FORMOSAT-7/COSMIC-2 Mission Status and Initial Results

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ROM-SAF IROWG Workshop
Helsingør, Denmark

September 19, 2019

NSPO

NOAA

NASA

NSF

UCAR
UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

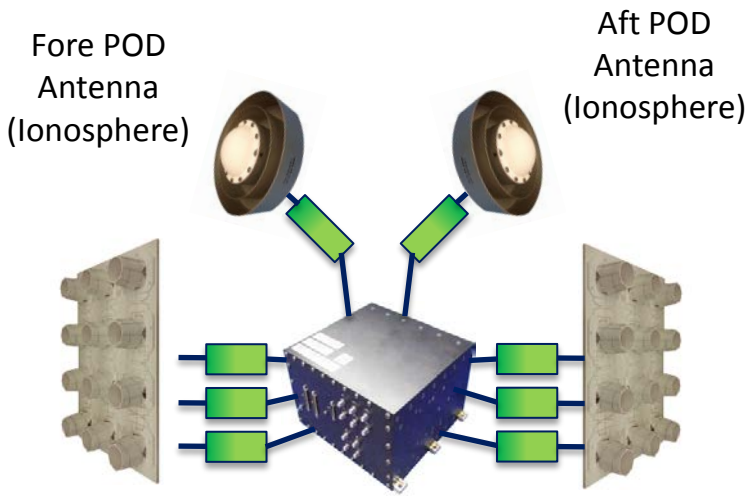
Outline

- Mission overview and status
- Initial neutral atmosphere results
- Initial ionosphere results
- Neutral atmosphere cal/val
- Summary

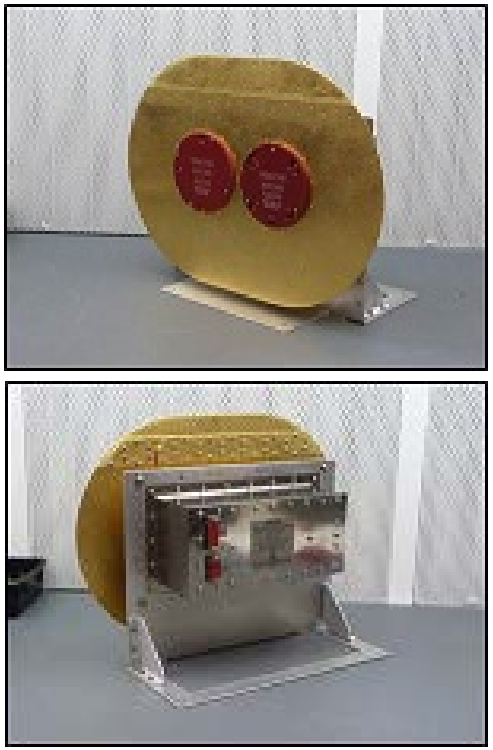
Mission Overview

- FORMOSAT-7/COSMIC-2 (COSMIC-2, C2) follows on the successful COSMIC-1 mission launched in 2006
- Six satellite constellation around the equator (24 degree inclination low Earth orbit)
- 5 year mission life to provide 4000+ radio occultation soundings per day for improved numerical weather prediction, space weather monitoring, trending of climate change
- All weather, uniform coverage over oceans and land with 30 min median data latency
- Each satellite has 3 payloads provided by USAF
  - Tri GNSS Radio-occultation System (TGRS) – primary payload
  - Ion Velocity Meter (IVM) – secondary payload
  - RF Beacon – secondary payload

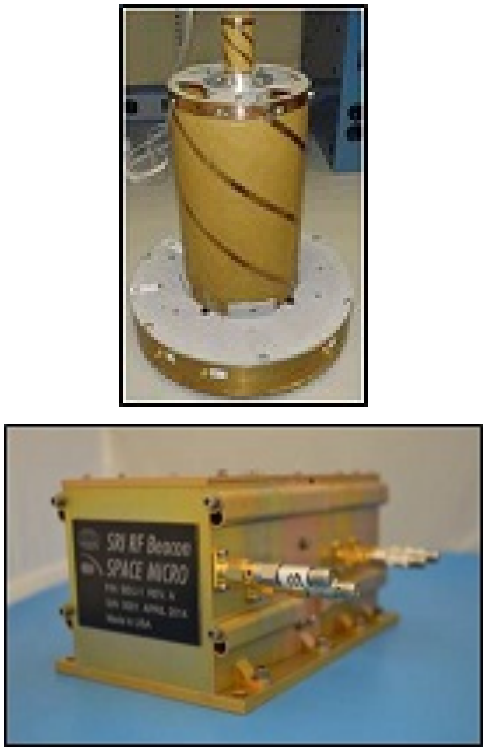
COSMIC-2 Instruments



TGRS



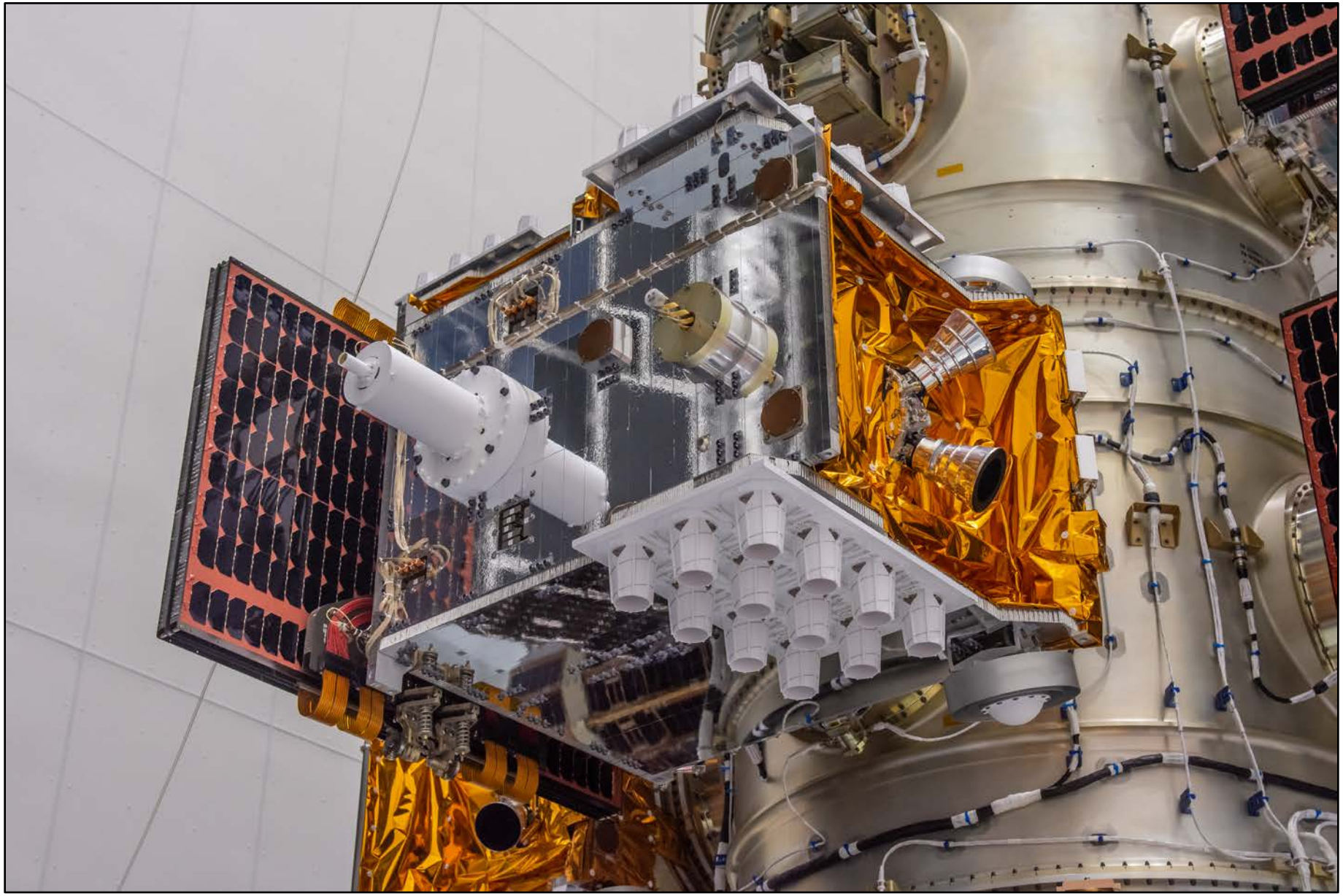
IVM



RFB

Mission Payload	**TGRS (Tri-GNSS Radio occultation System)**	**To measure the amplitude and phase/group delay of GNSS signals**
Science Payload	**IVM (Ion Velocity Meter)**	**To measure in-situ ion density, drifts (Electric fields), temperature & composition**
	RFB (Radio Frequency Beacon)	**To measure total electron content and ionospheric scintillation.**

COSMIC-2 on STP-2 Stack

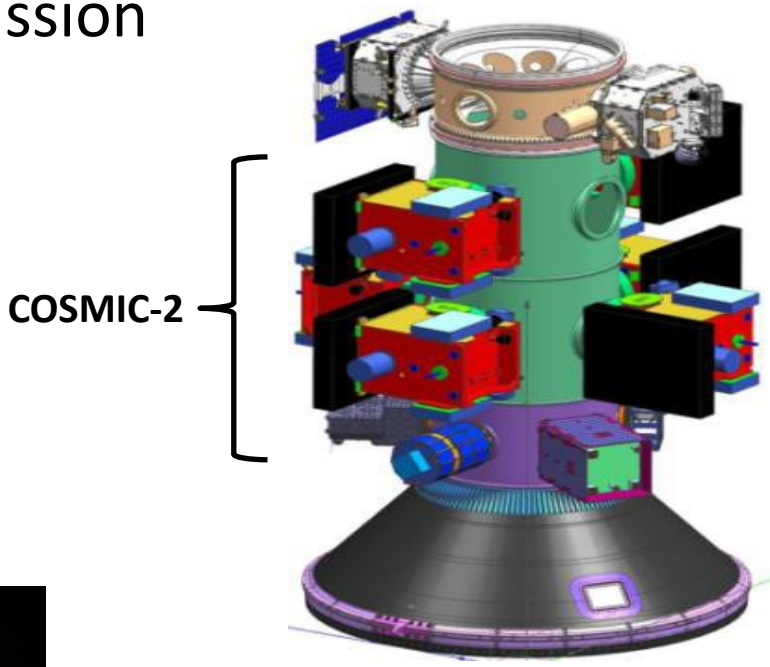


[Photo courtesy of SpaceX]

Satellite Overview and STP-2 Launch

- COSMIC-2 launched June 25, 2019 as part of the USAF Space Test Program-2 (STP-2) mission

Power Supply	2-axis drive solar array
Body dimensions	100 x 125 x 125 cm^3
Mass	<300 kg (per satellite)
Communications Capabilities	S band, upload speed 32kbps, download speed 2 Mbps
Payload Support	Data storage capacity 2Gbits, mass 39.4 kg, power supply 95W

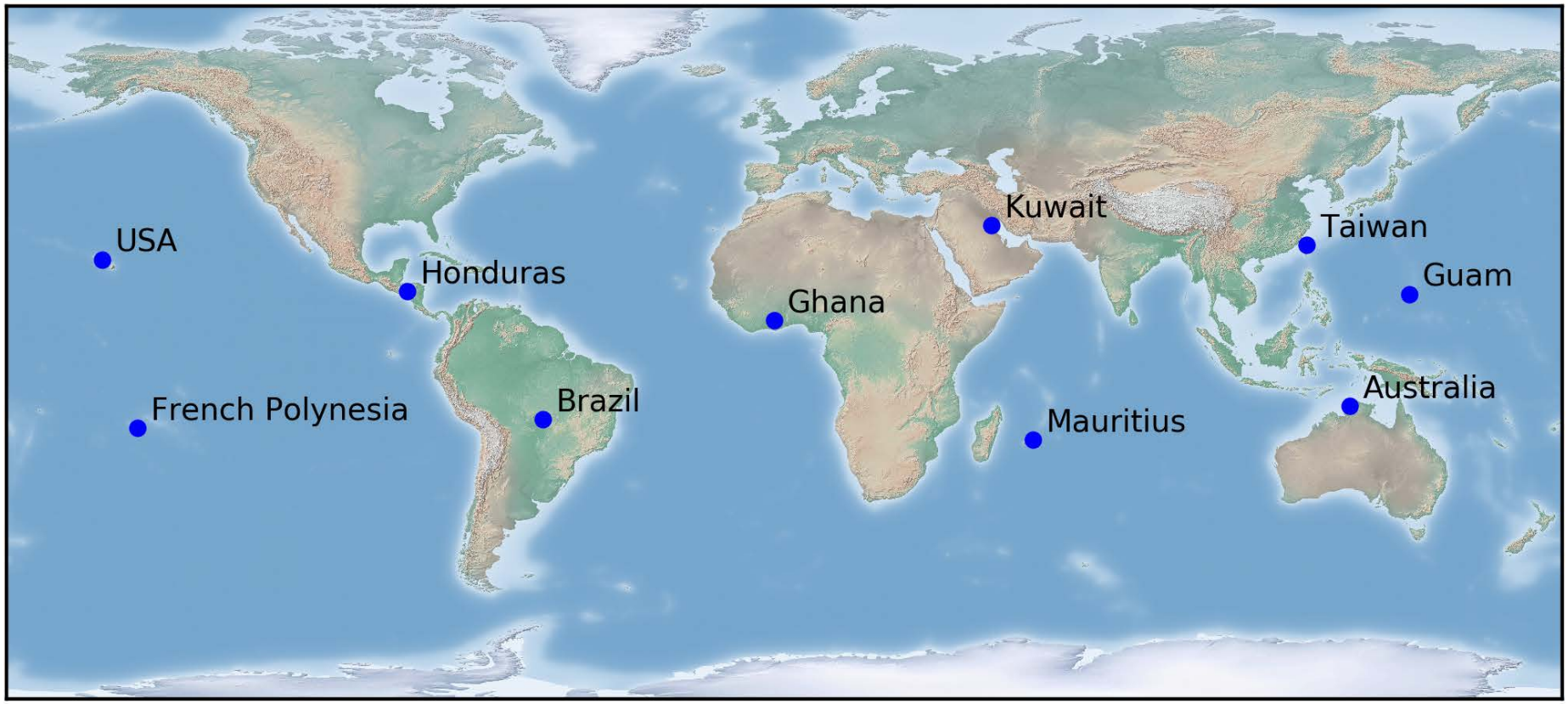


Falcon Heavy STP-2 launched from CCAFS LC-39A (Photo credit: NASA)

- Integrated Payload Stack (IPS)
  - Six COSMIC-2 Spacecraft
  - Demonstration and Science Experiment (DSX)
  - Six Auxiliary Payloads
  - Dispensers plus ballast
  - Eight PPODs with Twelve Cubesats

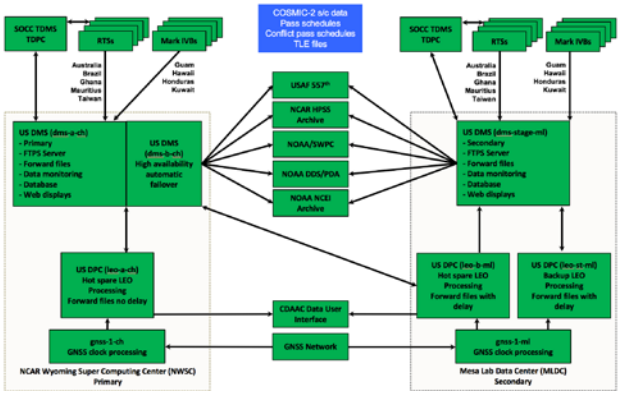
Ground Station Architecture

- Nine downlink stations enable rapid delivery of data to data processing centers (US DPC and Taiwan DPC)



US Data Processing Center

- Redundant, geographically separate processing centers
- Modular framework with broad capabilities in GNSS RO/R processing, POD, atmospheric retrievals, science analysis
- Extensive data management system
  - Coordinates downlink scheduling, telemetry data transfer, payload commanding
- FISMA IT security
- Low latency processing to meet 30 minute median requirement
- Ion velocity meter processing and product generation (with UT Dallas)
- Redundant archive systems at UCAR/NCAR HPSS and NOAA NCEI
- Direct product delivery to operational weather/space weather centers
- In use for operational KOMPSAT-5 and PAZ RO processing



Mission Status

- Spacecraft checkout June 25 – July 15: complete
- Satellite payload activation/checkout July 16 – 21: complete
- Early-orbit checkout of all 18 instruments: complete
- No hardware issues on TGRS and IVM
- RF Beacon checkout is complete and all units are undergoing commissioning with Kwajalein ground station
- Orbit phasing July 22 – 23: complete
- Satellite FS701 lowering to mission orbit (~550 km) July 24 – Aug 16: complete
- Payload commissioning July 24 – Oct 15: in progress

Spacecraft/Instrument Status

	FM1	FM2	FM3	FM4	FM5	FM6
Orbit Altitude	Final 550 km orbit as of August 16	725 km initial orbit				
Spacecraft Status	Currently nominal operation	Currently nominal operation (2 safe mode events)	Currently nominal operation (2 safe mode events)	Currently nominal operation (3 safe mode events)	Currently nominal operation (1 safe mode event)	Currently nominal operation (1 safe mode event)
TGRS	v4.3.2 Software	v4.3.2 Software	Commissioning	Commissioning	Commissioning	Commissioning
IVM	Commissioning	Commissioning	Commissioning	Commissioning	Commissioning	Commissioning
RFB	Transmit mode enabled	Transmit mode enabled	Transmit mode enabled	Transmit mode enabled	Transmit mode enabled	Transmit mode enabled

All Spacecraft currently nominal
Instruments in commissioning
Flight s/w for TGRS 1 updated
Remaining TGRS updates in progress
RFB transmit mode on

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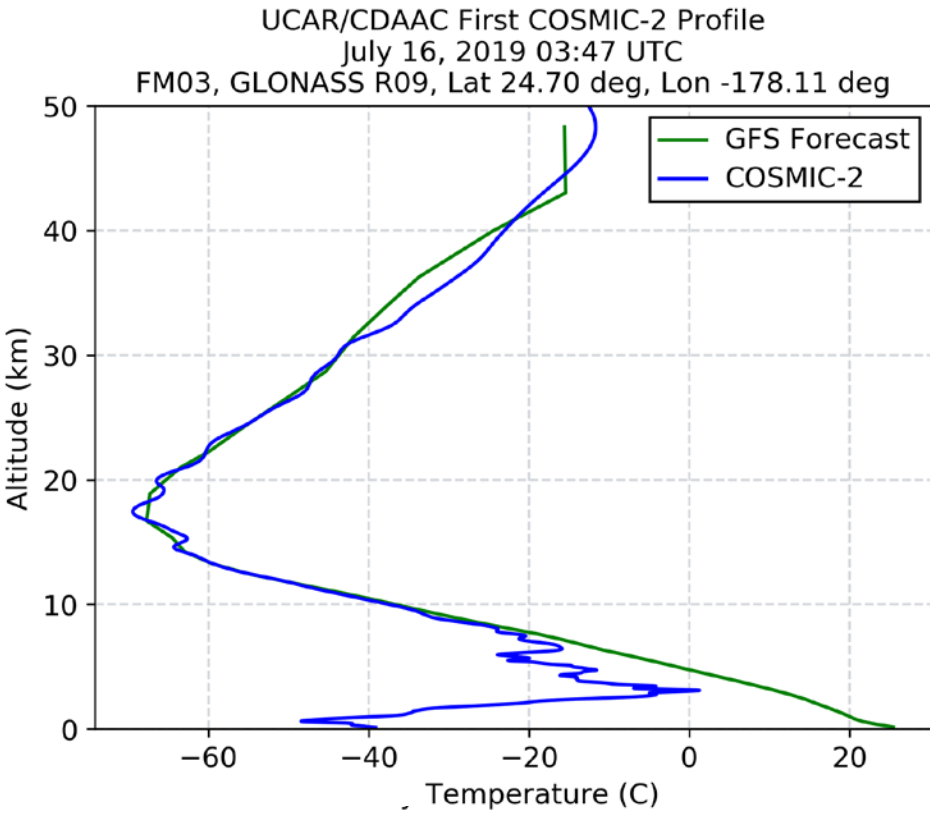
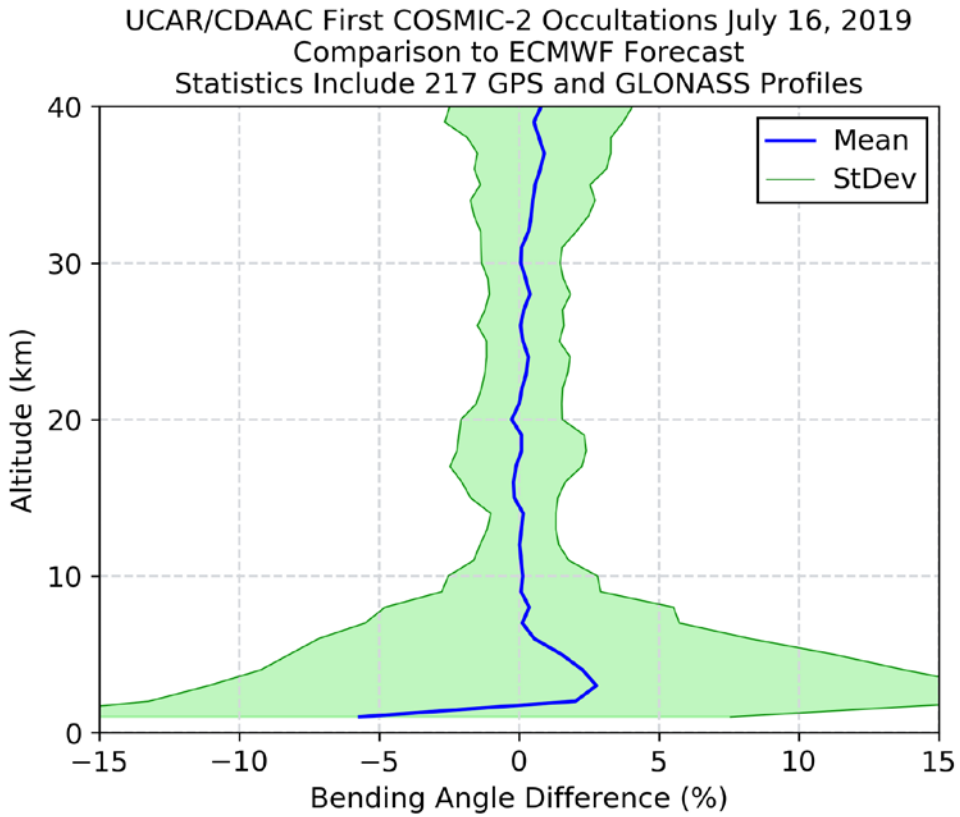
July 16, First COSMIC-2 Profiles

- Doug Hunt produced ~110 neutral atmospheric occultations within 3 hours of receiving the first level 0 data from FMs 1 and 3!
  - Ended up with > 200 profiles that day

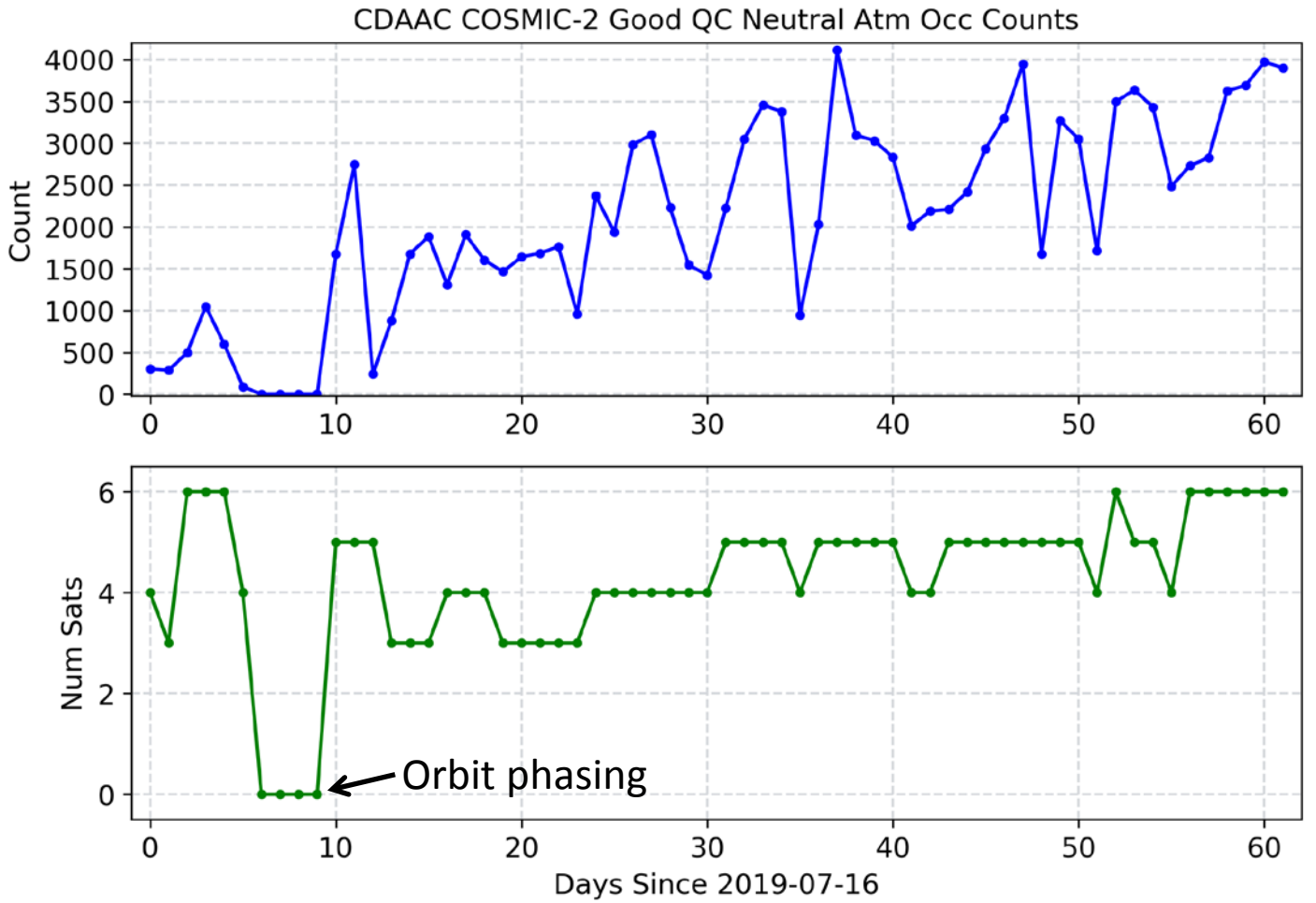




[Results as obtained on July 16 shown]

Occultations Counts

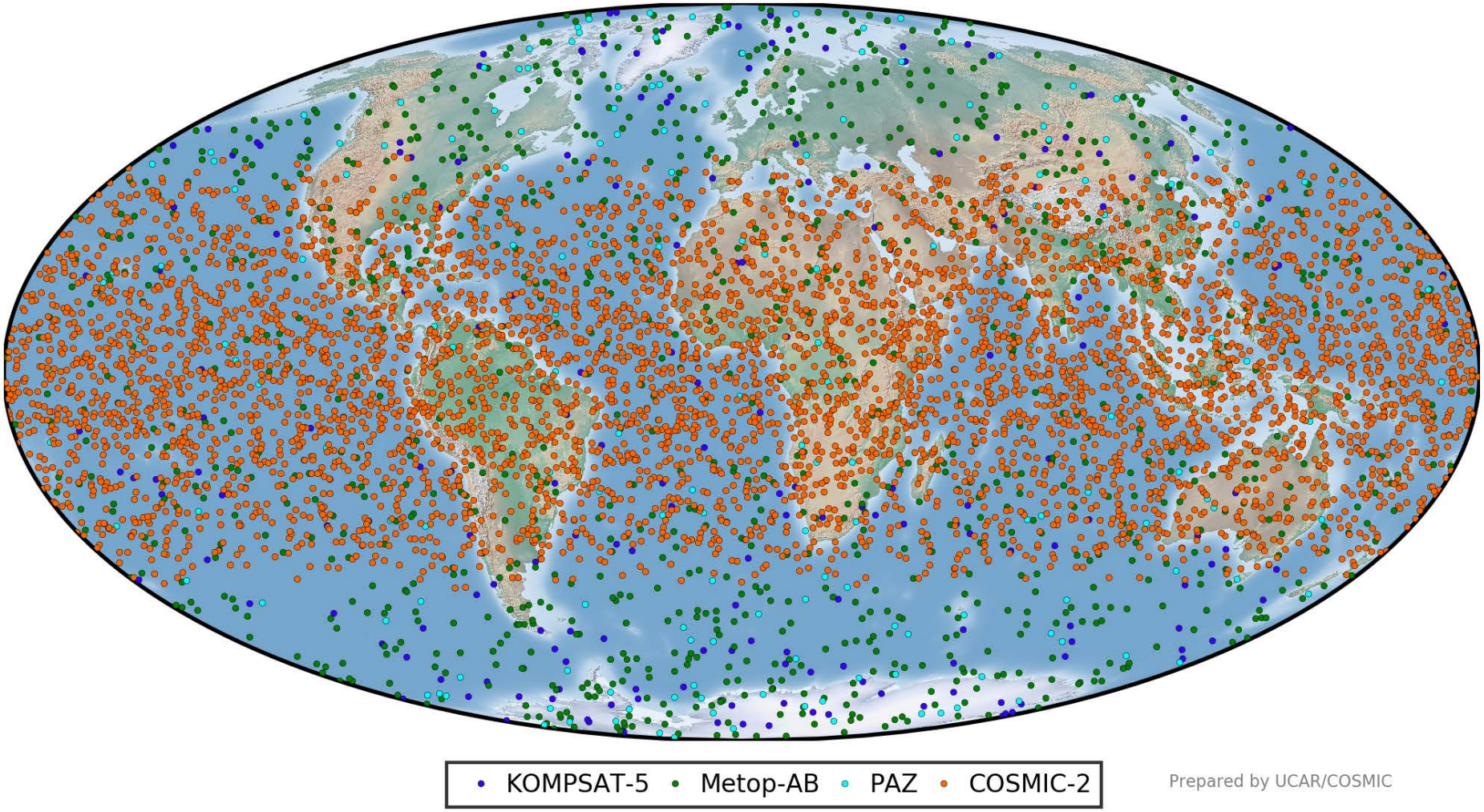
- Showing post-QC counts since instrument activation on July 16
- Level 1 requirement is 4000, should have no issues meeting this when all instruments stable



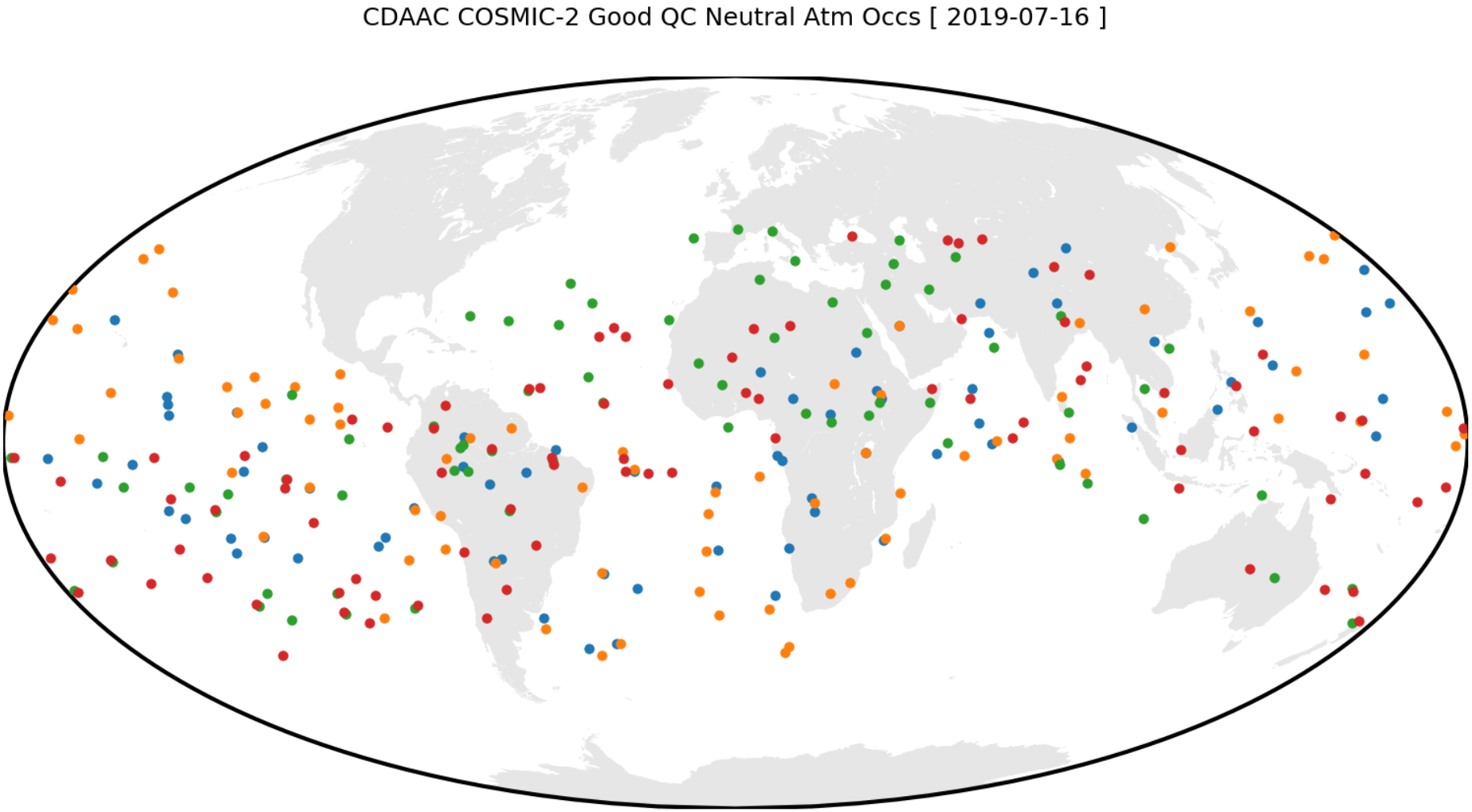
Trending towards > 4000 occ per day

Simulated C2 RO Coverage

- Simulated C2 occultations in this figure

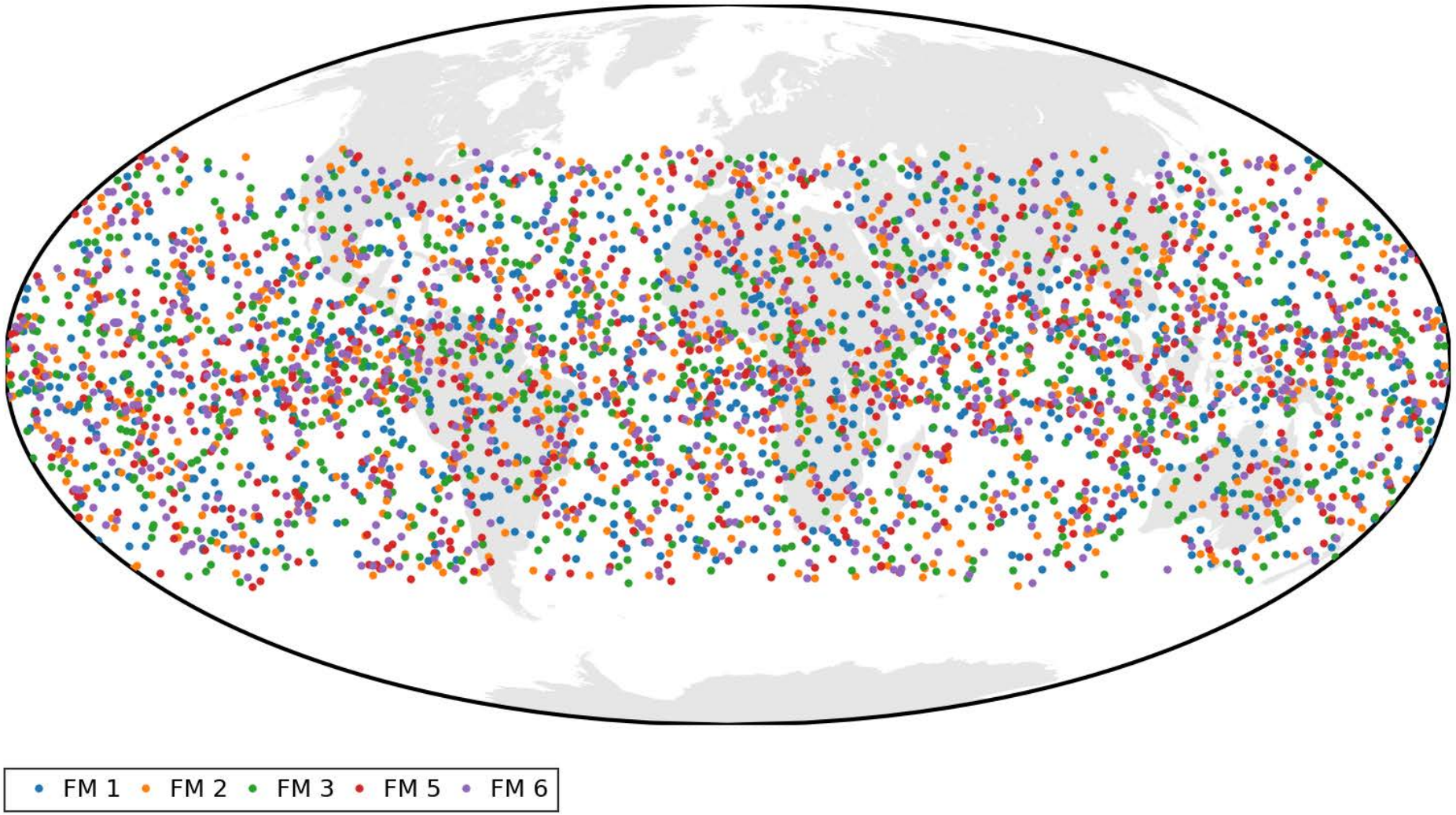


Actual C2 RO Coverage by Day



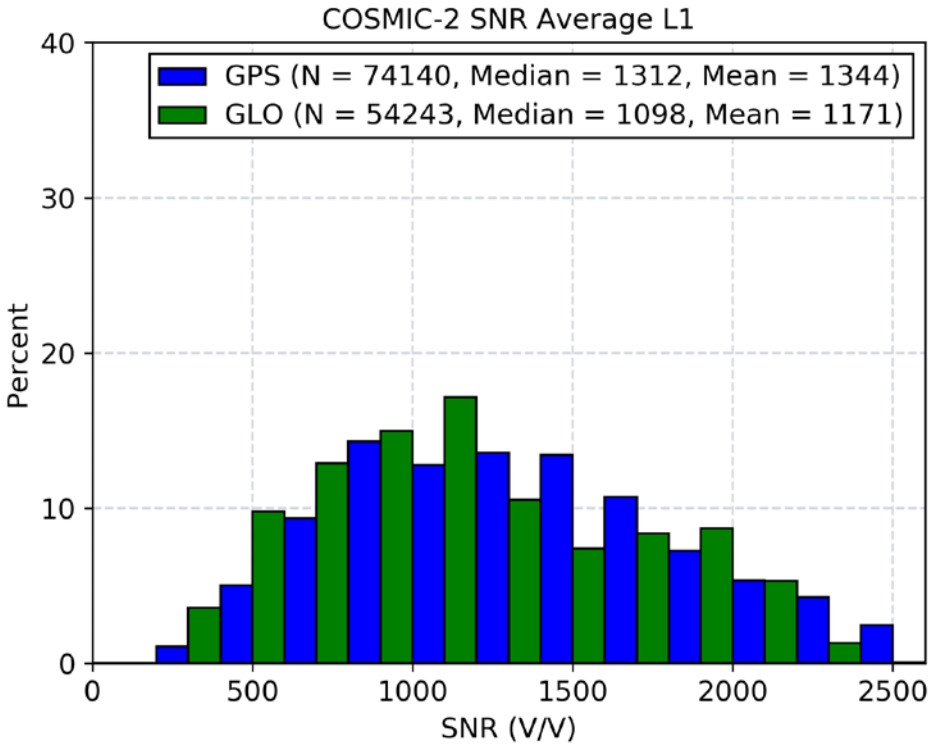
Actual C2 RO Coverage

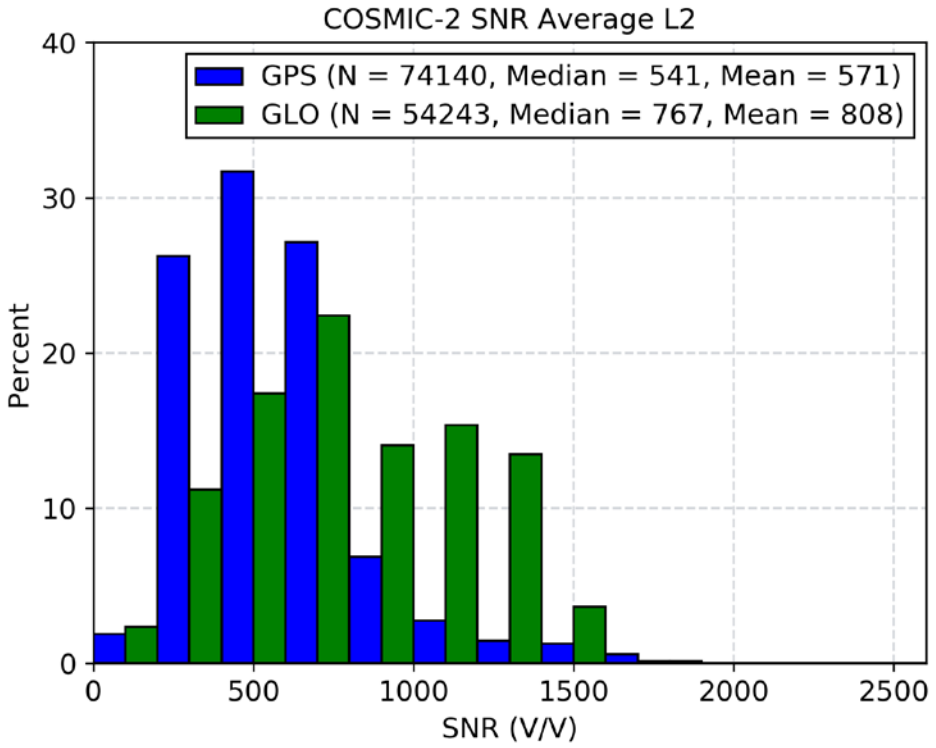
- Occultation locations on Aug 22, 2019
  - 4115 total after QC from 5 satellites, highest count so far



Average Occultation SNRs

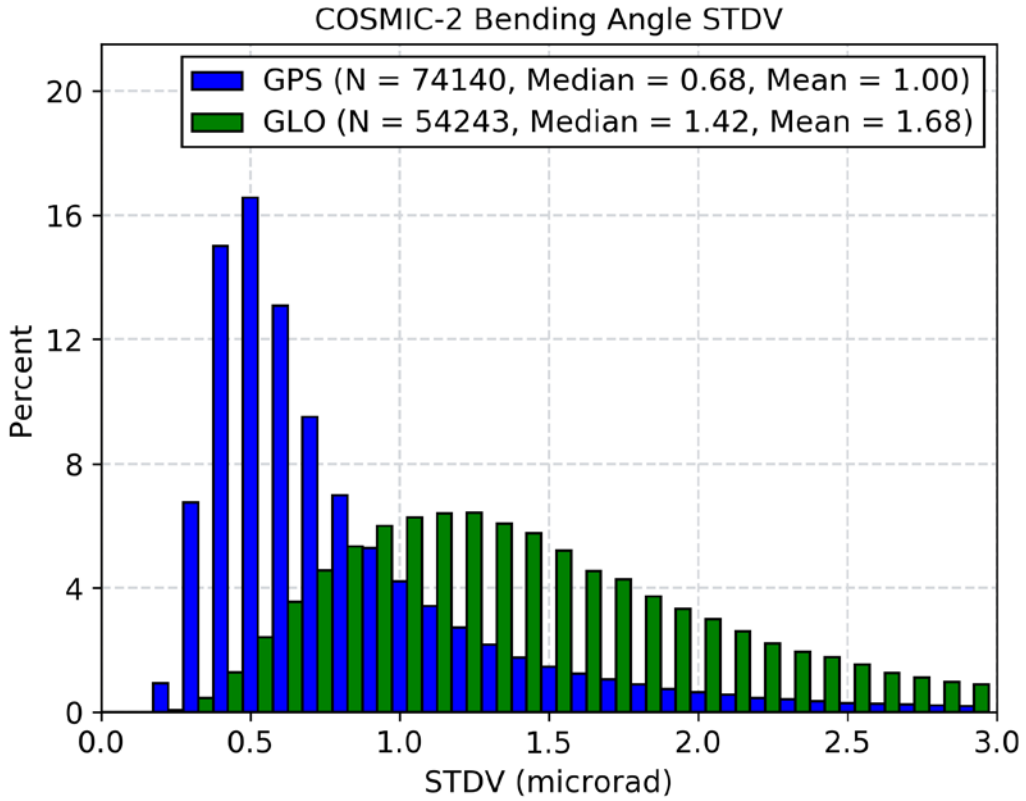
- L1 on left, L2 on right (includes L2C and L2P)
  - Significantly higher than average L1 SNR of ~800 V/V for COSMIC-1





STDV Statistics

- STDV is the standard deviation of the difference between climatological bending angle and RO bending angle between 60-80 km
  - This altitude range is chosen to avoid both atmospheric and ionospheric effects to measure the inherent noise of the RO data
- Results for constellation shown below
  - Per satellite results consistent with overall statistics

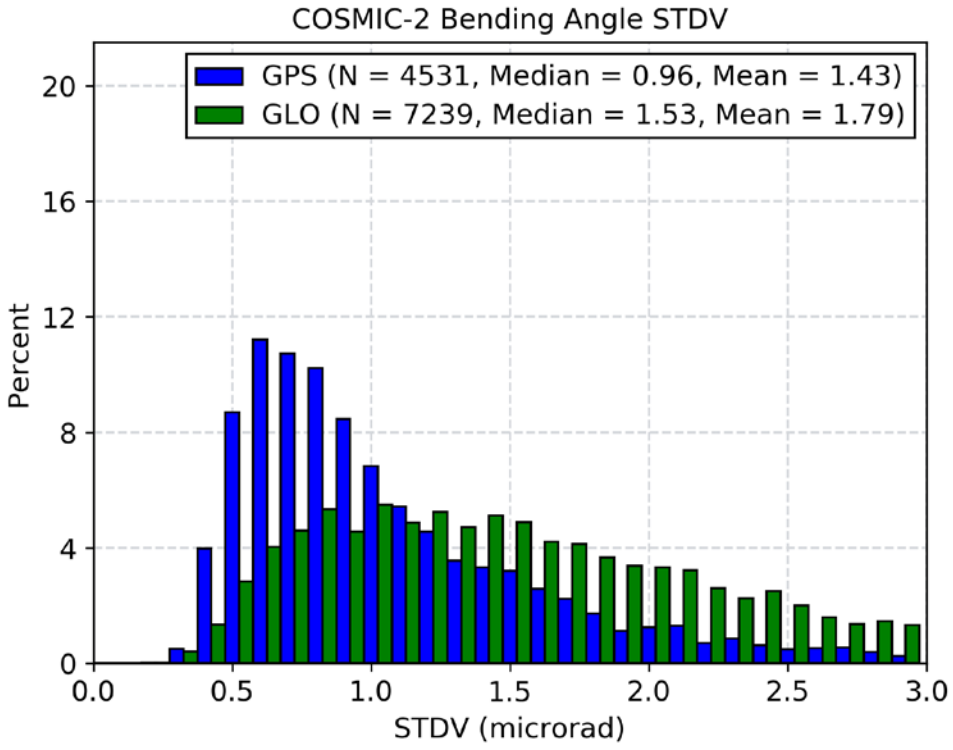


Overall mean:
1.3 microrad

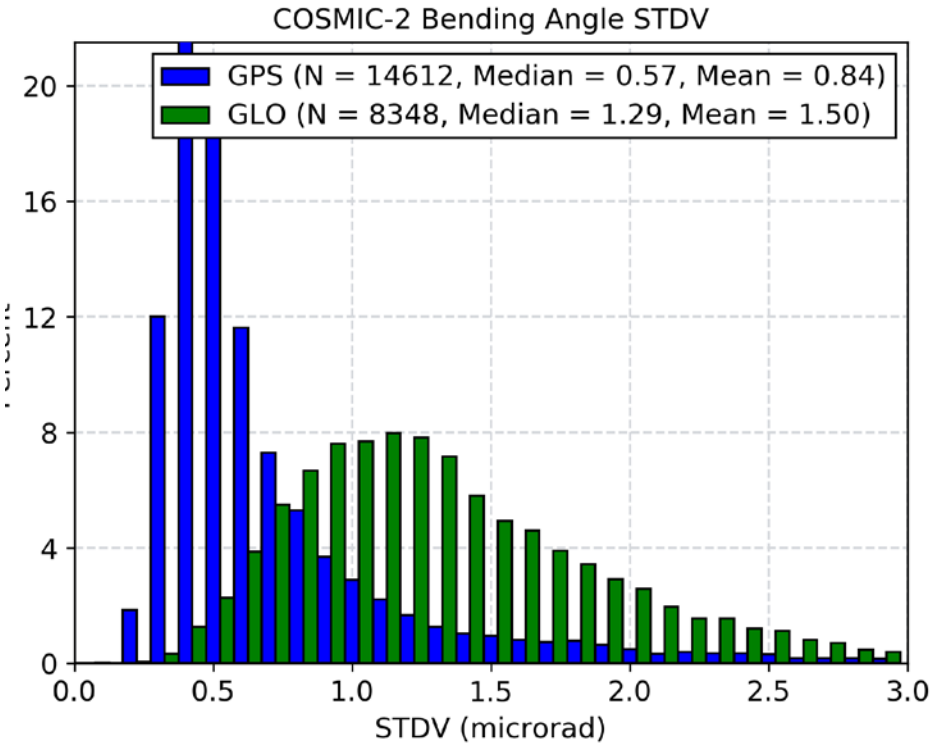
STDV for Low/High SNR

- Higher SNR clearly improves STDV
- STDV mean ratios for low/high SNR
  - GPS 1.7, GLO 1.2 (high freq transmitter clock variations dominate)

Average L1 SNR < 600 V/V

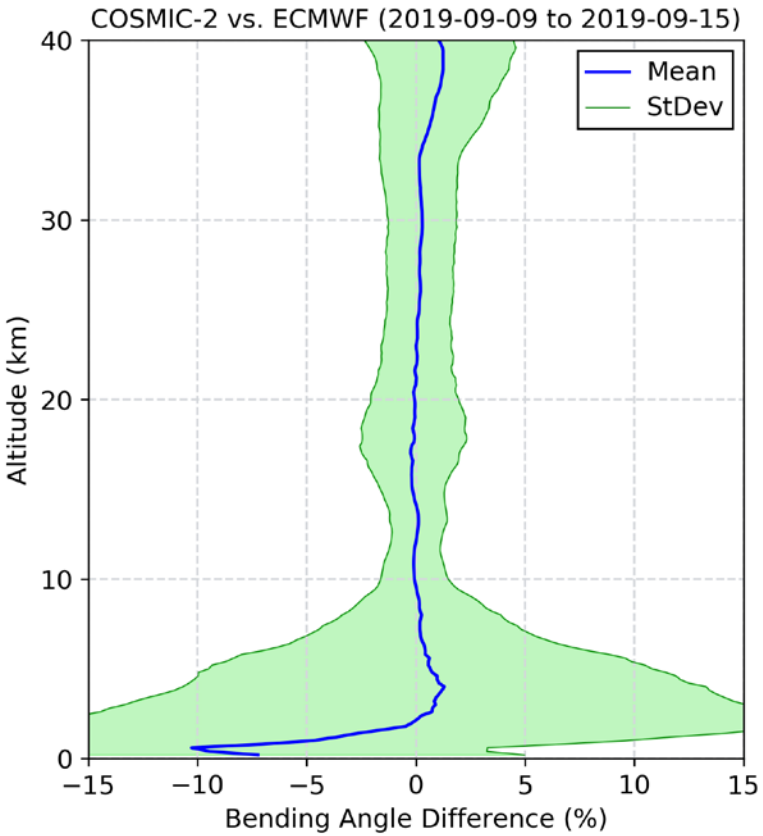


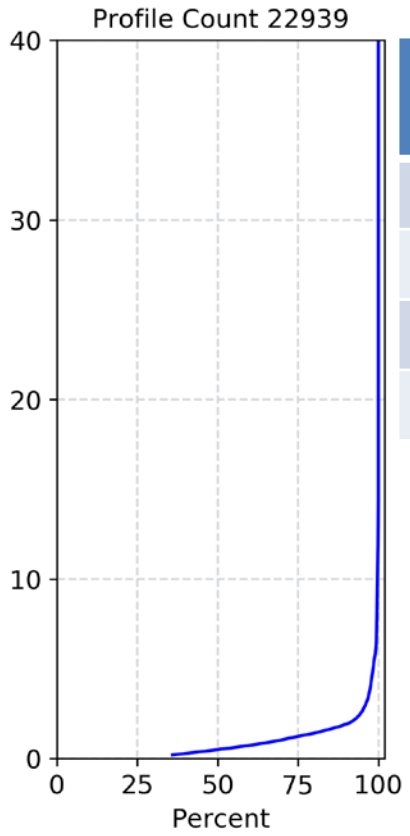
Average L1 SNR > 1800 V/V



Bending Angle Comparison to ECMWF

- All data for recent week
  - Results very reasonable

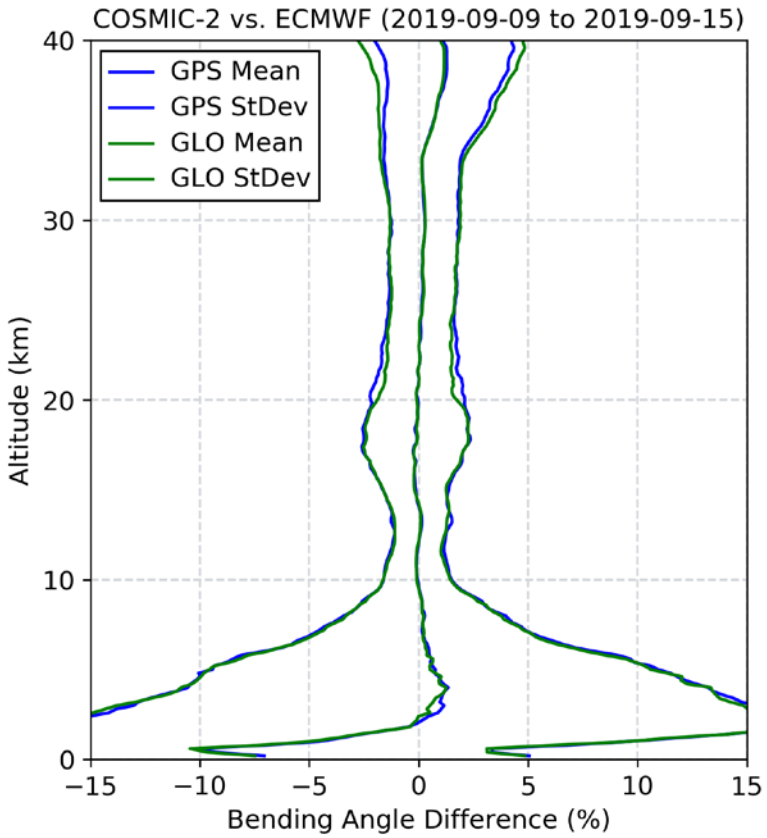


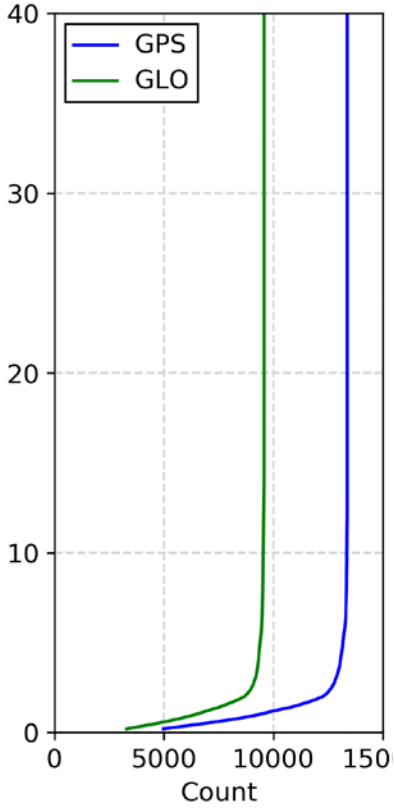


Altitude (km)	Avg Mean All (%)	Avg Std Dev All (%)
0 - 10	-0.6	9.4
10 - 20	-0.1	1.7
20 - 30	0.1	1.6
30 - 40	0.6	2.3

Bending Angle Comparison to ECMWF

- GPS, GLONASS data separately for recent week
  - Results very similar for both GNSS





Altitude (km)	Avg Mean GPS (%)	Avg Std Dev GPS (%)
0 - 10	-0.5	9.4
10 - 20	-0.1	1.7
20 - 30	0.1	1.7
30 - 40	0.6	2.2

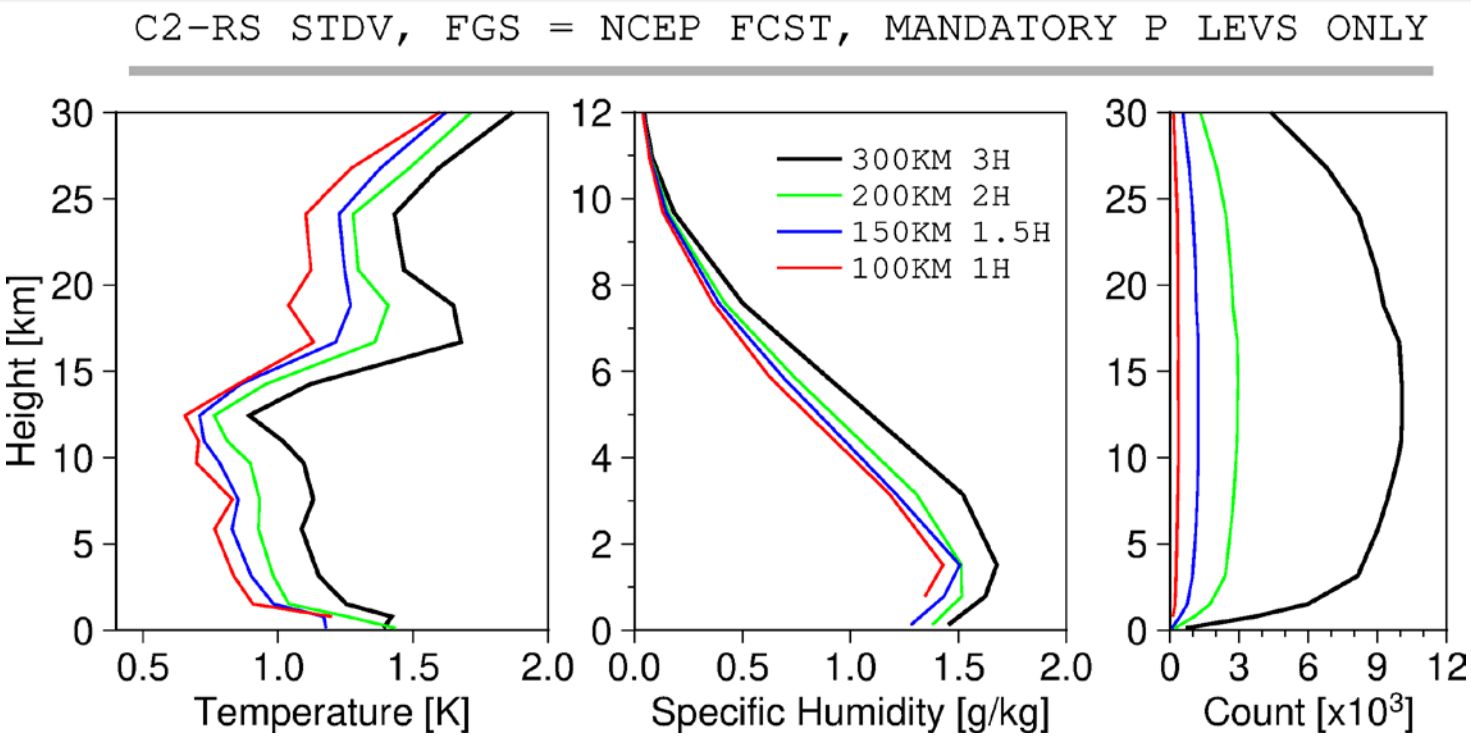
Altitude (km)	Avg Mean GLO (%)	Avg Std Dev GLO (%)
0 - 10	-0.7	9.4
10 - 20	-0.1	1.7
20 - 30	0.1	1.5
30 - 40	0.6	2.4

1D-Var Retrieval Comparison to Radiosondes

- Radiosonde data
  - NCEP PrepBufr
  - Quality control, respect NCEP QC (few steps specific to NCEP or DA overturned)
  - Additional (OMB-based and physical) QC applied [e.g., spikes (superadiabatic), supersaturation (> 120%), hydrostatic consistency between T and Z reports]
- Comparison period: 2019.197-240 (Jul 16 – Aug 28)
- Drifts of both balloon and tangent point are fully taken into account (level-wise collocation)
- Robust to outliers (excludes largest 2% departures at each level)
- Minimum sample size is set to 50

Courtesy T.-K. Wee

1D-Var Retrieval Comparison to Radiosondes

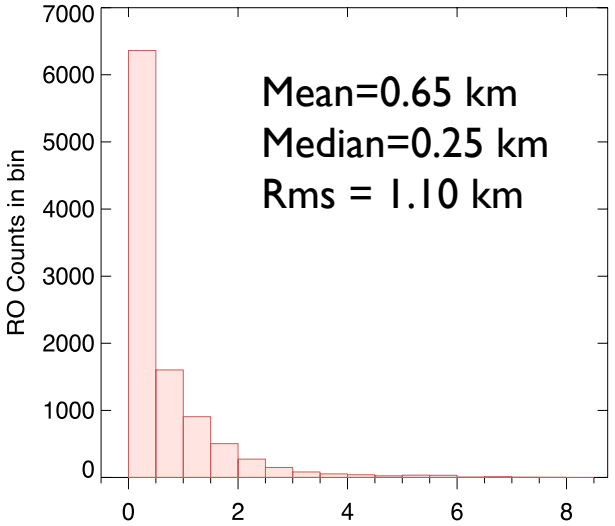


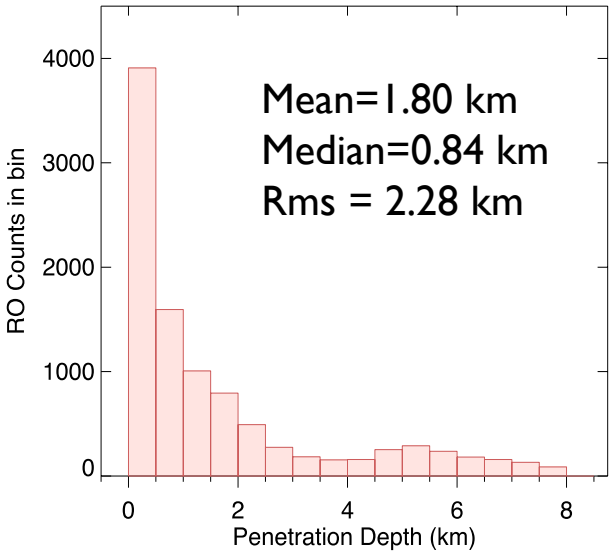
- Highlights
  - St. dev. keeps decreasing with decreasing separation (e.g. temp. near tropopause)
  - Rough C2 error estimates are 0.5-1.5 K in temperature and 5-10% of observed moisture

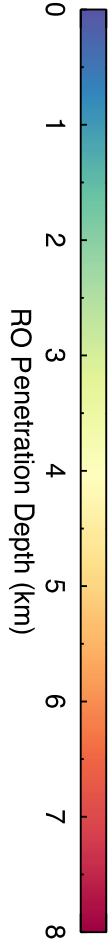
Courtesy T.-K. Wee

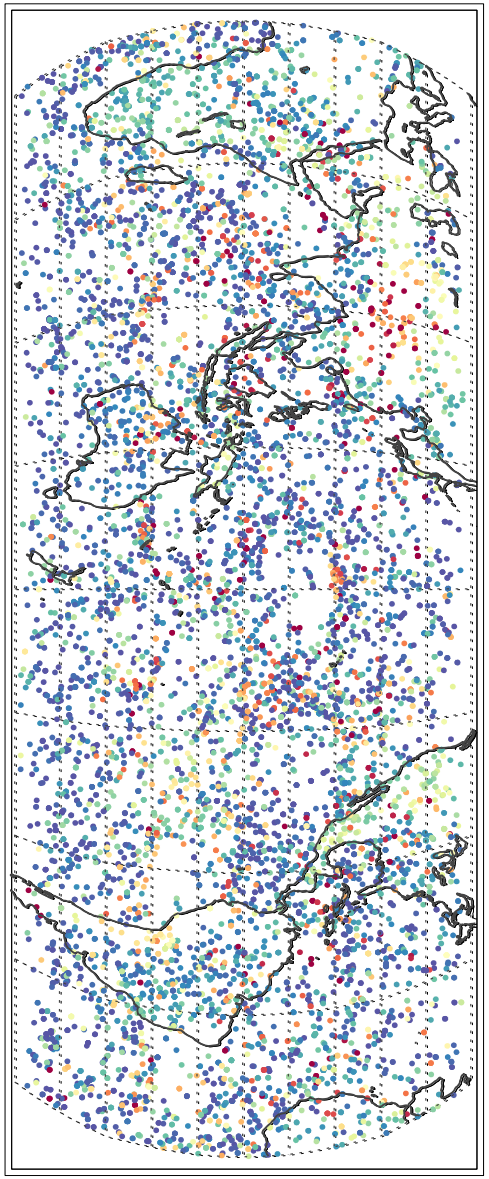
RO Penetration Depth Comparison

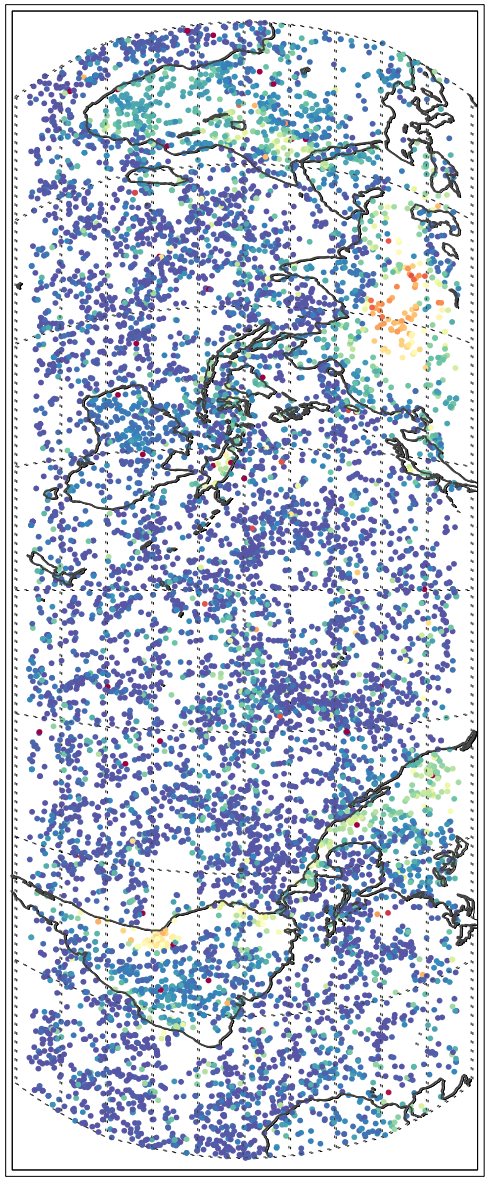
- C2 vs. KOMPSAT-5/ Metop-AB/PAZ for collocated profiles (300 km, 3 hrs, 10133 pairs)









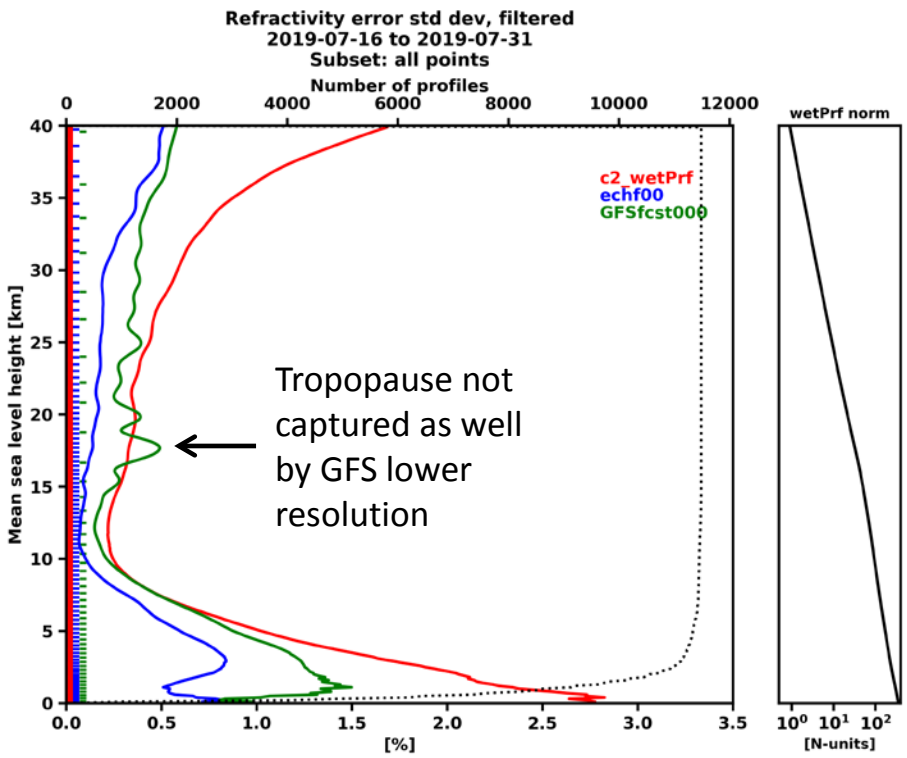


Courtesy Z. Zeng

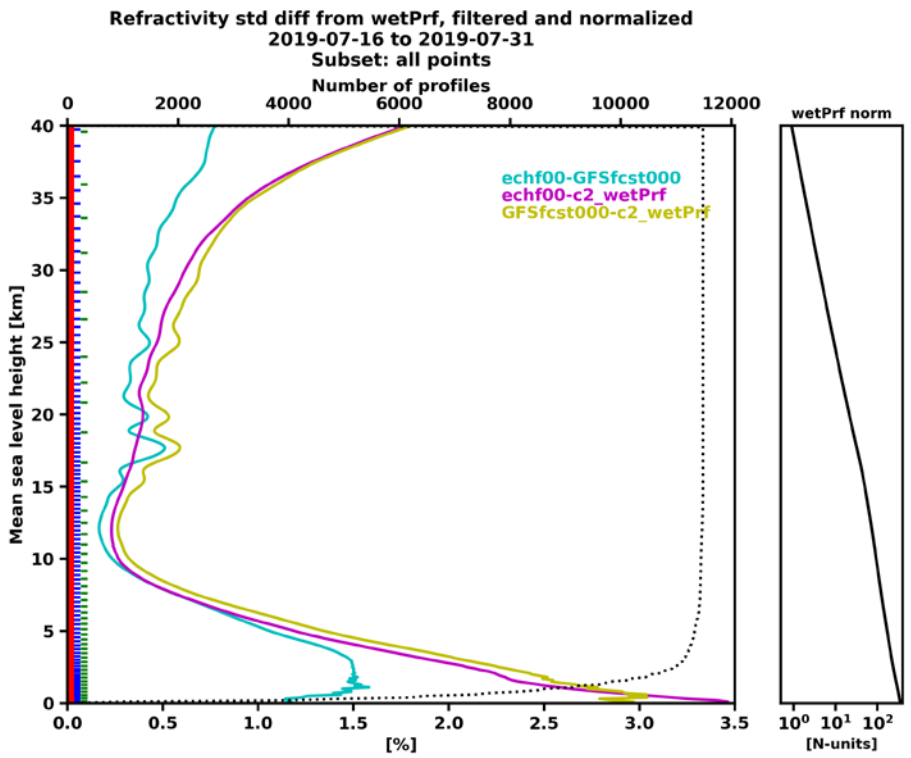
Three Cornered Hat (3CH) Method

- Derives random error characteristics using 3+ datasets
  - Includes measurement, representativeness, random errors
  - Assumes no correlation between datasets
- Refractivity error estimates shown

3CH Estimates



Std Dev of Differences



Courtesy J. Sjoberg

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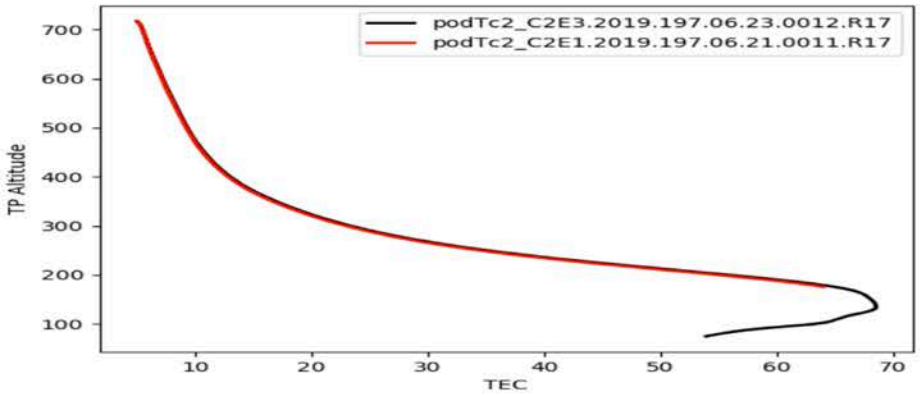
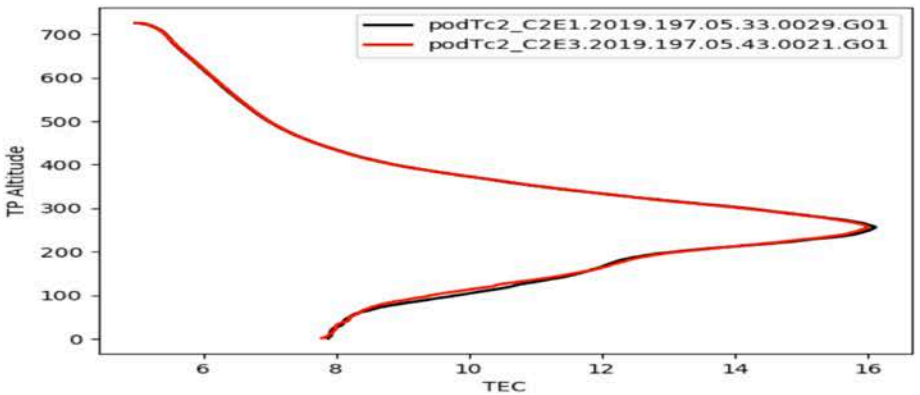
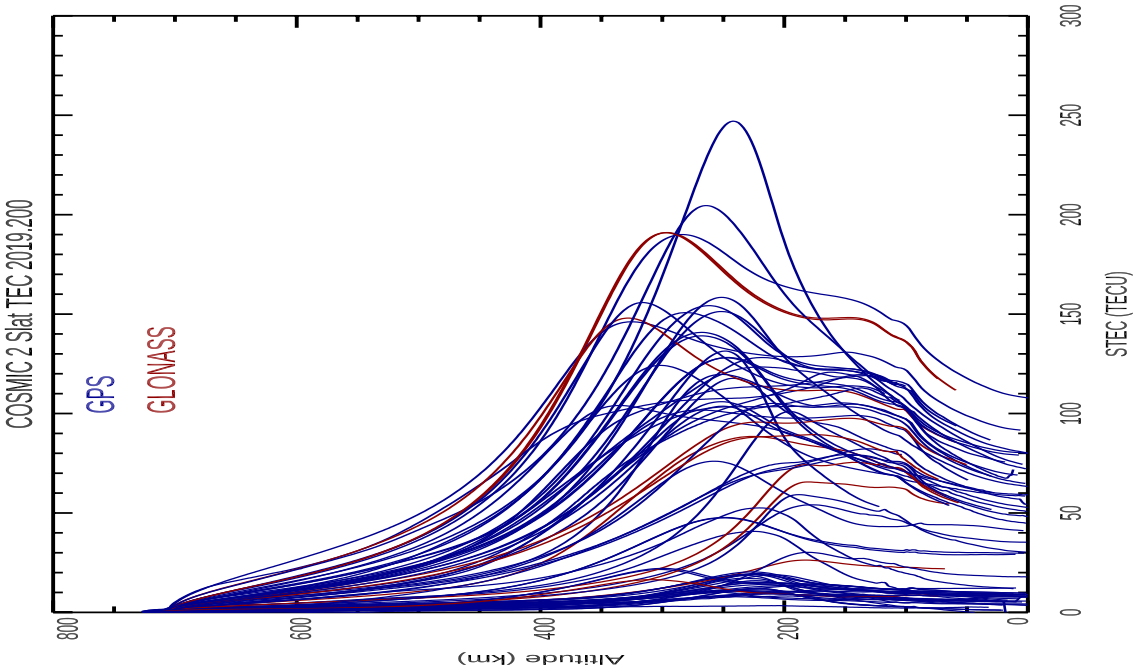
Initial C2 Relative TEC Data

Two GPS TEC Arcs



Two GLONASS TEC Arcs

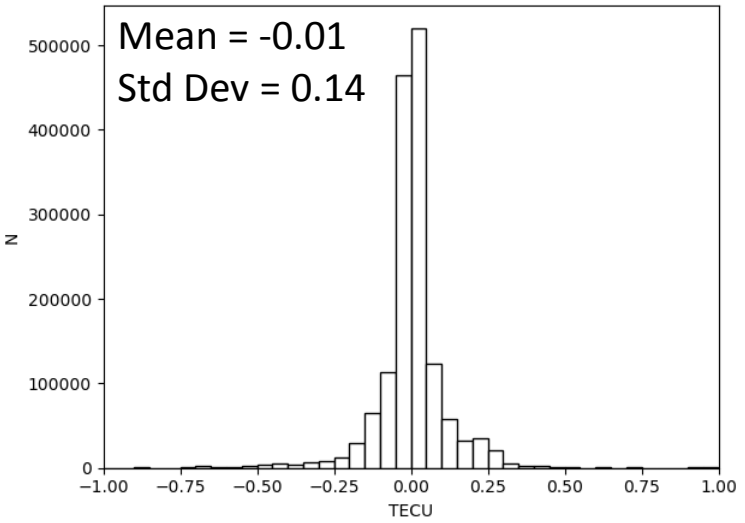




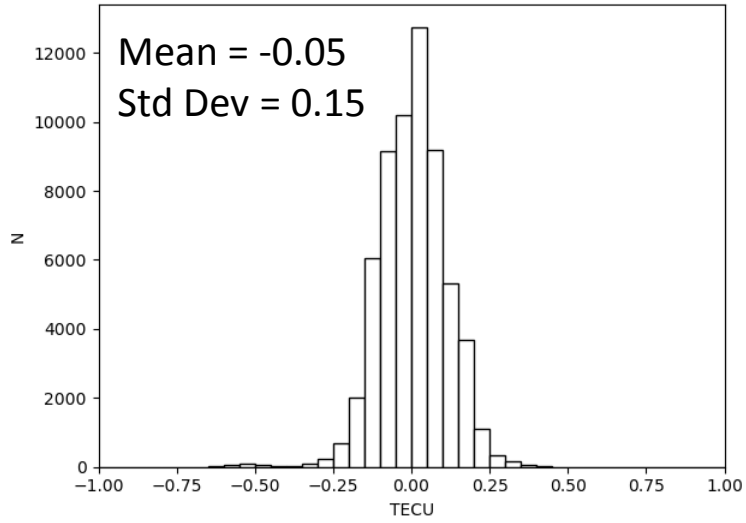
C2 Relative TEC Precision

- We use closely collocated observations from 2 COSMIC-2 satellites from the initial stages of the mission to estimate precision of the LEO relative TEC observations
- We determine the relative TEC by subtracting the TEC value from each arc at the time they initially overlap
- COSMIC-2 relative TEC arcs are compared for YYYY.DDD days 2019.200-202, and 2019.207-214
- The std dev for GPS relative TEC for COSMIC-2 pairs is 0.14 TECU for GPS, and 0.15 TECU for GLONASS
- A similar analysis for COSMIC-1 yields ~0.16 TECU std. dev. for GPS

COSMIC-2 GPS Relative TEC



COSMIC-2 GLONASS Relative TEC



Courtesy N. Pedatella

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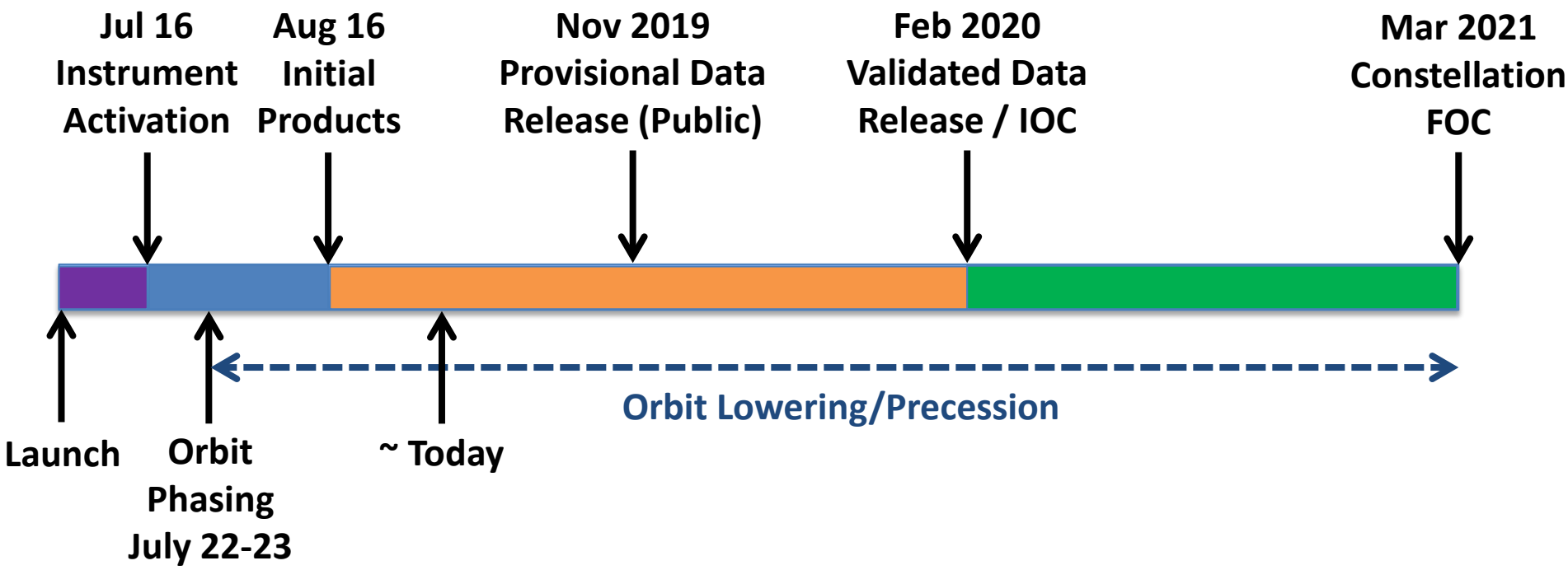
Neutral Atm Cal/Val and Plans

- Cal/val team from UCAR/COSMIC, CWB, JCSDA, NSPO, NOAA/STAR began work mid-August
- Multiple validation approaches, e.g. comparisons between C2 FMs, C2 vs. other missions and measurement techniques, NWP (O-B, O-A, impacts)
- TGRS v4.3.2 software patch in progress during September
- October dataset should be close to operational instrument configuration
- First public data/product release planned in November
  - External NWP centers get data at this time
- Validated products planned Feb 2020
  - Actual date will be driven by TGRS v4.4 software (space weather updates) schedule

Neutral Atm Cal/Val Schedule



- Launch and early orbit operations
- Checkout and commissioning
- Weather cal/val
- Weather operations

L = Launch
d = days
m = months
IOC = Initial Operational Capability
FOC = Full Operational Capability

Summary

- COSMIC-2 launched successfully on June 25, 2019
  - Spacecraft/instrument checkout complete
  - Instrument commissioning in progress
- COSMIC-2 processing is going well
  - Significant effort on mission simulations and experience with prior missions is paying off
  - Neutral atmosphere profile quality good
    - Further detailed comparisons coming throughout cal/val
    - TGRS software update in progress to address some issues
  - Initial ionosphere results positive
  - Team continues to work on instrument commissioning and cal/val
  - On track for first public data/product release in November 2019

Acknowledgements

- Thanks to the FORMOSAT-7/COSMIC-2 Program partners!

Upcoming IROWG C2 Presentations

- Schreiner, Performance Assessment and Requirement Verification of COSMIC-2 Neutral Atmospheric Radio Occultation Data, Th 13:00
- Meehan, The TriG Radio Occultation System on COSMIC-2 Early Performance Assessment, Th 13:20
- Sjoberg, Estimates of Errors in Radio Occultation and Multiple Reanalyses, Fri 10:20
- Braun, COSMIC-2 Early Orbit Space Weather Data Assessment and Validation Activity, Mon 11:00
- Sokolovskiy, Initial Assessment of the First Results of Sensing the Lower Troposphere with COSMIC-2, Tue 14:30
- Ho, NESDIS RO Science Studies and Quality Assurance through the STAR Integrated Cal/Val System, Tue 15:50
- Cao, The Significant Roles of COSMIC2 GNSS RO in NOAA Integrated Calibration/Validation System for NWP, Tue 16:10