The Significant Roles of COSMIC2 GNSS RO in NOAA Integrated Calibration/Validation System for NWP

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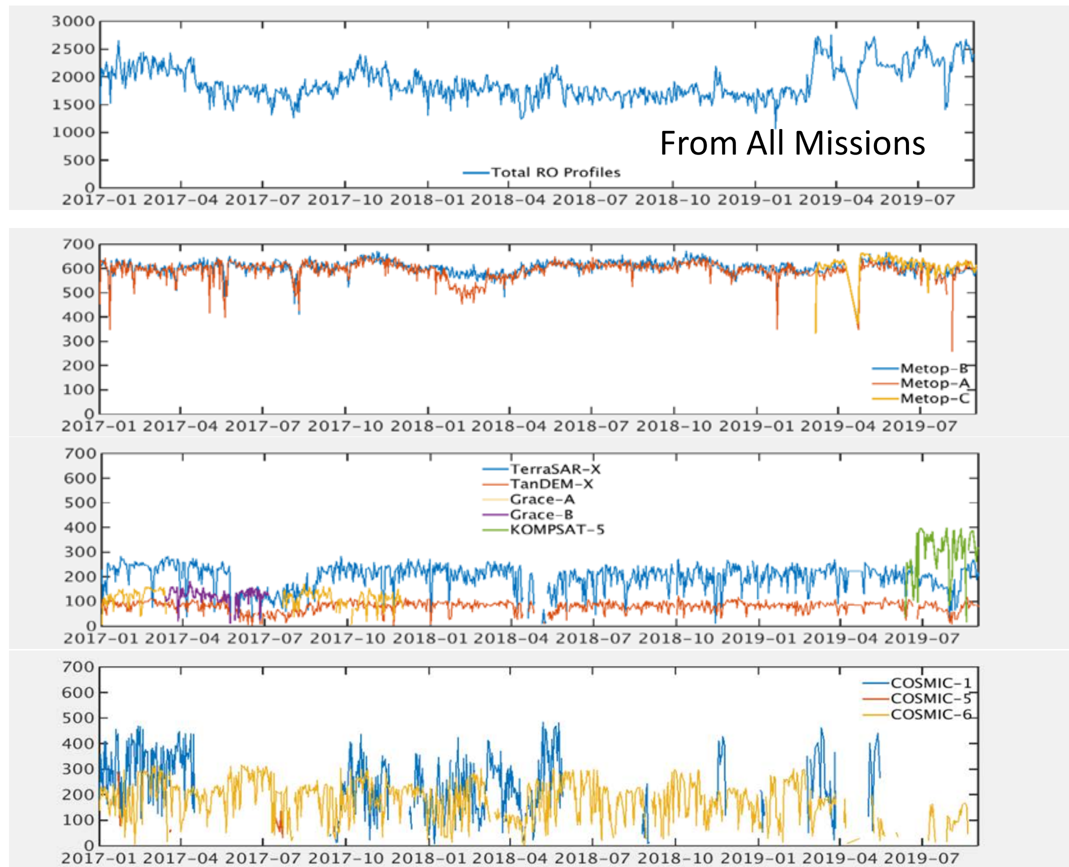
Operational Ready GNSS RO data for NOAA NWP

- Currently ~2500 RO profiles are available daily for operations
- COSMIC2 will produce > 4000 profiles daily
- Metop A/B/C ~600 each
- KOMPSAT-5 ~400 daily
- Smaller amounts from other missions
- Declining number of profiles from COSMIC1
- PAZ not yet used
- CWDP not yet used

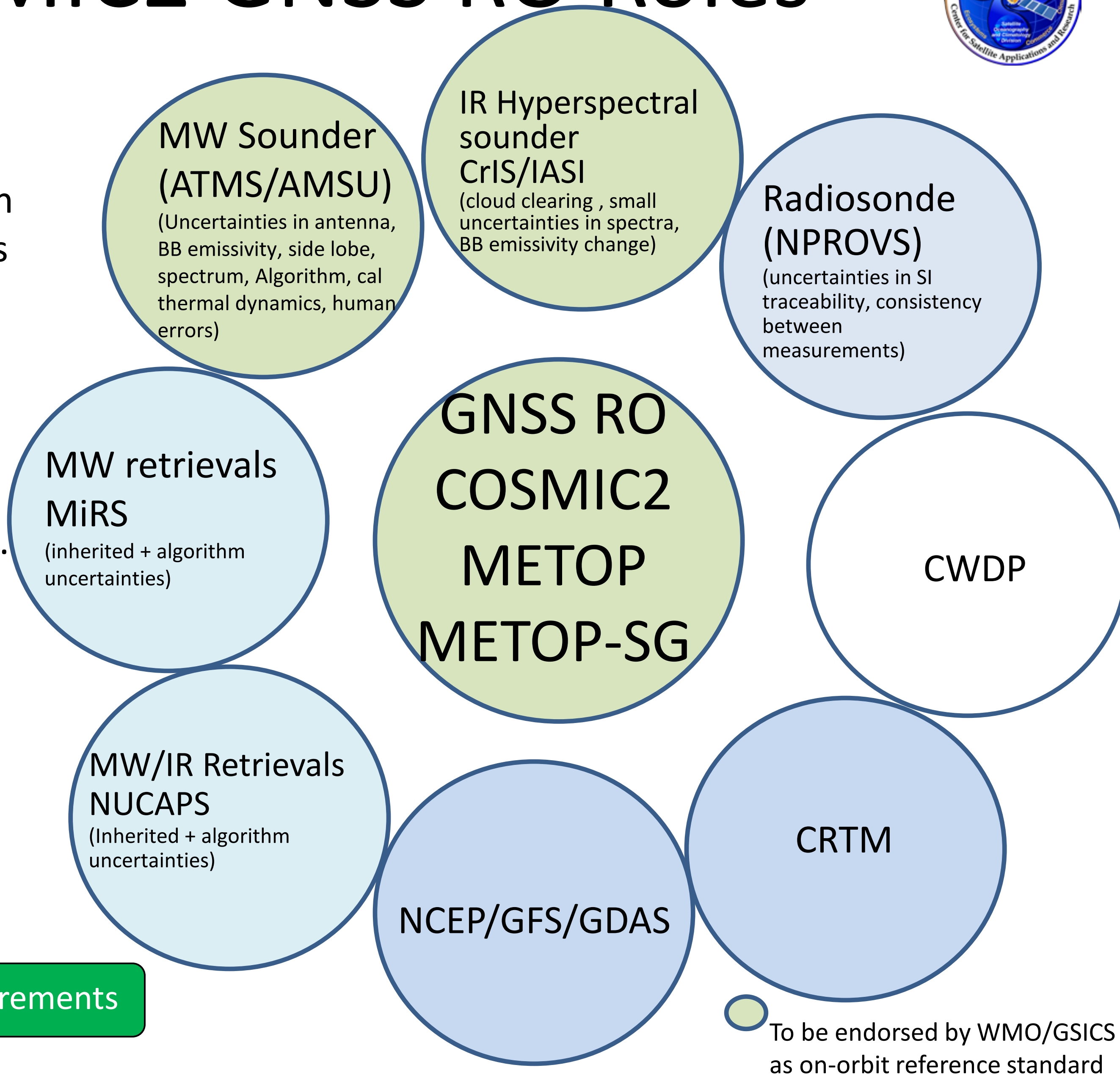


Daily RO Profiles in GDAS, 01/2017 to 09/2019

Much awaited COSMIC2 GNSS Radio Occultation for NWP

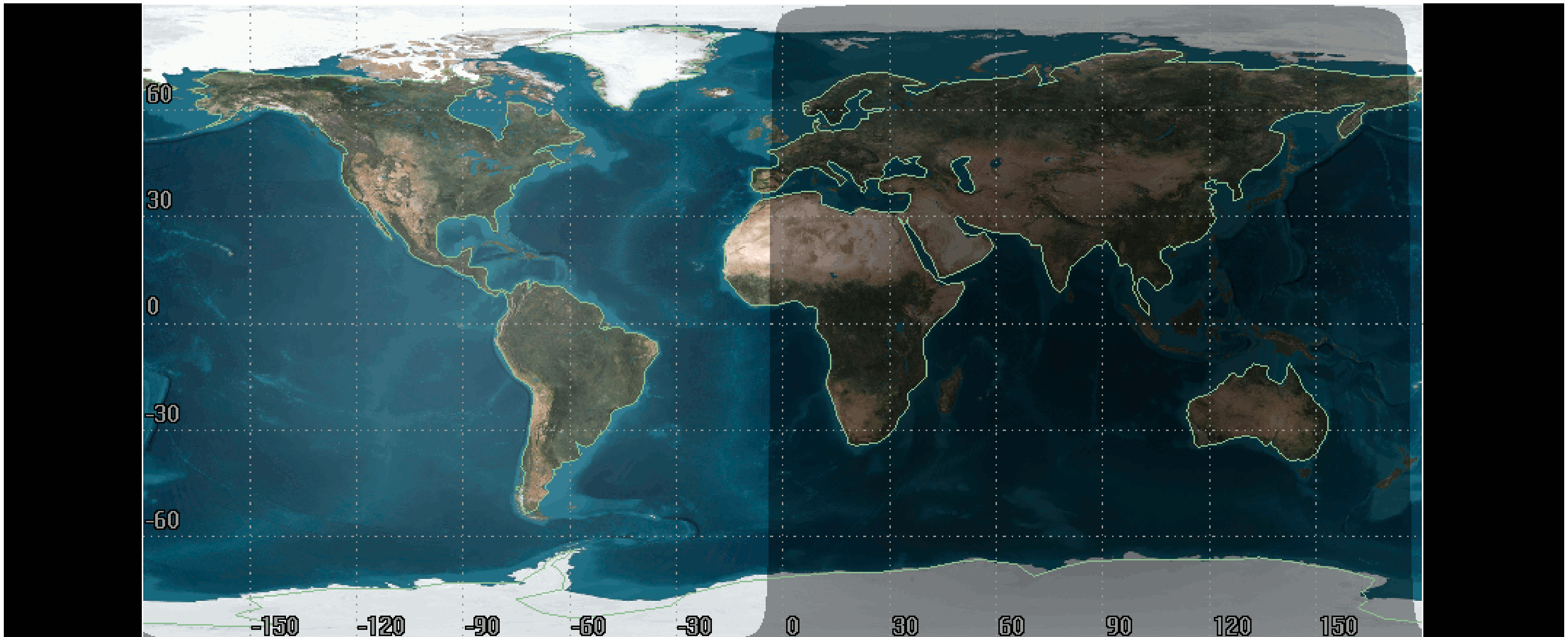
COSMIC2 GNSS RO Roles

- The success of COSMIC2 ushers in a new era of RO for operational NWP, which will have profound impacts on all activities related to atmospheric sounding.
- NOAA is strengthening support for COSMIC2, recognizing its significance.
- COSMIC2, together with Metop RO, is expected to become an on-orbit reference for atmospheric sounding, establishing consistency for all measurements.



The COSMIC2 “**anchor**” measurements

On-orbit Reference for All RO Missions

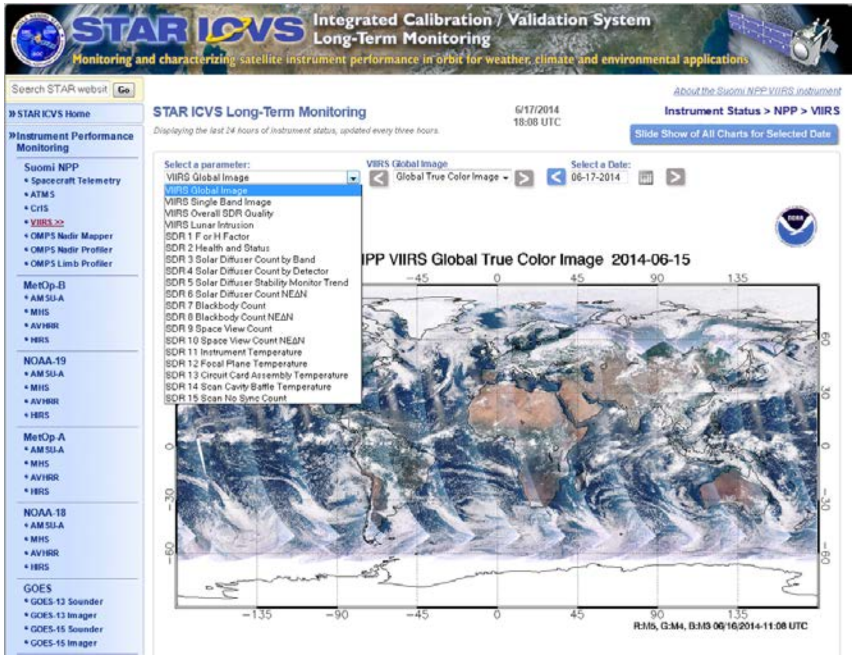


CWDP (Commercial Weather Data Pilot) is coming

COSMIC2, together with Metop, will provide important reference for all RO measurements, from complex missions to simple experiments

Background- NOAA Integrated Calibration/ Validation System (ICVS)

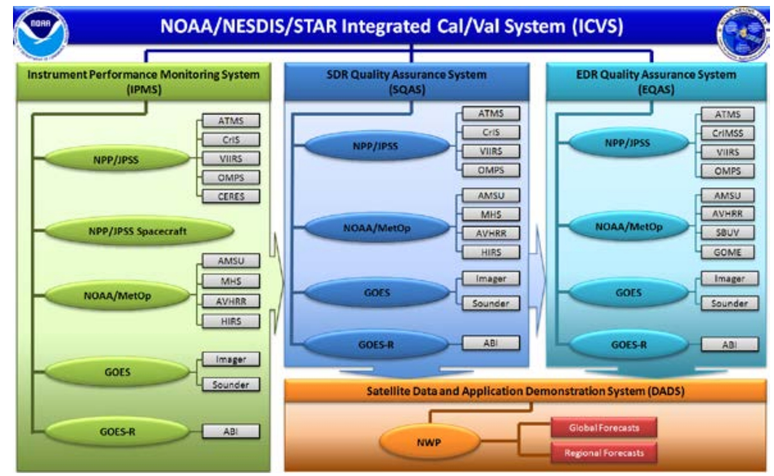
- The development of the current version of ICVS started in 2011 for Suomi NPP launch, with continuous improvements
- Monitors ~30 instruments on eight NOAA Polar orbiting Satellites, and ABI on 2 geostationary satellites
- Monitoring includes spacecraft diary, ACDS, instrument calibration related parameters
- Monitors **4594** parameters for JPSS satellite instruments , of which 927 for ATMS, 1495 for CrIS, 1143 for VIIRS, and 843 for OMPS.
- A total of **2457** parameters for all other POES Satellites, including NOAA instruments on Metop A/B/C.
- Users include NWP centers, instrument scientists, program managers, other data users.



ICVS monitors all NOAA satellites and instruments, with ~7000 parameters updated daily on the web

Background- Integrated Calibration/Validation System (ICVS)

- Near real-time performance monitoring for all NOAA environmental satellites and instruments
- Benefits:
  - ➢ Near real time and long term instrument status, performance monitoring, and anomaly diagnosis
  - ➢ Near real time and long term level 1 data product quality monitoring
  - ➢ Provide real time support for sensor calibration activities
  - ➢ Provide rapid and preliminary estimate of satellite data impact in NWP applications
  - ➢ Ensure the integrity of the climate data records from all satellite instruments

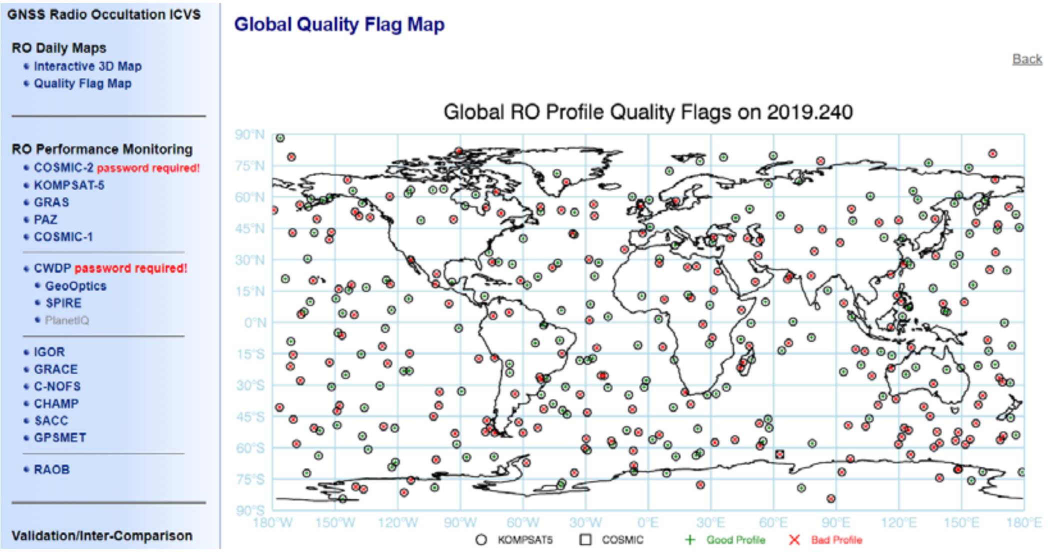


- Inter-calibration with a constellation of international satellites in conjunction with the Global Space-based Inter-calibration system (GSICS)

Make satellite observations intercomparable and tied to international standards for weather, climate, ocean and other environmental applications

GNSS RO ICVS Extension

- GNSS radio occultation (RO) has been recognized as a key observable for Numerical Weather Prediction (NWP) and climate change detection.
- It has matured to become an important, sustained component of NOAA satellite observations and contributor to NWP, complementing microwave and infrared sounding measurements.

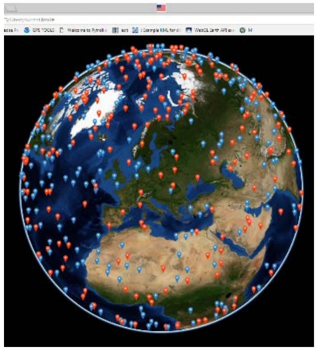


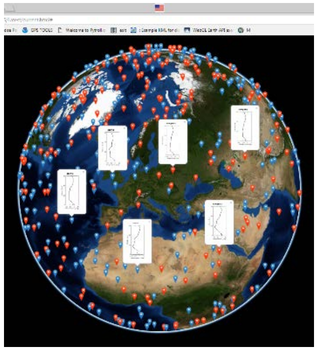
- The successful launch of FORMOSAT-7/COSMIC-2 marks the transition of GNSS RO from research to operations for weather forecast.
- It is important to ensure the consistency, accuracy, precision of the measurements with well understood uncertainties.

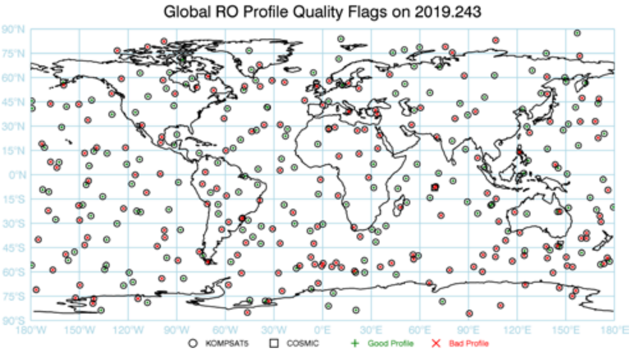
GNSS RO ICVS is a natural extension of the NOAA ICVS system, with more dynamic and interactive capabilities

GNSS RO Integrated Cal/Val System (ICVS)

- GNSSRO ICVS with a web interface to support all RO missions including COSMIC-2, KOMPSAT5, and CWDP. The system includes:
  - Monitoring RO product parameters and instrument performance at all levels.
  - Routine comparison of atmospheric profiles with other satellite observations and retrievals including microwave, and infrared.
  - Routine comparison of profiles with those from Radiosondes.
  - Dynamic web interface with many capabilities.
  - Long-term monitoring of the parameters.

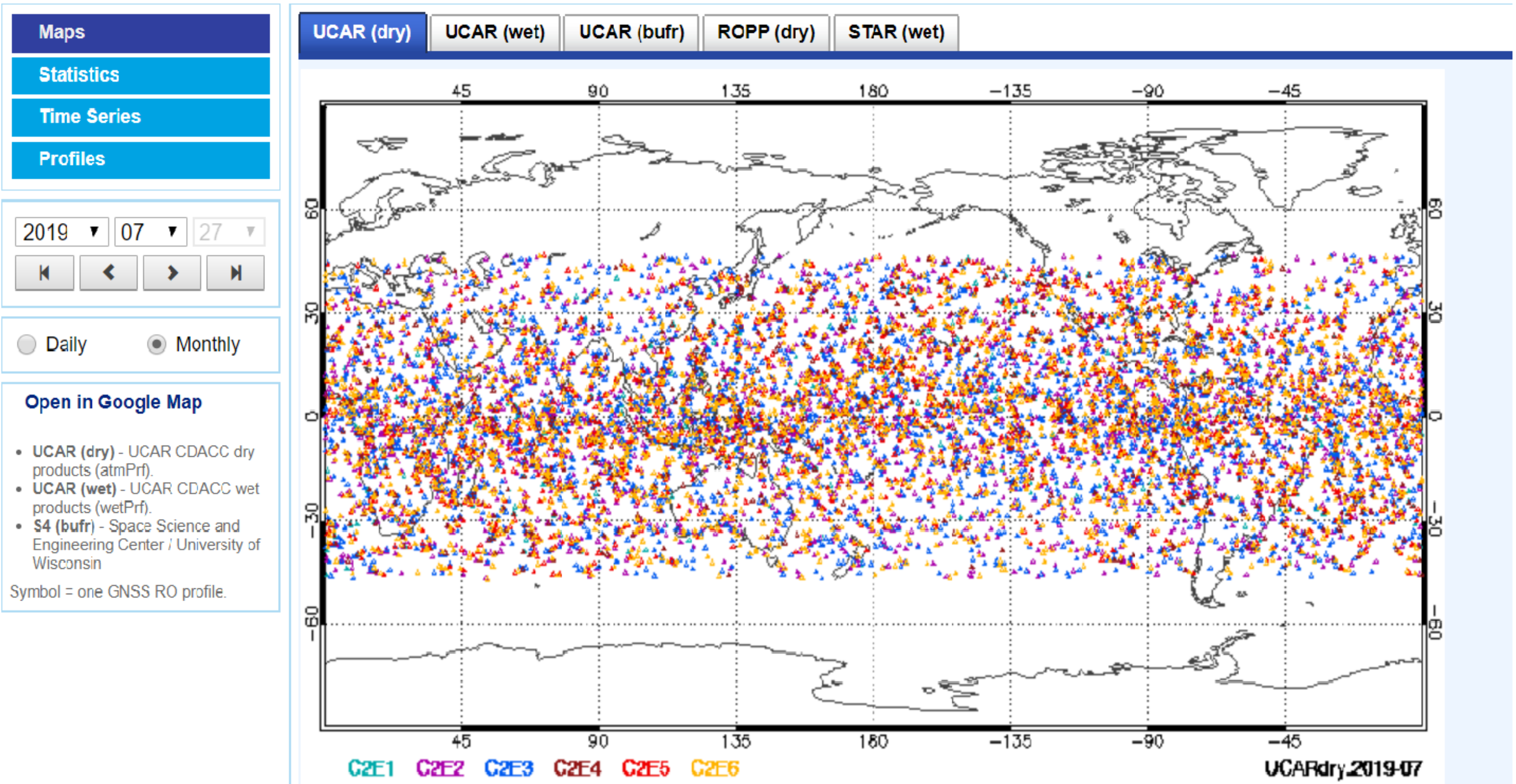






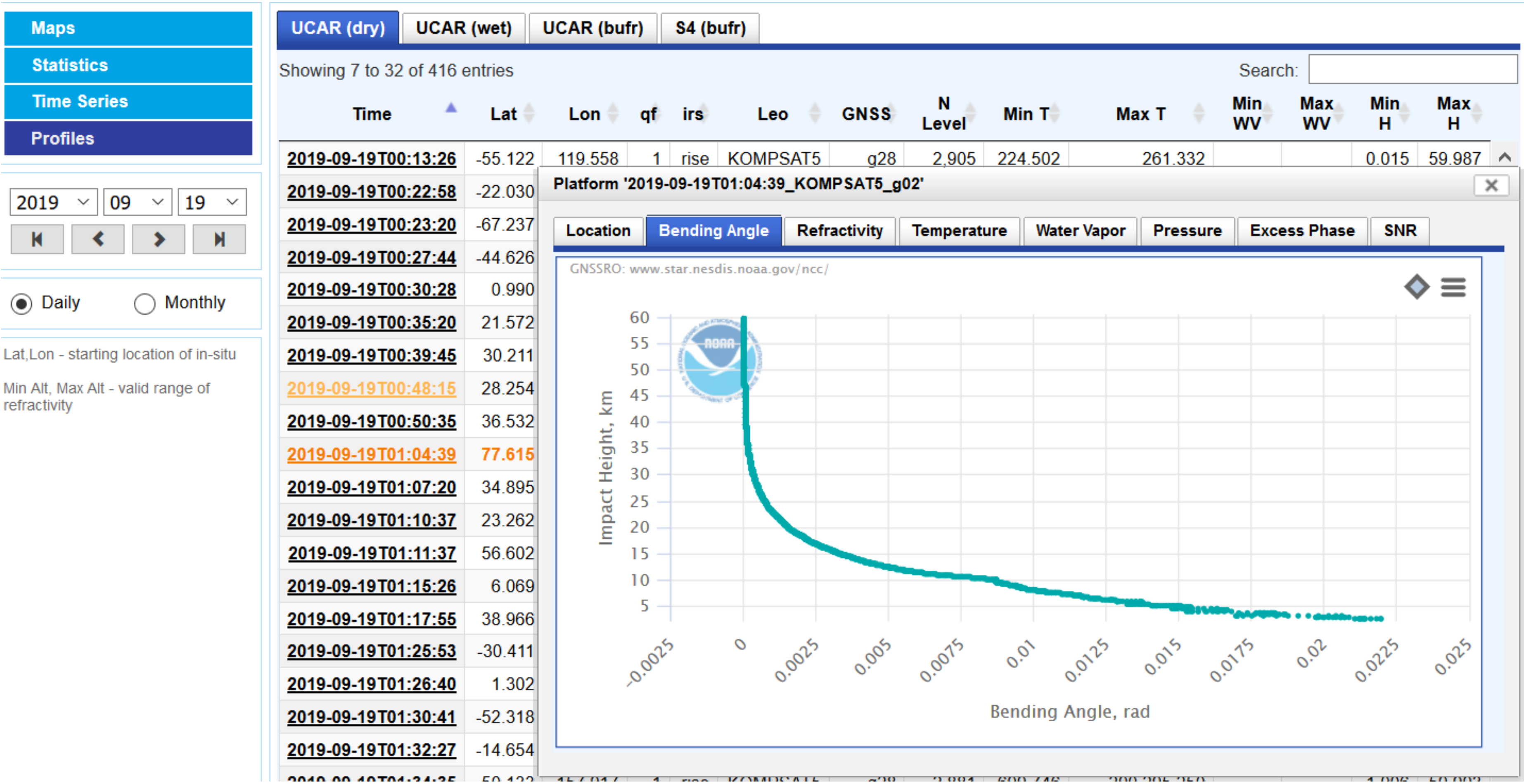
System updated daily on the web; will be available for everyone to use

Early COSMIC2 Data



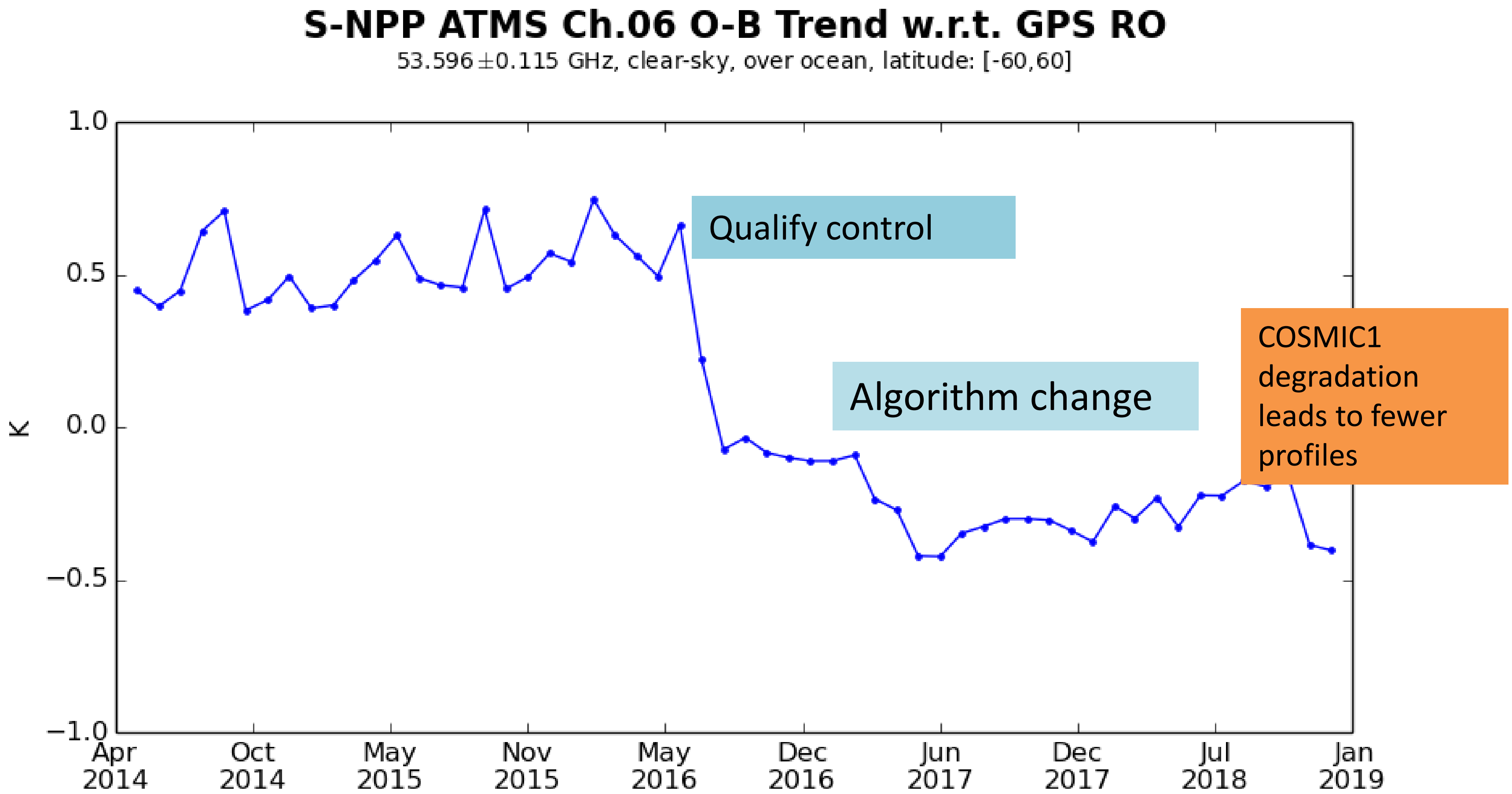
Launched on 6/25/2019, started producing data a few weeks later

GNSS RO ICVS Data Quality Monitoring



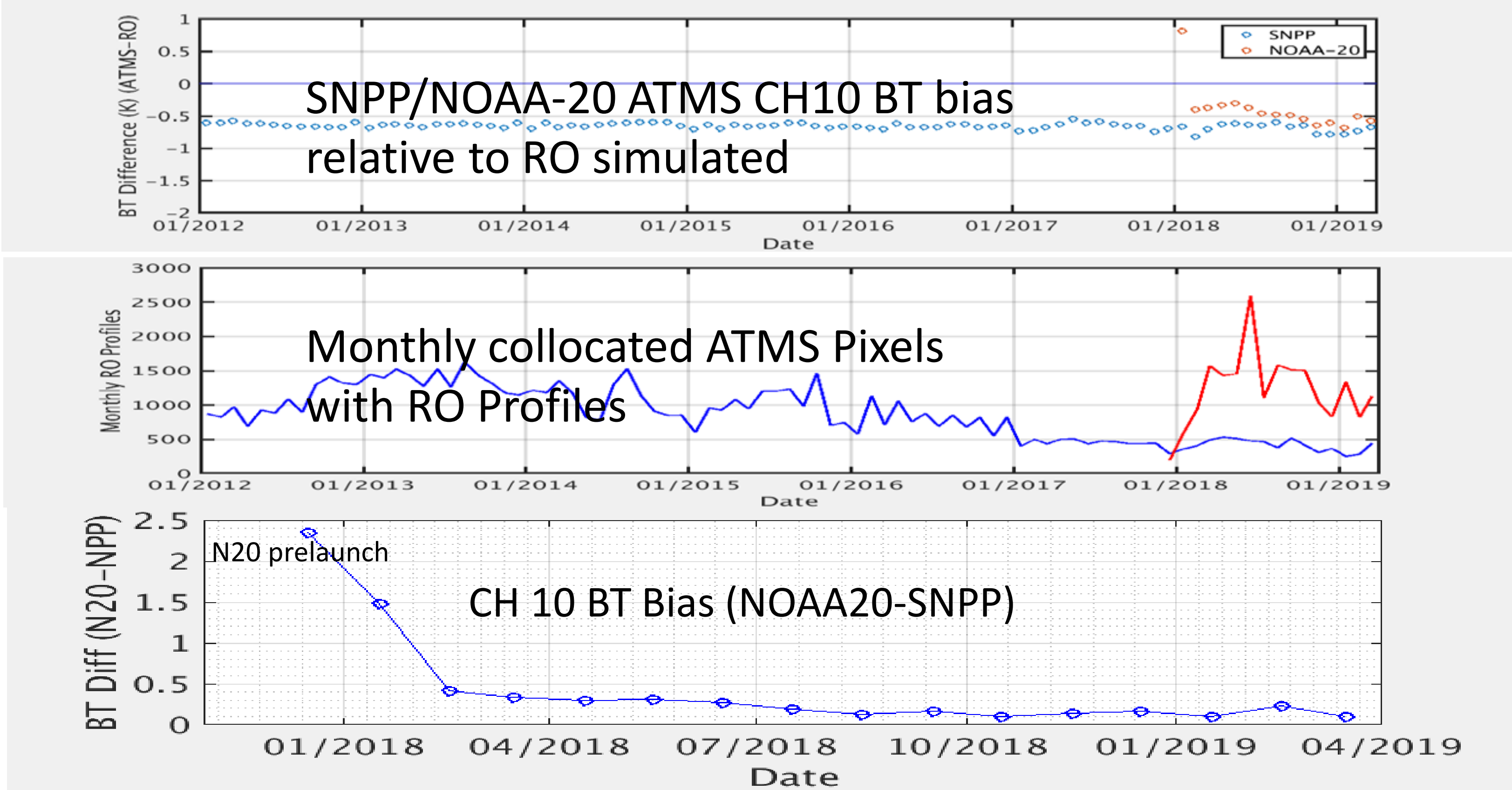
All available parameters are monitored with interactive functions (sample bending angle shown here)

Comparisons between ATMS Ch6 and GPS RO



Bias between ATMS and RO are routinely monitored; anomalies are investigated

Comparisons with SNPP/NOAA-20 ATMS



- Comparison with ATMS on SNPP/NOAA-20 reveals calibration anomalies
- NOAA-20/ATMS early orbit bias due to calibration issues
- Use RO-CRTM for double differencing to study biases between ATMS on SNPP and NOAA-20 (ROM SAF RO CDR/ICDR used for analysis)

ATMS Intersatellite comparison using RO for double differencing

Infrared Sounder Calibration Traceability

Both GNSS Radio Occultation (RO) and hyperspectral infrared sounder (NOAA-20/CrIS) measurements are accurate, stable, and SI traceable (Time or Atomic Frequency Standard (AFS) vs. Radiance Standard, respectively)

NIST Blackbody
(w/ NIST traceable PRTs)

→

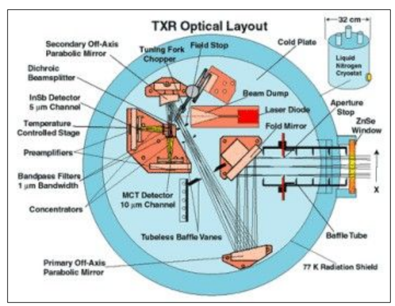
TXR
(transfer radiometer)

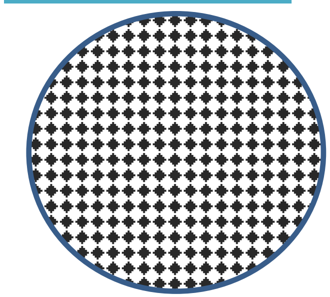
→

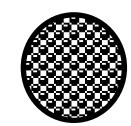
External Blackbody at Vendor Laboratory

→

Onboard Blackbody on CrIS







Source: NIST https://www.nist.gov/laboratories/tools-instruments/thermal-infrared-transfer-radiometer-txr

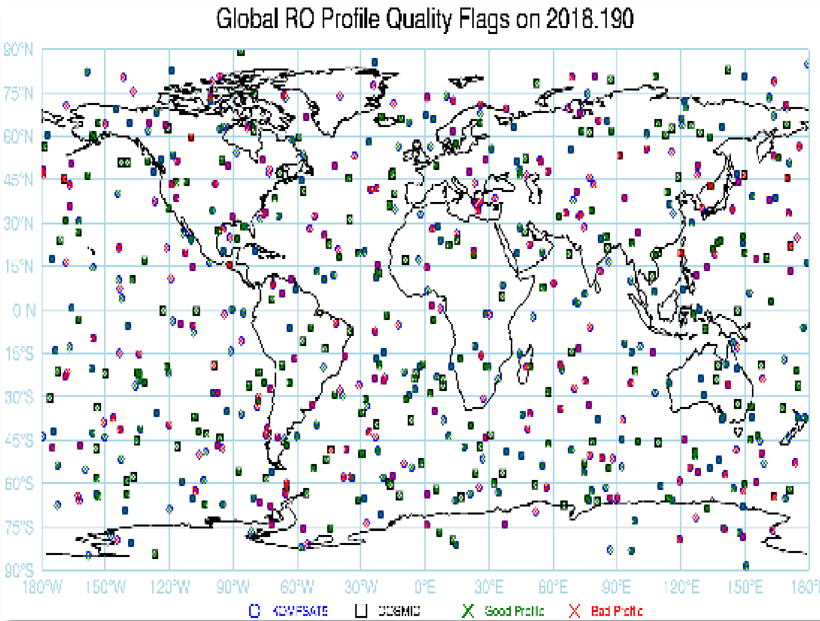
Infrared Sounders have a long chain of traceability compared to RO

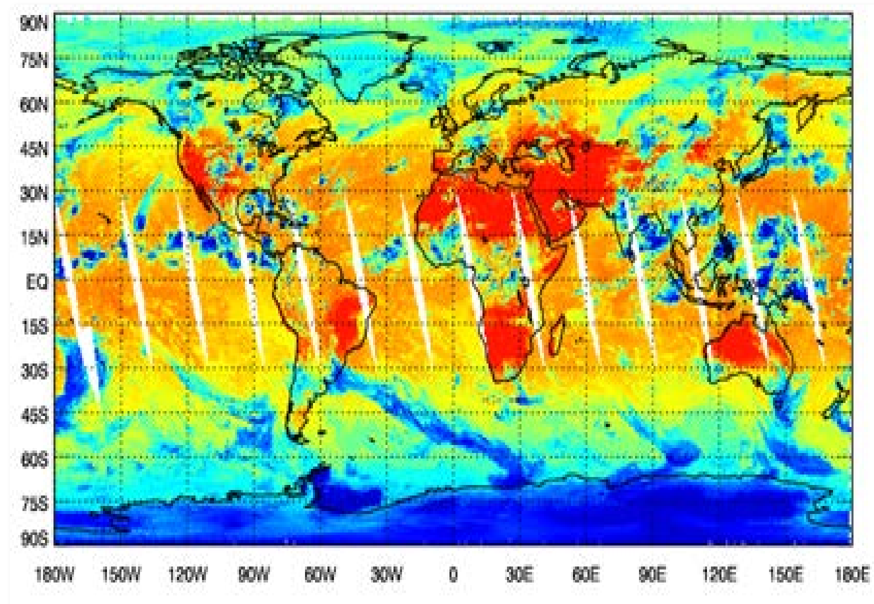
Caveats in Comparing RO and IR sounding

- Effects of cloud for IR sounders (clear sky hard to find)
- Time difference can be **several hours**
- Colocation uncertainties: point/line integral in RO, vs. pixel in IR
- Active limb sounding in RO vs. nadir sounding in IR
- Samples: a few hundred ROs per satellite per day vs. full global coverage twice daily
- RO uncertainties in the upper atmosphere due to small bending angle
- RO Low troposphere uncertainties due to water vapor, SNR, turbulence, multipath

Comparing RO and IR observations is challenging which leads to large uncertainties in studies

Spatial Characteristics of RO vs. IR sounding



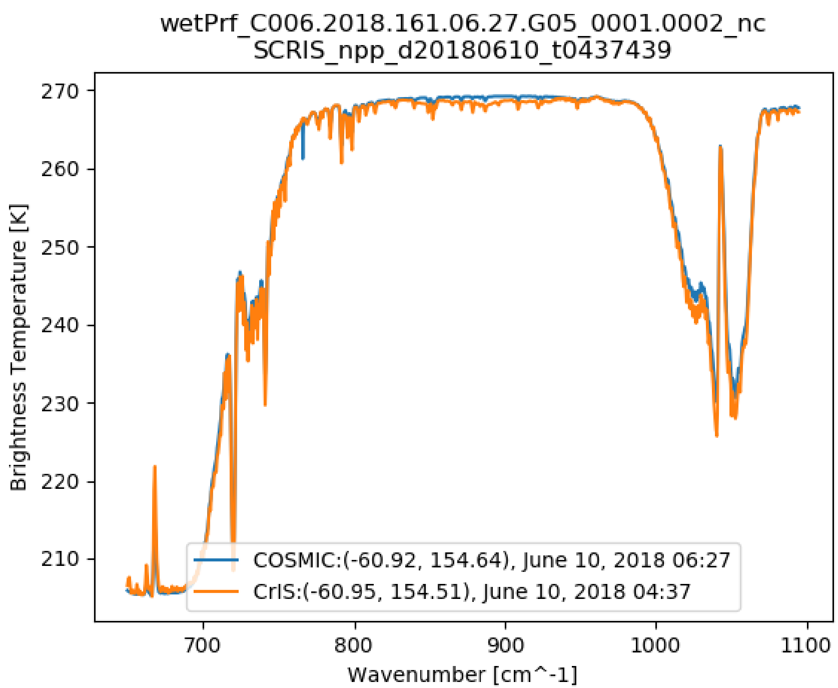


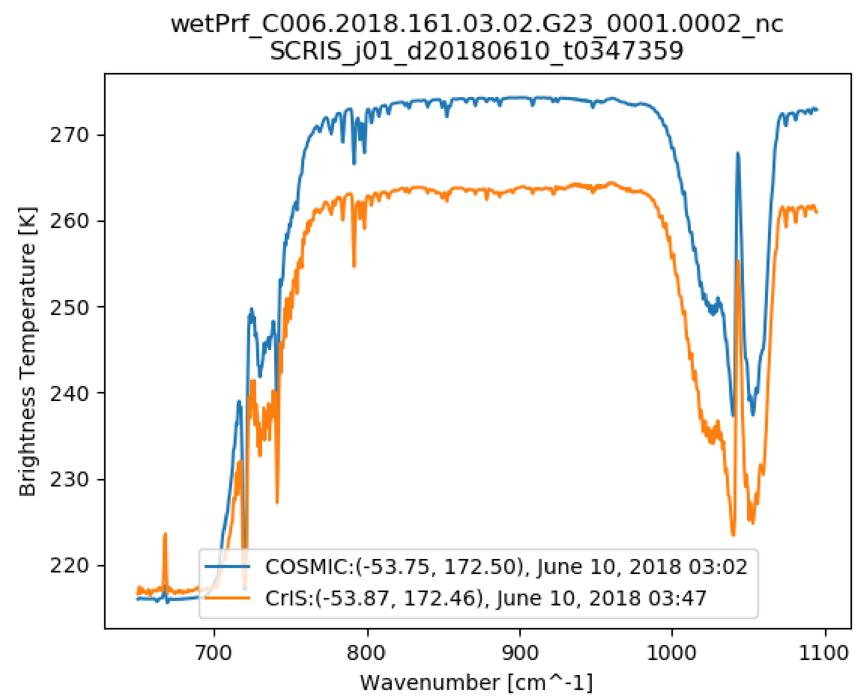
GNSS RO are point measurements (or line integrals over up to 250km ground track); a few hundred points per day globally for each satellite; a single measurement parameter

Infrared sounder has global coverage twice daily; simultaneous measurement of temperature, water vapor, ozone, trace gas.

Comparison is not straight forward

Comparison of COSMIC1 RO and CrIS Brightness Temperatures



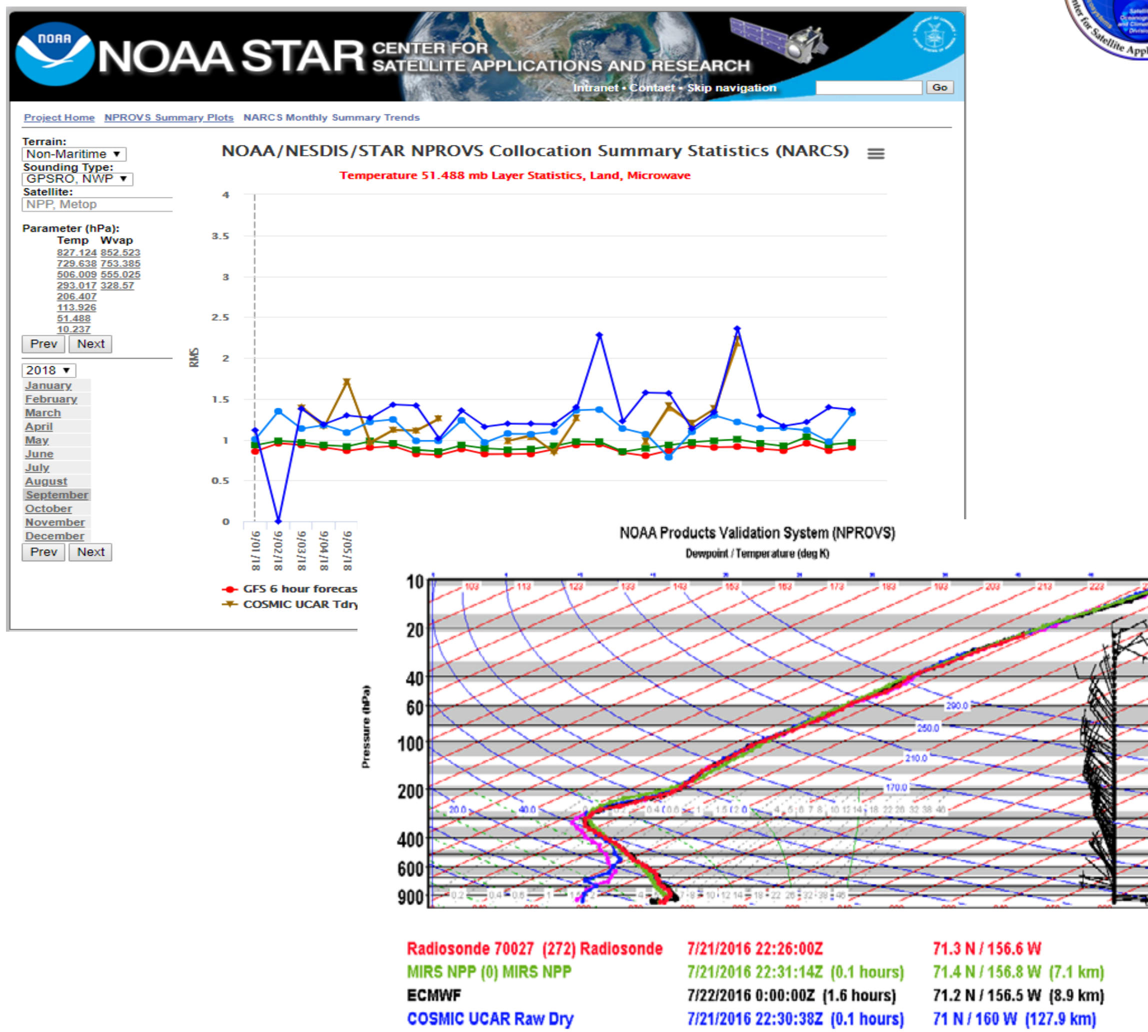


Major challenges: Spatial matching; clear sky; time difference

Some data matched well, but others didn't due to complex issues; not all issues are due to measurements

Cross Comparison with Radiosonde

- Well established system for atmospheric sounding product validation (NPROVS)
- Comparisons involves radiosondes, ECMWF, GFS, COSMIC, GRAS, and Microwave retrievals (MiRS).



Courtesy of Sun & Reale

Leveraging the NOAA NPROVS system for validation

NOAA/STAR GNSS RO Capability Development

Data Assimilation

Data Assimilation

- Non-local Bending Angle (Ray-tracing)
- Local Bending Angle (Forward Abel)
- Local Refractivity

As JCSDA partners, STAR and NCEP work closely to perform impact assessment

Multi-sensor Validation

Validation

- Radiosonde (NPROVS)
- Microwave Sounders ATMS, AMSU-A
- Infrared Sounders CrIS, AIRS, IASI
- Retrievals (temperature, water vapor)
- ECMWF model

Well established NOAA system ICVS and NPROVS for sounding validation

Integrated Cal/Val System (ICVS) for Monitoring

Performance Monitoring

- Operational monitoring
- RO measurements
- Parameters for all RO data levels
- Statistics
- Long-term monitoring

Well established system for all NOAA satellites expanded to include RO

RO Data Processing

Independent Verification

- Telemetry (RDR, L0)
- Excess phase (SDR, L1a)
- POD (SDR, L1a)
- Bending angle (SDR, L1b)
- Impact parameter (SDR, L1b)
- Refractivity (EDR, L2a)
- Geometric height (EDR, L2a)
- Temperature, water vapor, pressure (EDR, L2b-c)

L0->L1 experimental

L1->L2 using ROPP + STAR in house

RDR – Raw Data Record; **SDR** – Sensor Data Record; **EDR** – Environmental Data Record

ICVS for COSMIC2 is a critical tool for data quality assurance at all levels

Conclusion

- NOAA STAR has developed a comprehensive integrated cal/val system (ICVS) to ensure the data quality of all NOAA satellite measurements, including Radio Occultation, for which COSMIC2 will play an important role in many areas.
- This web-based system supports instrument performance monitoring, inter-comparisons with other independent measurements, and data assimilation in collaboration with data users.
- The system is supported by subject matter experts with deep dive analysis on the fundamental measurements, leveraging expertise in all remote sensing measurement techniques, and related traceability/standards.
- Radio occultation is becoming increasingly important for numerical weather prediction, which requires similar level of support as for microwave and infrared sounding instruments.
- The next step is to develop low level processing capabilities & incorporate it in ICVS (Level 0/RDR->Level 1/SDR->Level 2/EDR) to support full chain processing validation.

Acknowledgements

- Thanks to the COSMIC2 team for the hard work, including NSPO, UCAR, NOAA/NESDIS/OPPA, NOAA/NESDIS/STAR, JCSDA, USAF, and others
- Thanks to EUMETSAT, ROM SAF for collaboration and technical assistance
- Special thanks to Rich Ullman of NOAA/NESDIS/OPPA for initiating the COSMIC2 cal/val project at STAR