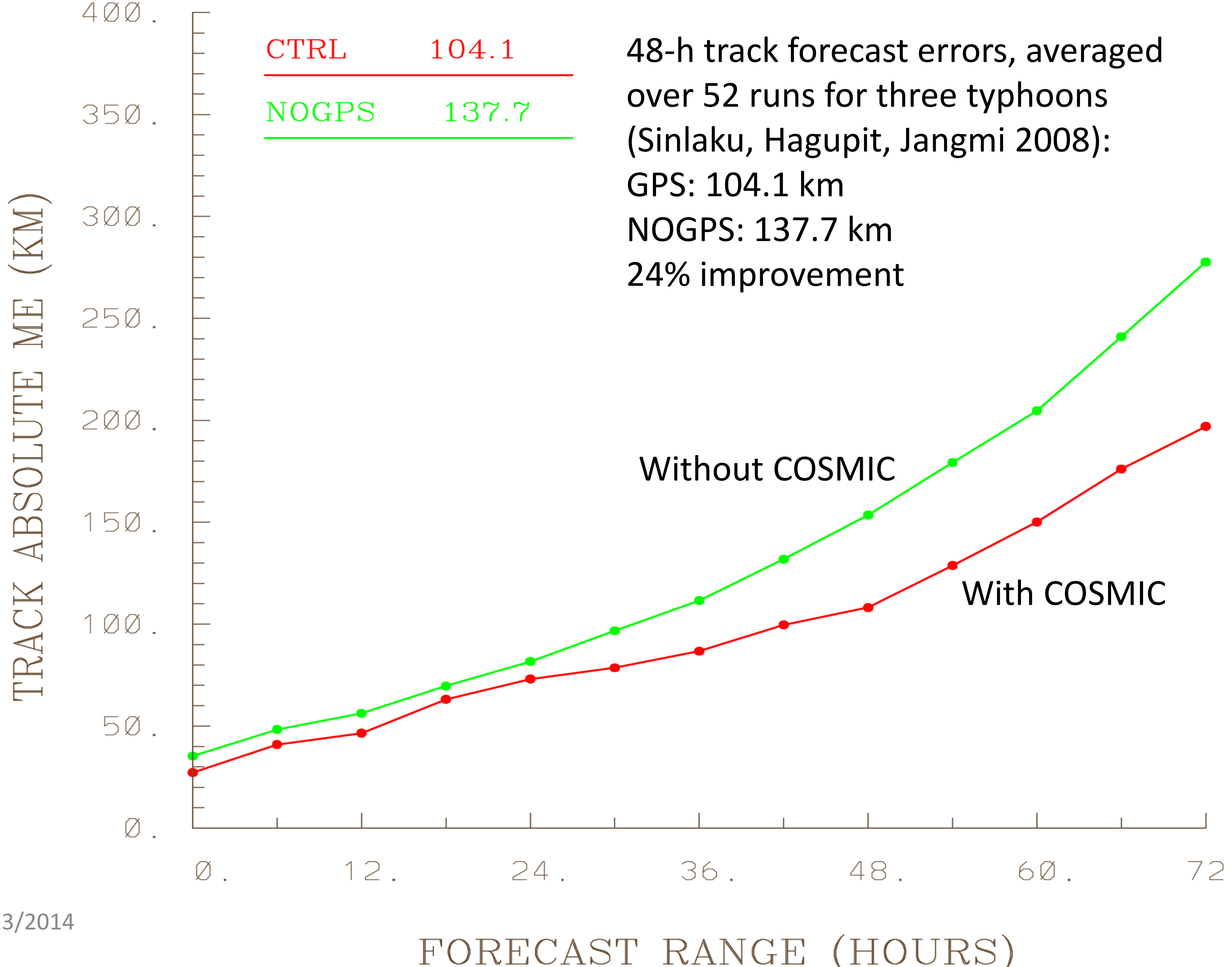
"GPS-RO is found to have the largest mean influence among satellite observations in the analysis. It is the fourth best satellite system for analysis information content and the second largest satellite contributor together with IASI and AIRS to decreasing the 24 h forecast error."

Cardinali and Healy (ECMWF) in *Quarterly Journal of Royal Meteorological Society*, 2014.

RO and tropical cyclones

- Considerable uncertainties in analyses over the tropics
- RO observations are of high vertical resolution and high accuracy and minimally affected by clouds and precipitation
- Advantages for tropical cyclone observation and prediction:
  - Water vapor: Important for convective development, genesis, intensity, track and precipitation forecasts
  - Temperature: Important for track forecasts
  - Can estimate intensity of TC using RO
- COSMIC has demonstrated significant impact in TC forecasts; COSMIC-2 with 5X number of higher quality observations, will be significantly better

Forecast track errors for 52 TC forecasts in 2008



48-h track forecast errors, averaged over 52 runs for three typhoons (Sinlaku, Hagupit, Jangmi 2008):
GPS: 104.1 km
NOGPS: 137.7 km
24% improvement

RO, IR, and Microwave are complementary

- RO, IR and MW provide independent information
- RO "anchors" NWP models and reduces bias corrections needed for IR and MW observations in NWP models
- RO can be used to calibrate and validate IR and MW retrievals
- RO is a valuable complement to NPP and JPSS

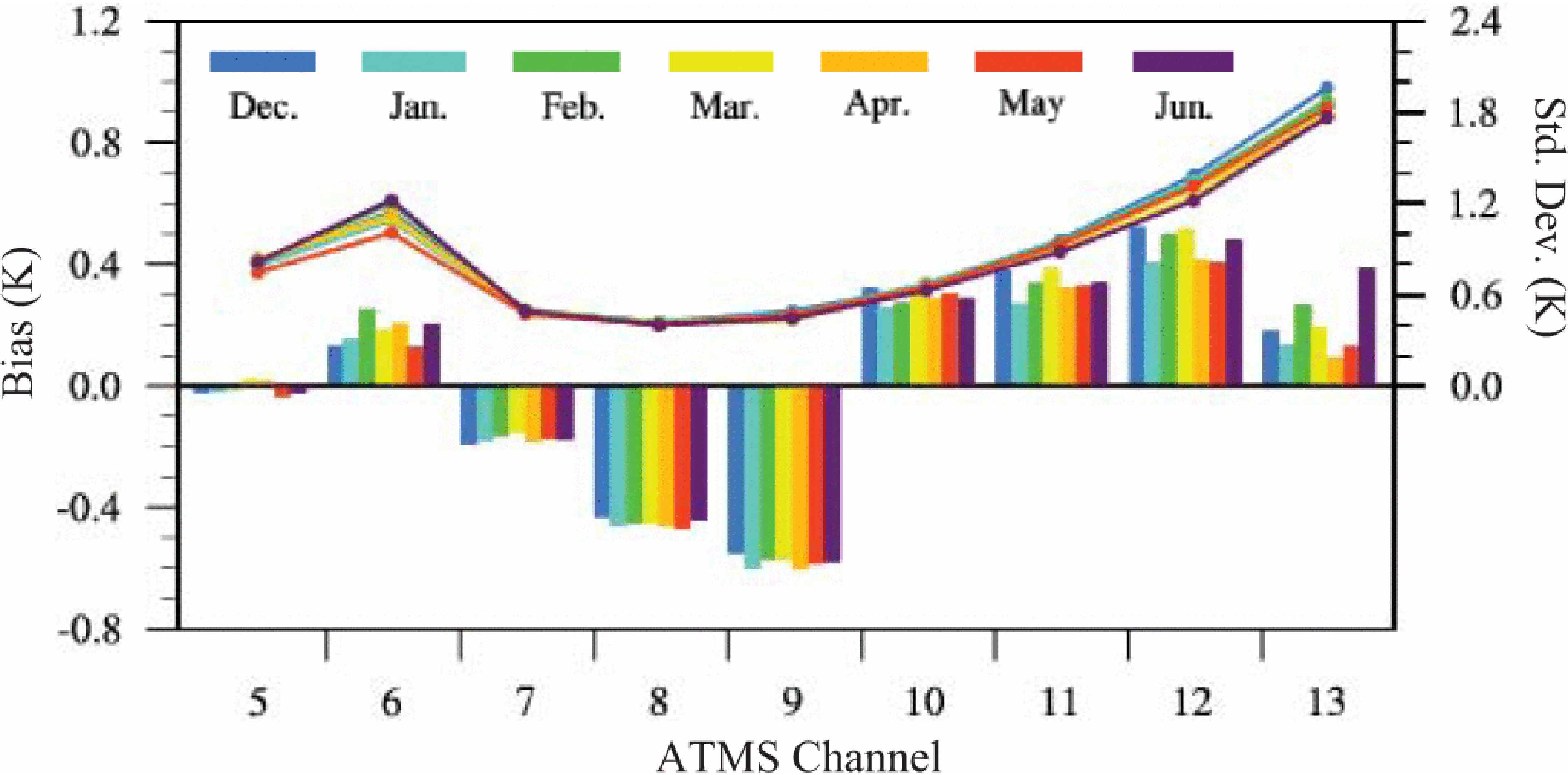
Calibration and reduction of biases in AIRS and AMSU

AIRS and AMSU exhibit biases in temperatures, limiting their value in NWP and observing long-term climate change. RO can help by:

1. Monitoring the long term stability of retrievals/measurements

2. Improving temperature and moisture retrievals in troposphere and stratosphere.

Calibration of Advanced Technology Microwave Sounder (ATMS) on Suomi NPP using COSMIC RO Measurements



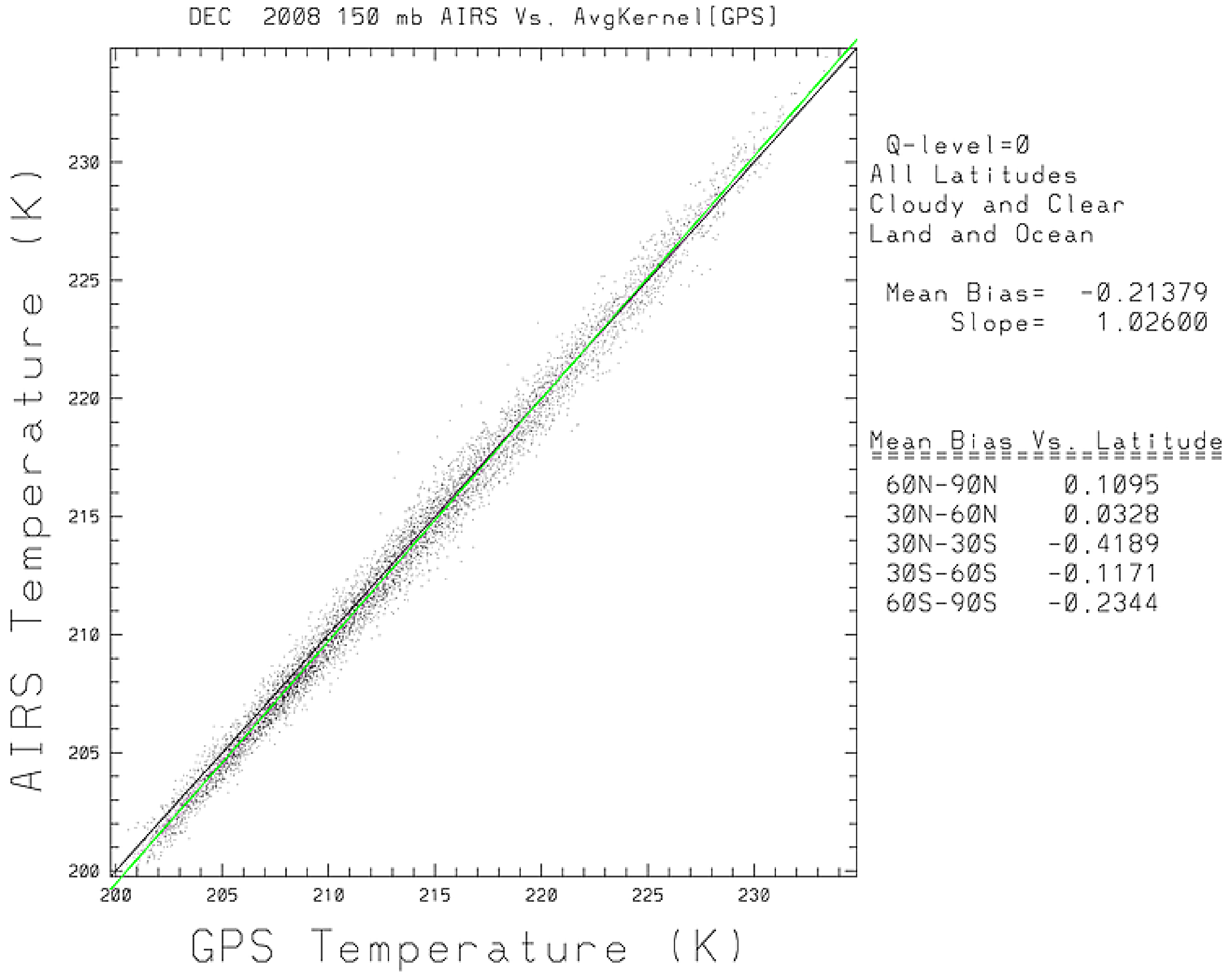
Dec 2011-June 202

"With the high quality of GPS RO observations…, ATMS upper-level temperature sounding channels are calibrated with known absolute accuracy." Zou, Lin and Weng, 2014, IEEE.

AIRS vs. COSMIC Temperature (K)

Corr ~ 1.0

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



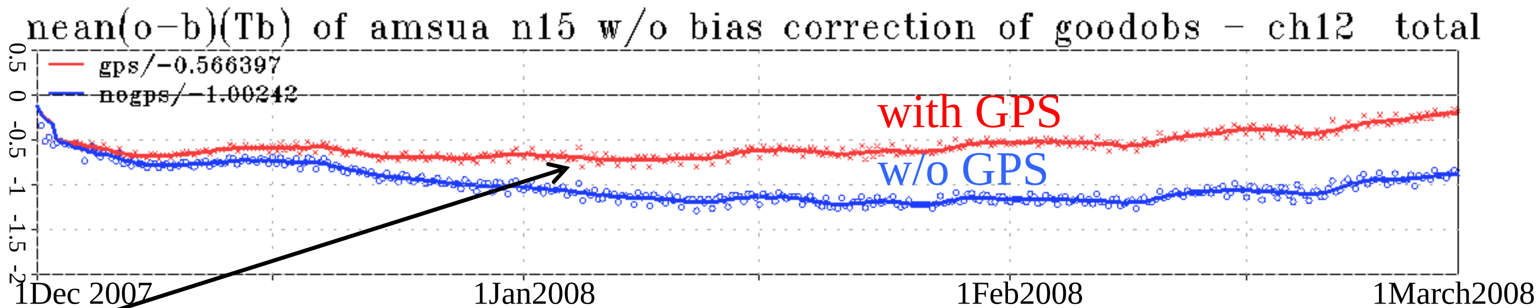
Agreement here is very good, validating AIRS retrieval algorithms and calibration

Impact of RO on satellite radiance assimilation

- Satellite radiance observations contain systematic errors (biases), and so require the use of bias corrections in NWP
- These biases corrections do not account for model biases. Model analyses and forecasts thus require some data to be assimilated without bias corrections to 'anchor' the model, avoiding a drift of the bias corrections in the radiance observations
- RO is an <u>anchor measurement</u>: unbiased or bias is small enough so they do not need bias corrections
- Thus RO has both direct and indirect benefits-assimilation of useful information AND improving effect of bias corrections in other observations.

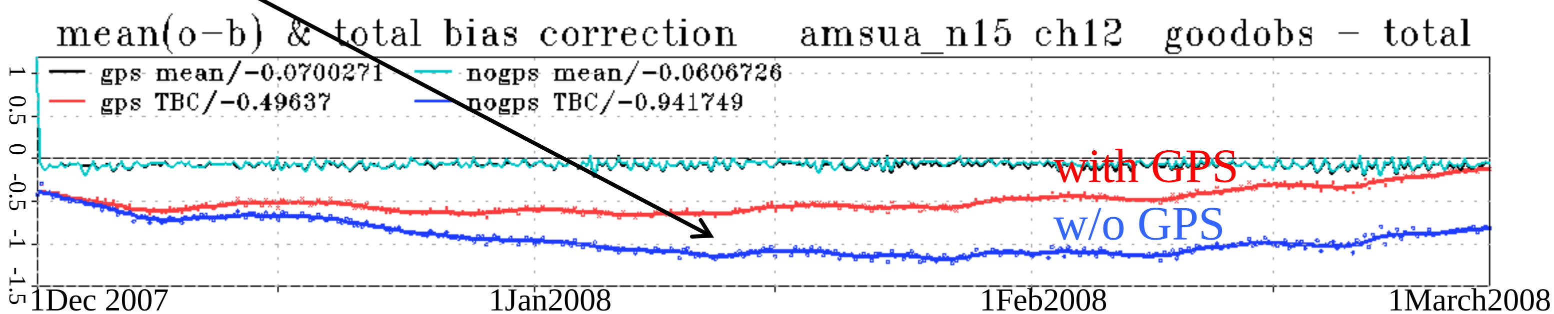
Bias Corrections in NCEP model AMSU-A NOAA-15, Channel 12 (~10 mb)

Temporal evolution of (o-b) without bias correction



Difference of ~ 0.5 K

Temporal evolution of the total bias correction



Cucurull, Anthes, and Tsao, 2014

Impact of Loss of Microwave and Radio Occultation Observations in Operational NWP in Support of the US Data Gap Mitigation Activities

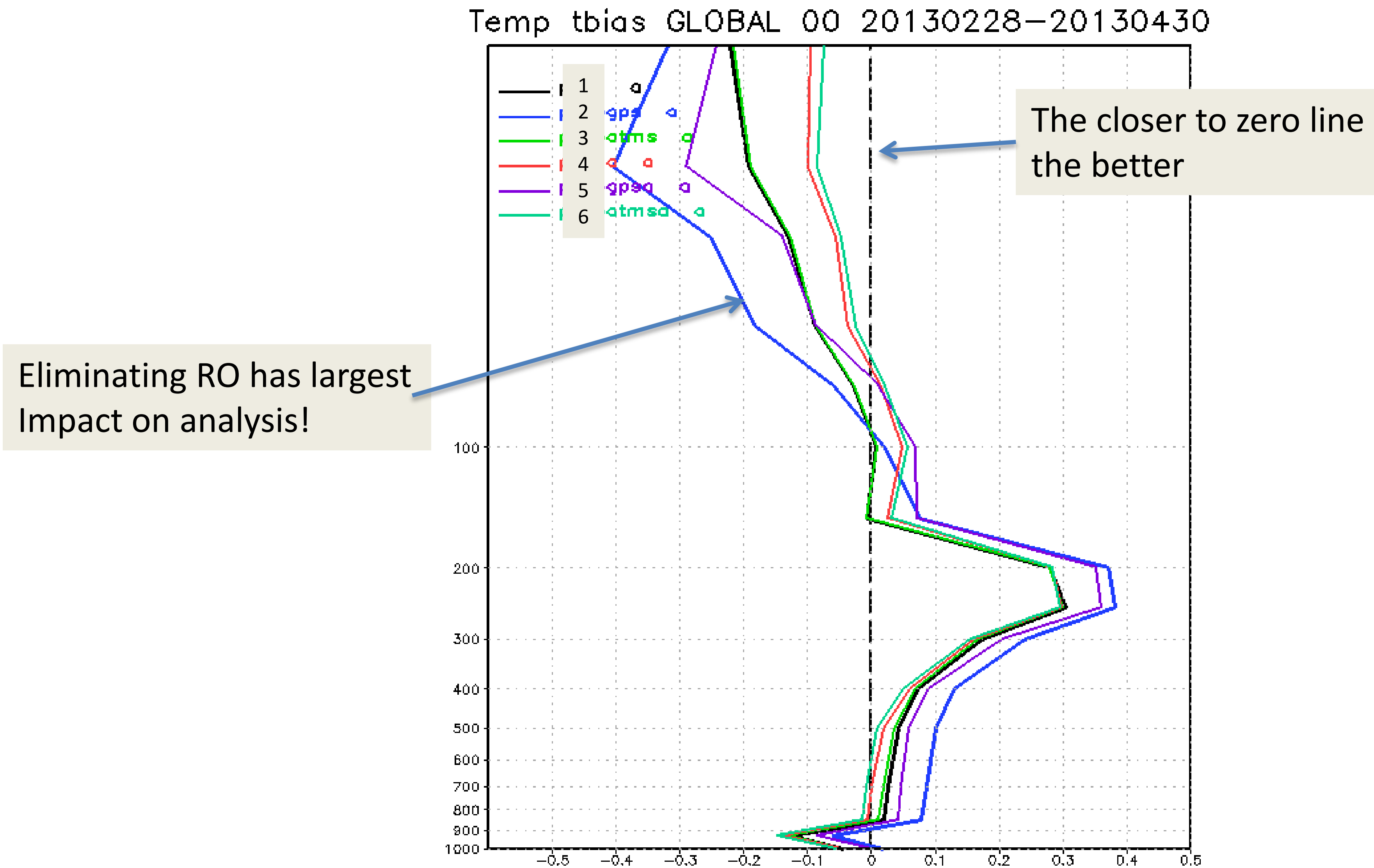
Six NCEP GFS forecast experiments March-April 2013

Experiment	Description
1 CTL	Control experiment, current operational NCEP's global data assimilation system.
2 noRO	Experiment CTL without RO observations
3 noATMS	Experiment CTL without ATMS observations
4 noAMSU	Experiment CTL without AMSUA/MHS on NOAA-18 and NOAA-19, AMSUA on Aqua, and AMSUA on NOAA-15.
5 ATMS- only	Experiment CTL without AMSU and RO
6 RO-only	Experiment CTL without AMSU and ATMS

ATMS: MW on SuomiNPP (700K observations per day)
AMSU: MW on NOAA-15,18,19 and AQUA (2,300K observations per day)
RO: COSMIC, METOP-A,B, Terra-SAR-X and GRACE-A (400K observations per day)

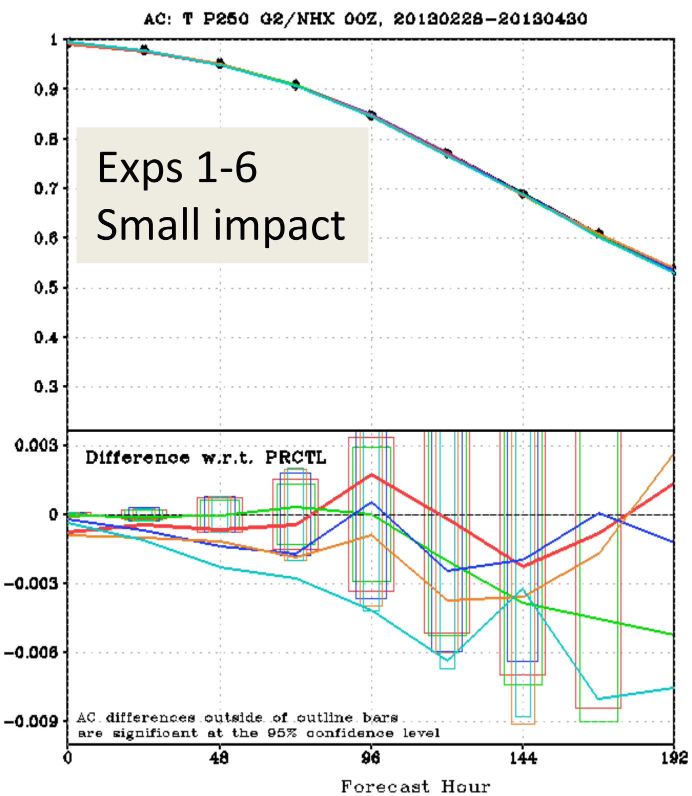
Cucurull and Anthes, 2014 (Paper in preparation)

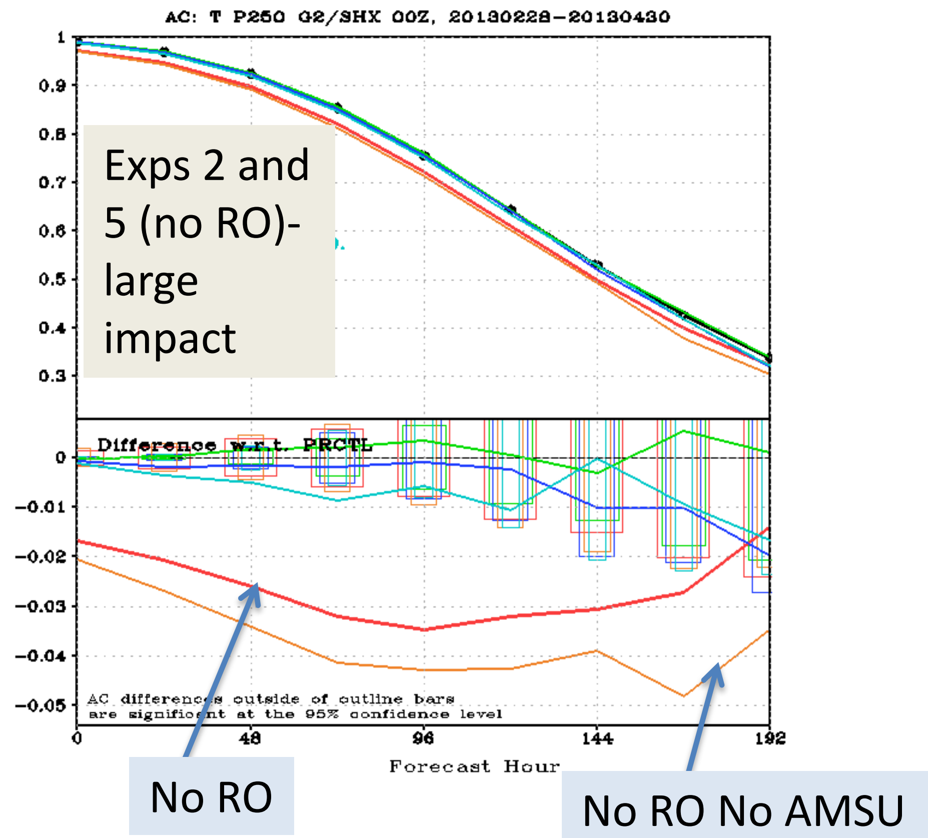
Analysis Fit to Radiosondes



Cucurull and Anthes, 2014 (Paper in preparation)

Loss of RO, ATMS, AMSU Impacts in NH and SH





Eliminating RO, ATMS, AMSU have no significant effect in NH

Eliminating RO has large impact in SH

Cucurull and Anthes, 2014 (Paper in preparation)

ECMWF Tech Memo #701, 2013

Four Experiments with ECMWF model (Jan-Feb and July-Sept 2011)

Baseline: All obs except ATOVS, HYPER and RO
RO only (~2,000 profiles per day)
ATOVS only (~230,000 profiles per day)
HYPER only (~60,000 profiles per day)

ATOVS: MW on NOAA-15,18,19, AQUA, METOP-A
HYPER: IR (AIRS on AQUA; IASI on METOP-A)
RO: COSMIC (5 sats) and METOP-A

Massimo Bonavita (ECMWF Tech. Memo 701, May 2013)

ECMWF Study Conclusion

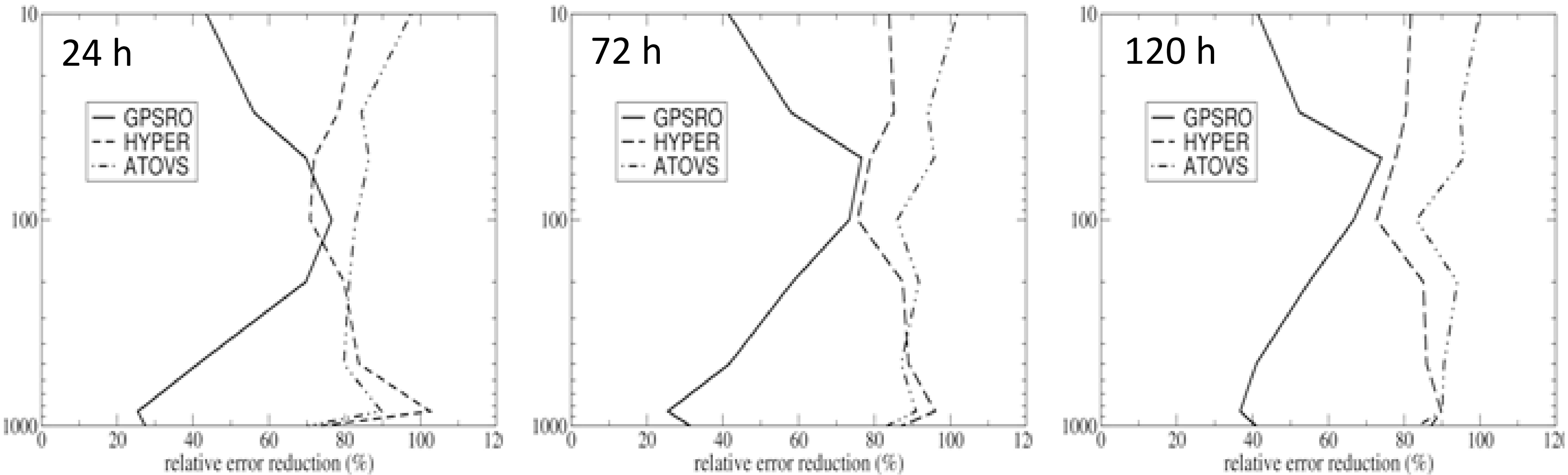
"The NWP forecast impact of GPSRO observations is compared with that of conventional (ATOVS) and hyperspectral satellite nadir sounders. It is found that while GPSRO data have a smaller impact than those of either class of nadir sounders, they are still able to account for a considerable fraction (30% to 70%) of the global forecast error reduction afforded by the use of the full observing system over a system which only uses conventional observations.

This is remarkable in view of the relative sparseness of the GPSRO spatial and temporal coverage and an indication of the potential improvements that a denser GPSRO observing network would be able to provide."

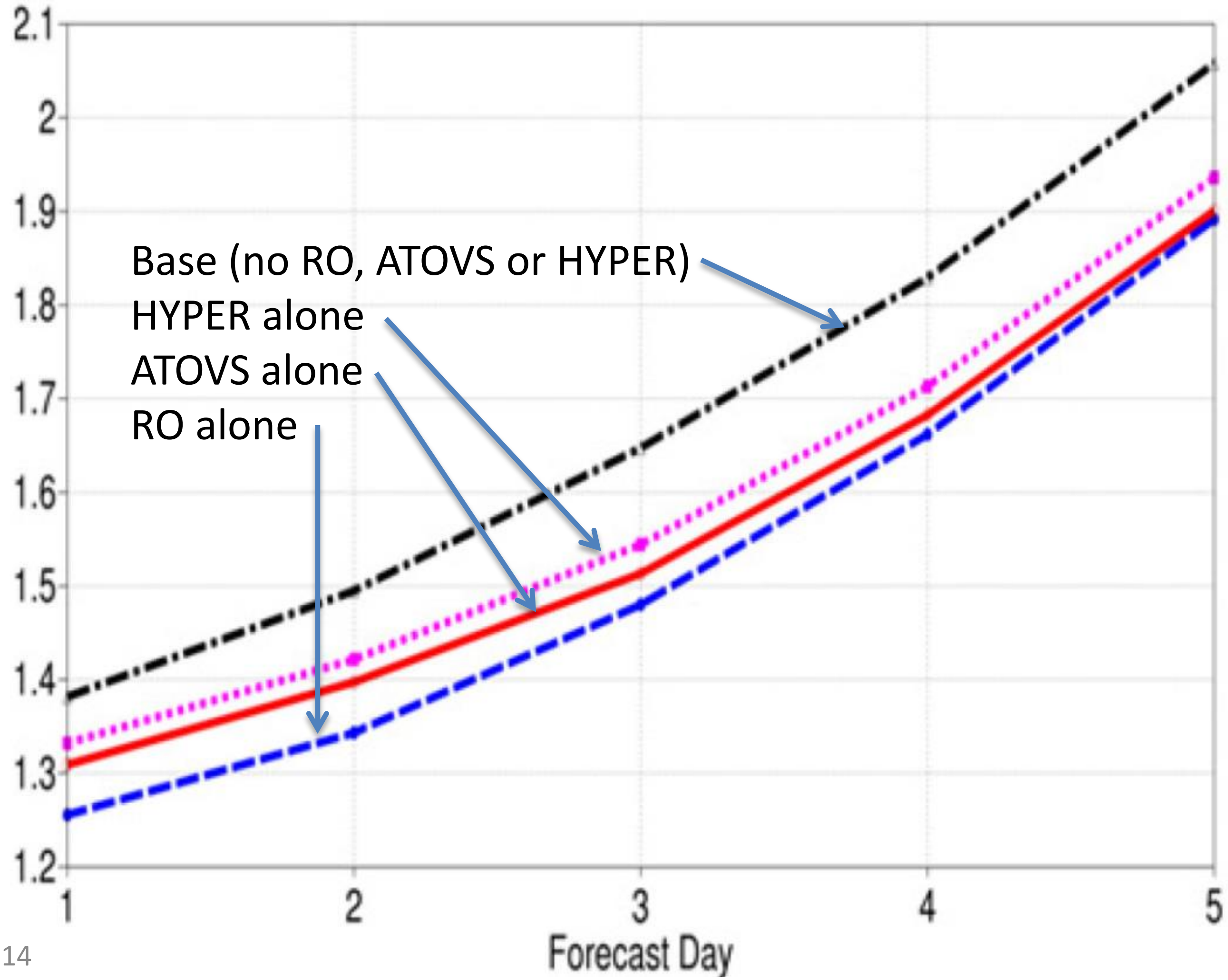
Massimo Bonavita (ECMWF Tech. Memo 701, May 2013)

Global % temperature error reduction from RO, HYPER and ATOVS at 24, 72 and 120 hours

RO alone provides 30-70% of total error reduction compared to Base (no satellite soundings at all)



RMS errors in temperature at 100 mb in four experiments. By this metric, RO is the most important system. (This is not true for all variables at all levels, but is shown to indicate the importance of RO, especially in the upper troposphere/lower stratosphere.)



Emerging RO Gap

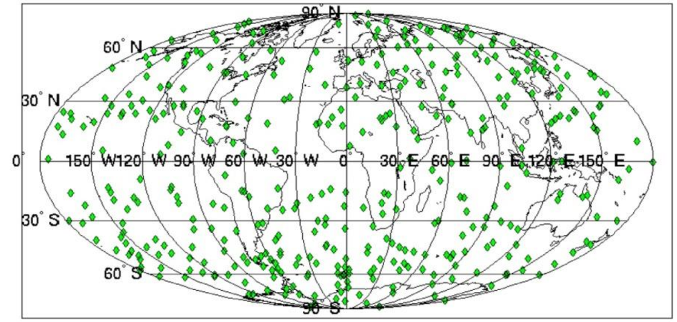
Operational RO missions	Soundings/day	Status
COSMIC-1	~12,000-15,000	Three years past nominal lifetime; Gradually degrading
METOP-A	~500	No soundings below 8 km
METOP-B	~500	No soundings below 8 km
COSMIC-2 Equatorial	~5,000	Launch in 2016
COSMIC-2 Polar	~5,000	Not completely funded Launch in 2018 or 2019

With COSMIC-2 Polar Constellation we will have good global coverage. Without C-2 Polar there will be a serious gap in middle and polar latitudes.

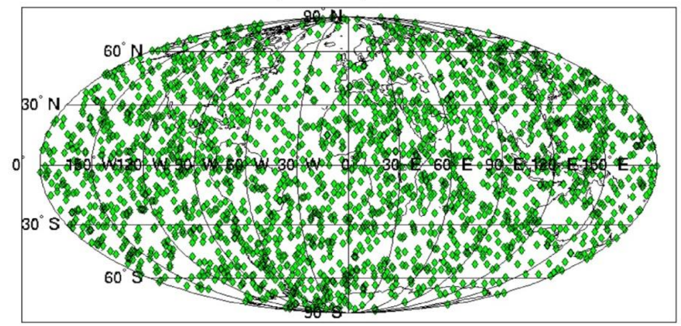
COSMIC-2

- Improved receiver and better antenna will improve data quality
- Many more soundings---10,000/day
- Greater impact on weather forecasts
- Improve hurricane forecasts by 25-50%
- Monitor rapidly changing pre-tornado environment
- Continue climate benchmark observations without gap
- Significant improvement in space weather observing and prediction

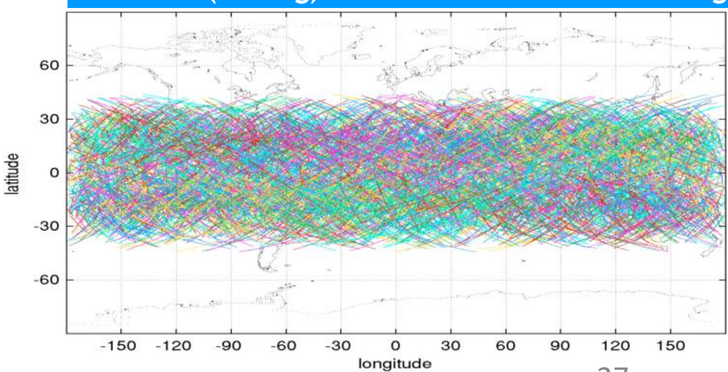
COSMIC Occultations-3 Hrs Coverage



COSMIC-2 Occultations - 3 Hrs Coverage



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



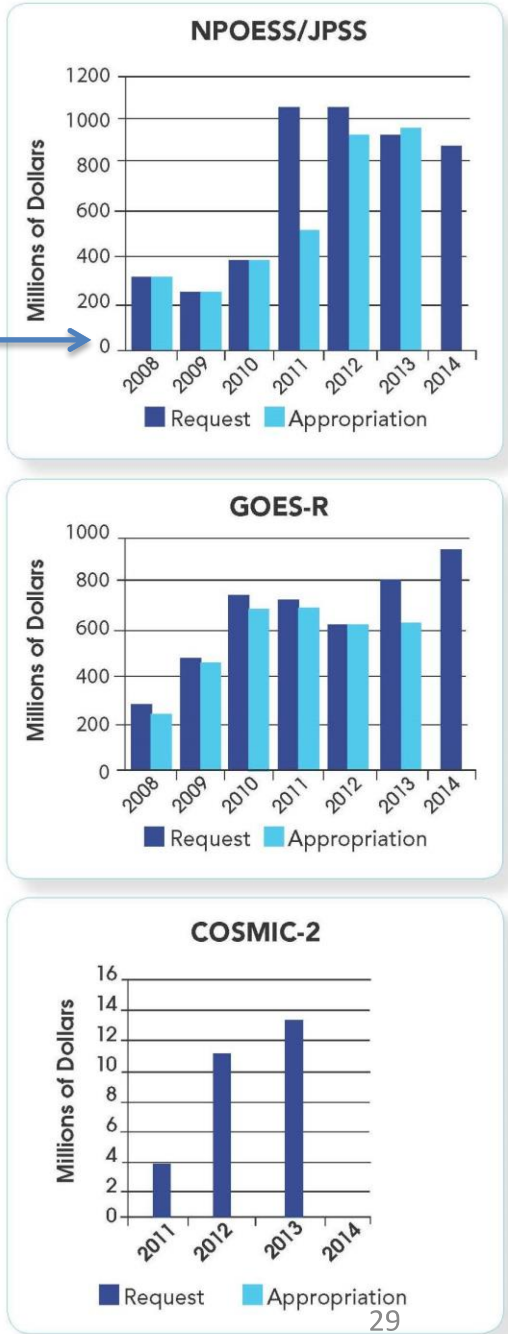
COSMIC-2 Summary

- 12 satellites with improved receivers, antenna
  - 6 launched into Equatorial orbit early 2016
  - 6 launched into polar orbit 2018 or 2019
- Total cost (10 years) ~$420M
  - Taiwan ~$210M
  - Air Force ~$140M
  - NOAA ~$70M
- UCAR Role
  - Program management support; liaison with Taiwan
  - Mission science, engineering and TAA/export support
  - Data processing, analysis, distribution

Comparison of COSMIC-2 costs with other Satellites

COSMIC-2

FIGURE 5: NPOESS/JPSS, GOES and COSMIC-2 Budgets



Source: NOAA Blue Books for Fiscal Years 2008-2014

Total JPSS life cycle (20 years) costs through 2028 ~ $17B or ~$850M/year.

COSMIC life cycle costs $420M over 15 years or ~$28M/year. Cost to U.S. half ($210M total or $14M/year)

Weather disasters cost US more than $100 billion in 2012 alone.

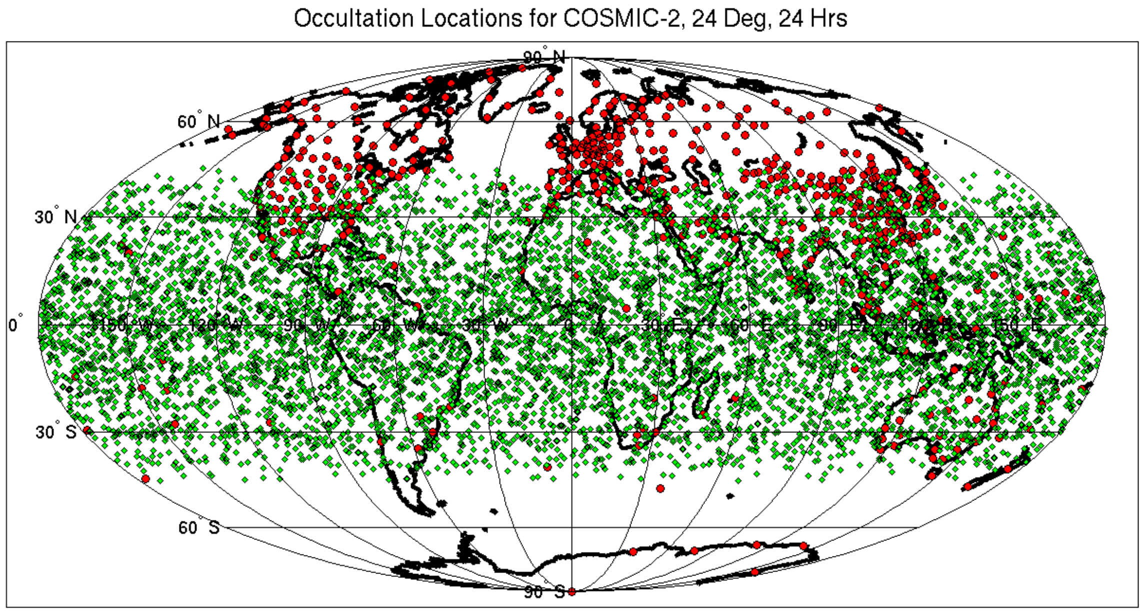
Source: Space Foundation, July 2013: Weather Satellites-Critical Technology in an Uncertain Environment.

COSMIC-2 Funding History

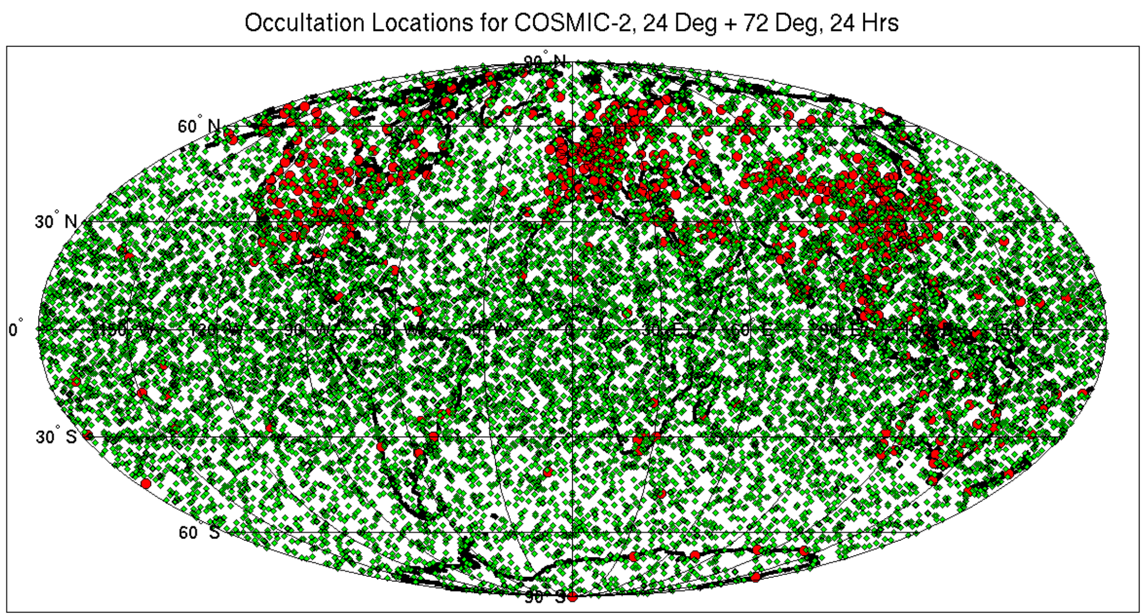
- Taiwan has had $210M in hand since 2011
- NOAA had COSMIC-2 in President's budget for FY10 and FY11, but Congress did not approve
- Air Force came to partial rescue in FY12
- NOAA has COSMIC-2 start at $2M in FY14 budget
- NOAA President's Request for FY15 $6.8M
- Taiwan Congress has suspended ~$100M for 2nd launch pending NOAA FY-15 budget and AF funding for 2nd launch sensors.

Importance of C-2 Second Launch

1st Launch 2016



With 2nd launch 2018 or 2019



Second Launch Funding (UCAR internal estimates)

- 2nd launch (polar) of COSMIC-2 is very important to US – 1ST launch is primarily tropical coverage
- USAF needs $20M more to purchase instruments plus ~$17M for integration and instrument support for a total of $37M
- Amount of money needed by NOAA to finish 2nd launch ~$10M over NOAA first launch requirement of ~$60M for a total of ~$70M

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 NCEP and all major international weather centers
- Large impact on hurricane forecasts
- With COSMIC-2, an even greater impact is expected.

Summary

- RO adds to the value of IR and MW soundings by adding accurate and precise independent information and improving the effect of their bias corrections
- Therefore balanced system of IR, MW and RO is most efficient and cost effective
- RO is an inexpensive, powerful ‘gap filler’ if afternoon orbits of IR or MW are lost
- More importantly, the possible gap in RO observations would have larger impact than an IR or MW gap
- Full implementation of COSMIC-2 is highly cost effective and would have many benefits in addition to mitigating IR and MW gap.