Initial GNSS-RO Results from Sentinel-6

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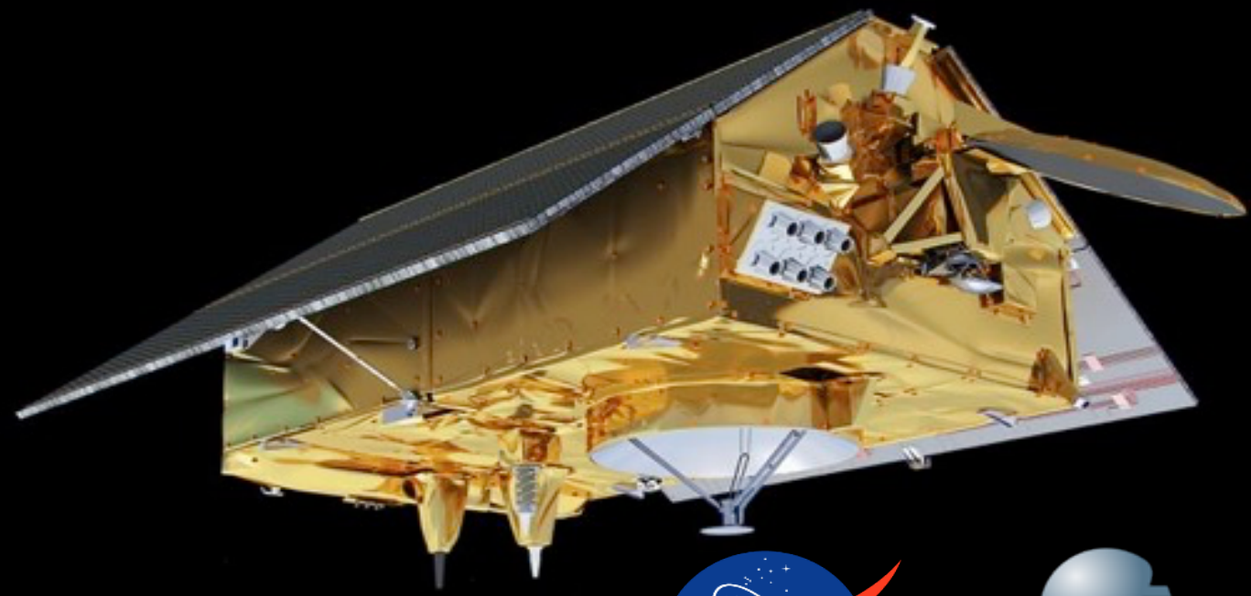

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Outline

- Mission overview
- GNSS-RO instrument and status
- Near-real-time (NRT) processing
- Initial assessment results
- Summary

Mission Overview

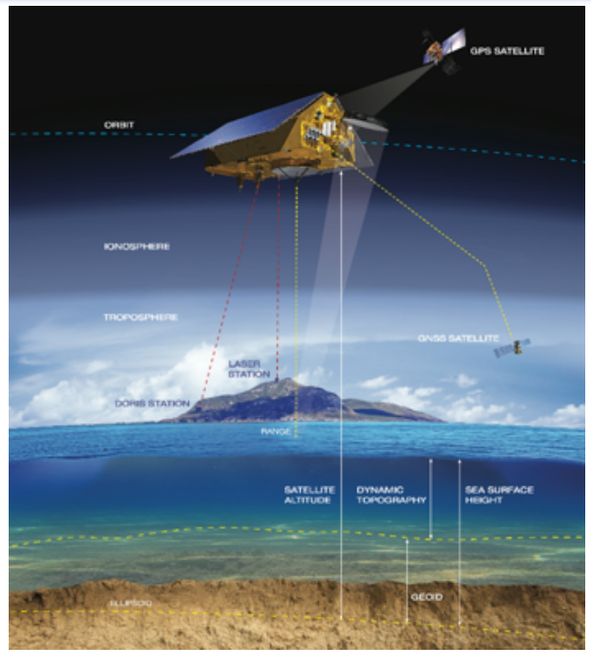
Mission Objectives

- Operational ocean altimetry to provide continuity of ocean topography measurements beyond Jason-3
- Global sea surface height to an accuracy of ≤ 4 cm every 10 days, for determining ocean circulation, climate change and sea level rise
- NASA, EUMETSAT, ESA and NOAA partnership with CNES providing technical support
- Operational mission as part of a *two-satellite* EUROPEAN Copernicus/Sentinel program

Instruments

- Ku/C-Band Radar Altimeter (Next gen Poseidon: Thales)
- DORIS (Precise Orbit Determination System)
- GNSS Receiver (POD System)
- Advanced Microwave Radiometer – Climate Quality (AMR-C)
- GNSS-Radio Occultation (GNSS-RO)
- Laser Retro-Reflector Array (LRA)

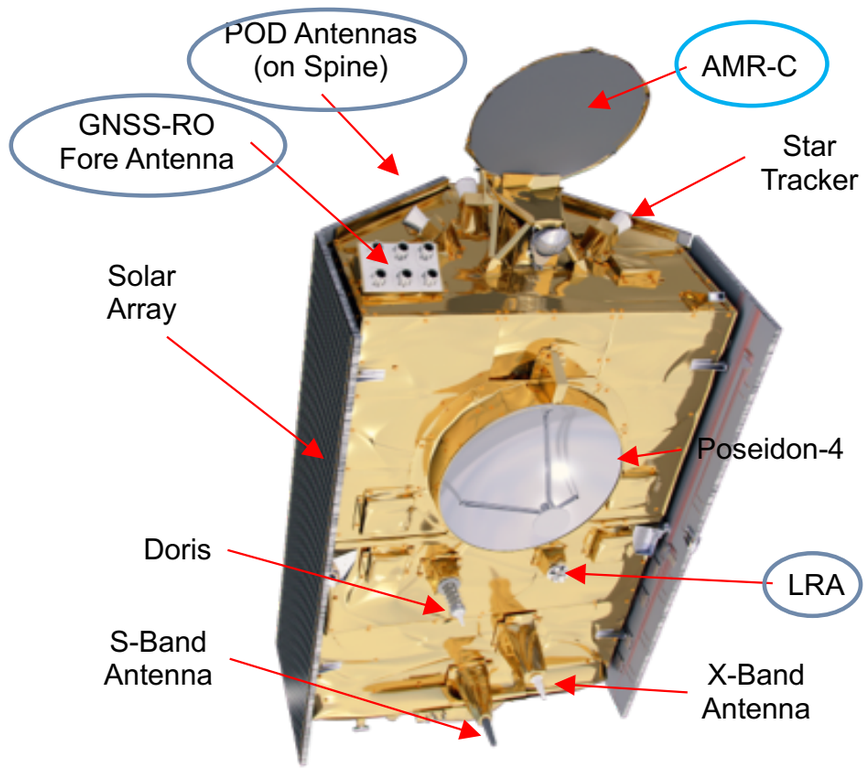
NASA responsible items in BLUE



- Launch Dates: Nov 21, 2020 (S6 Michael Freilich), Nov 2025 (TBC)
- Launch Vehicle: SX F9 for S6-MF; TBD for S6-B
- Project: Cat II
- Risk Class: B for (AMR-C & LRA); C for GNSS-RO
- Spacecraft Bus (Airbus: Cryosat Heritage)
- Mission life of 5 ½ years (goal of 7 ½ years)
- **1336 km Orbit, 66º Inclination**

Flight System Overview

	Instruments	Measurement Descriptions
Range	Poseidon-4: Radar Altimeter	Measures distance between the satellite and the sea surface; includes SAR mode for improved coastal region measurements
Range	Advanced Microwave Radiometer (AMR-C)	Water vapor path delay corrections; includes new high frequency channels for higher resolution in coastal regions (HRMR)
POD	DORIS	POD receiving RF signal from Earth-based beacon system.
POD	GNSS-POD	POD receiving RF signal from GPS and Galileo satellites
POD	Laser Reflector Array (LRA)	Supports POD reflecting laser from ground-based stations
RO	GNSS-RO (TriG)	Atmospheric profiles based on measurement of bending angles from GPS and GLONASS satellites



NASA instrument

POD: Precise Orbit Determination
RO: Radio Occultation
HRMR: High Resolution Microwave Radiometer

NASA Level 1 RO Requirements

Sentinel-6 Key L1 Requirements
Baseline
The Sentinel-6 project shall measure bending angle and refractivity profiles using radio occultation observations to infer information on atmospheric temperature and humidity for weather forecasting and climate monitoring.
The following baseline requirements are specific instrument performance requirements for NASA-provided instrument development in support of the baseline mission radio occultation science objectives. ***There are no Threshold requirements*** associated with the Radio Occultation measurement.
The GNSS-RO instrument shall be designed with a baseline mission lifetime of three years.
The GNSS-RO instrument shall be capable of providing a minimum of 770 profiles per day for the baseline mission.
The maximum Root Sum Square (RSS) measurement uncertainty of the neutral bending angle shall be per Table 4.1 for each specified altitude range.

Table 4.1: Bending Angle Measurement Uncertainty

Requirement #	MSL Altitude Range	Bending Angle Uncertainty (microrad)	Vertical Resolution (km)
4.3.2.3	10-20 km	30	0.15
4.3.2.4	20-30 km	3	1.5
4.3.2.5	30-60 km	2	1.5

RO Mission Data Products

Producer	Latency	Format	User Data Access GTS	Archive
JPL	**NRT (3 h)**	**BUFR**	**L1b, L2**	**–**
EUMETSAT	**NTC (60 d*)**	**NetCDF**	**–**	**L1b**
EUMETSAT /ROM SAF	**NTC (60 d*)**	**NetCDF**	**–**	**L2**
JPL	NTC (60 d*)	NetCDF	–	L1b, L2
JPL	NRT (best efforts)	NetCDF	–	L1b, L2 (for 60 d)

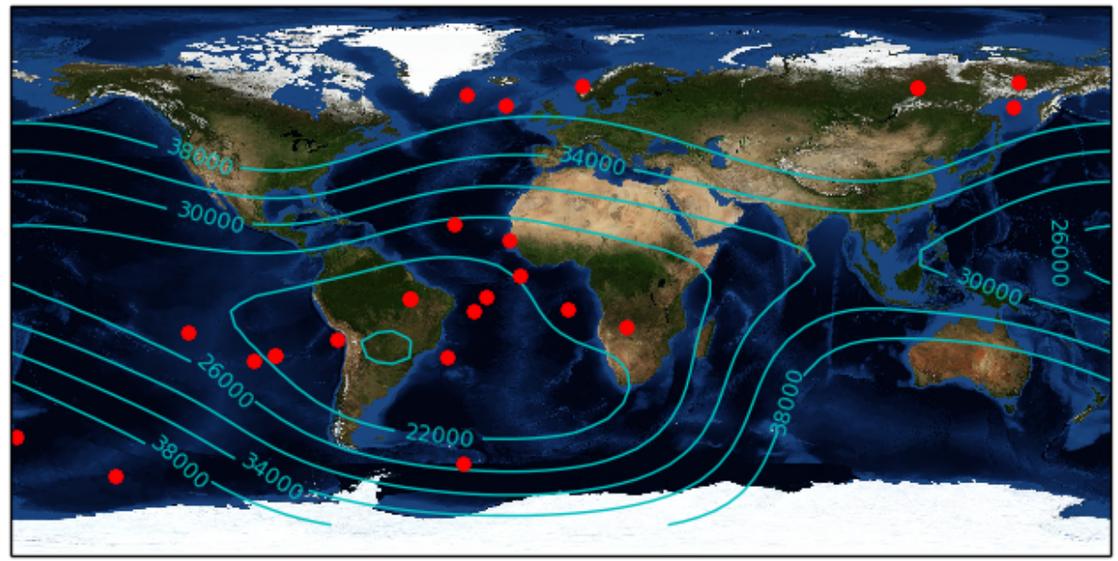
* ~ 16 d actual expected

NRT: Near-Real-Time
NTC: Non-Time-Critical

L1b: Bending angle profile with impact parameter
L2: Refractivity profile with mean-sea-level altitude

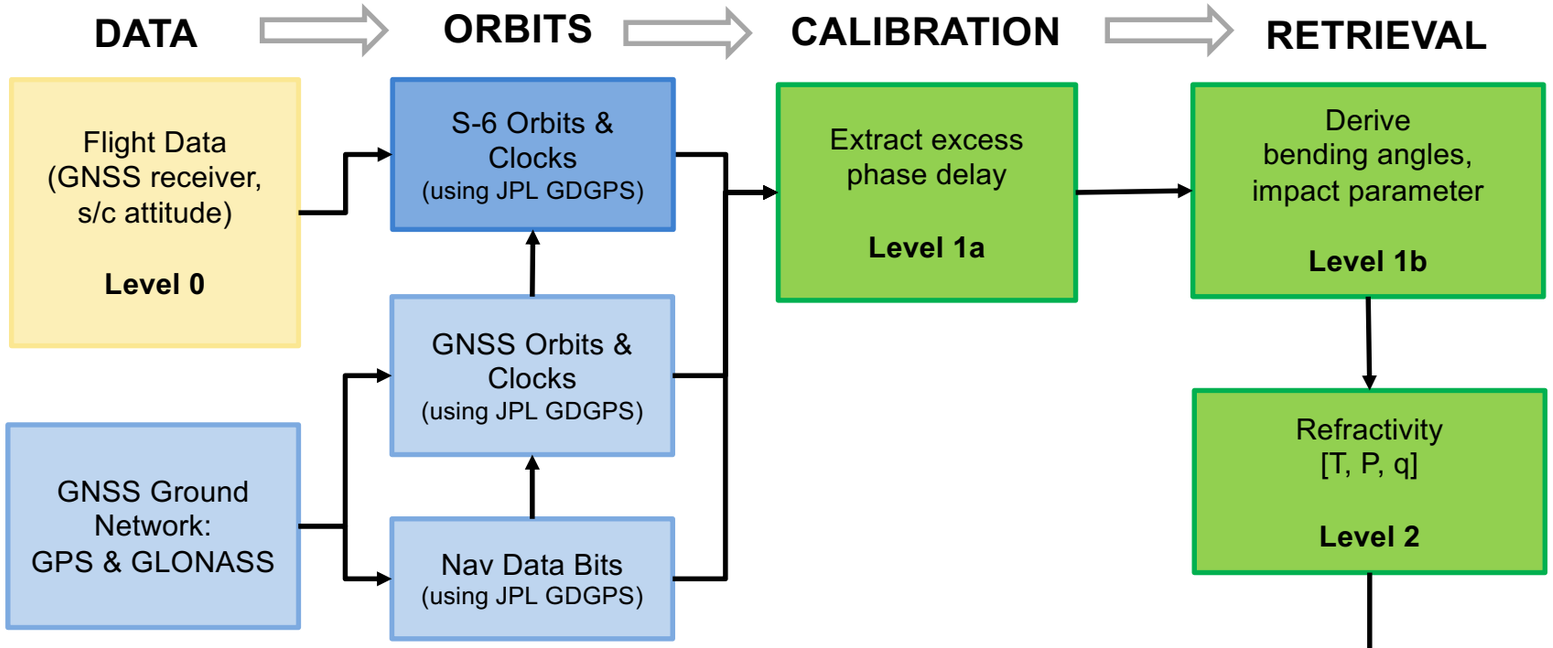
GNSS-RO Instrument Status

- **The GNSS-RO instrument was turned on 1 week after launch.**
- Antenna beam-forming was enabled by default and works as expected.
- Instrument power and temperature were within expected and acceptable limits.
- Receiver team has completed the on-orbit operations needed for instrument checkout and Cal/Val, including beamforming checks, tracking altitude adjustments, deep tracking, and L2C POD tracking confirmation.
- Autonomous reboots occur once every ~3 days (slightly less frequent than expected pre-launch), mainly over the SAA and high latitudes.



The instrument is healthy with software updates being planned to enhance number of occultations and to address some intermittent issues.

JPL RO Data Processing



Radio Occultation Atmospheric Retrieval Software (ROARS)

Level	Format	Description
0	Instrument Format	Raw POD and RO phase data
1A	JPL Specified	Excess phase with time
1B	BUFR (NRT) NetCDF (NRT, NTC)	Time, location, and bending angle vs. impact parameter
2	BUFR (NRT) NetCDF (NRT, NTC)	Time, location, and refractivity over geometric height

NRT Latency Assessment

- **Assessment from Jan, 2021**:

Stage	Mean (min)	Maximum (min)
Last sensing time of first occ → GNSS-RO L0 creation time	112.1	119.0
GNSS-RO L0 creation time → ROP start at GOC-DN	3.63	8.72
ROP processing time	6.70	7.35
Delivery to NOAA/GTS	6.5*	6.5*
Total latency	129.0	136.2
Margin on 3 h	51.0 (28.3%)	43.8 (24.3%)
Pre-launch best estimate	150.7	168.5

← 17 min allocation

* per latency budget since dataflow not yet active

- **NTC Validation Product Requirement**: 60 d from last moment of first sensing to availability at NASA/GES DISC archive
  - Current assessment is within 16 d based on a typical day (significant margin)
  - Almost all of the latency is waiting for GNSS Final POD products to be generated

S-6 POD: Initial Assessment

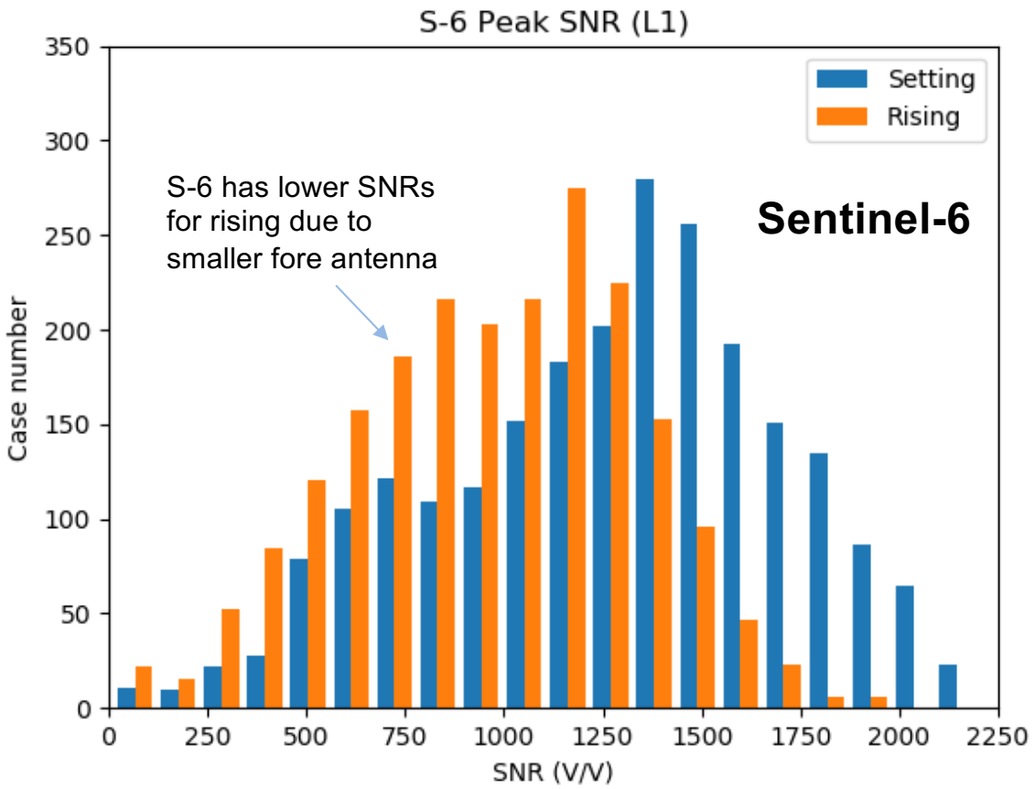
- Position requirement: 10 cm RMS difference per axis
- Velocity requirement: 0.1 mm/s RMS difference per axis with a goal of 0.05 mm/s along-track

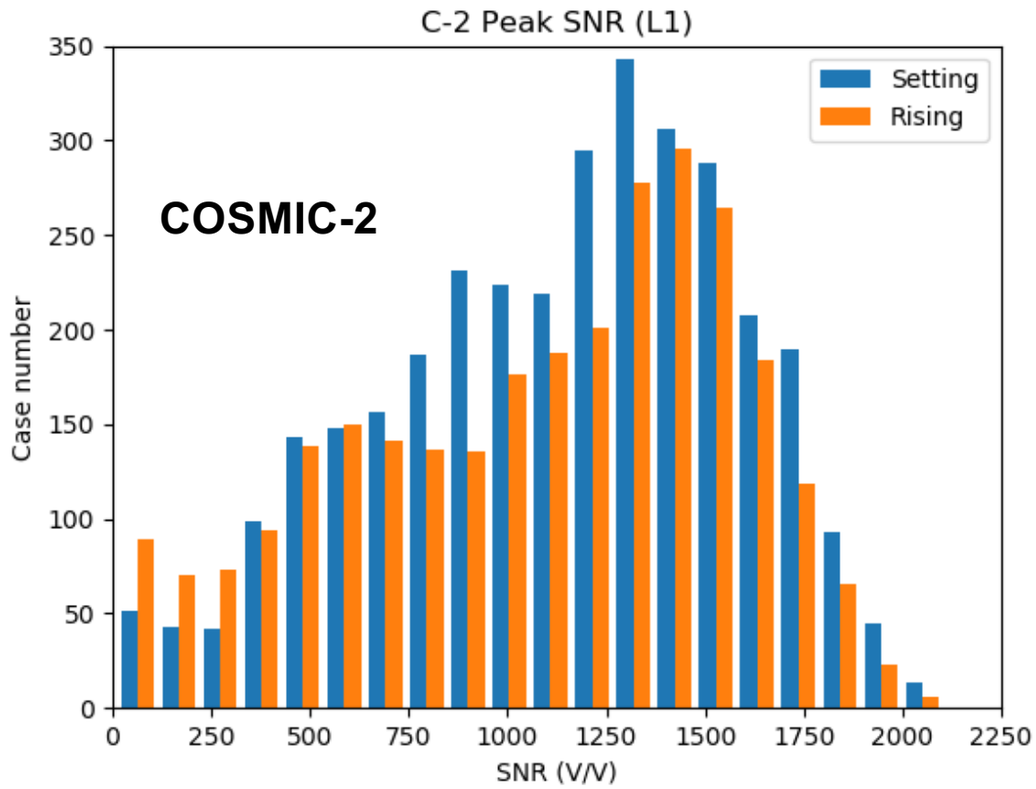
- Current assessment of NRT solutions based on orbit overlaps of latest common 2 hours
- Current assessment of NTC solutions based on orbit overlaps of common 6 hours
- Assessment from Jan, 2021:

Latency	RMS of position differences (cm) in HCL			RMS of velocity differences (mm/s) in HCL		
NRT	H: 2.17	C: 0.63	L: 2.34	H: 0.022	C: 0.004	**L: 0.014**
NTC	H: 1.38	C: 0.57	L: 1.36	H: 0.021	C: 0.005	**L: 0.009**

- Improvements and analyses are ongoing but initial indications are that requirements should be met with margin

Instrument Performance: SNR



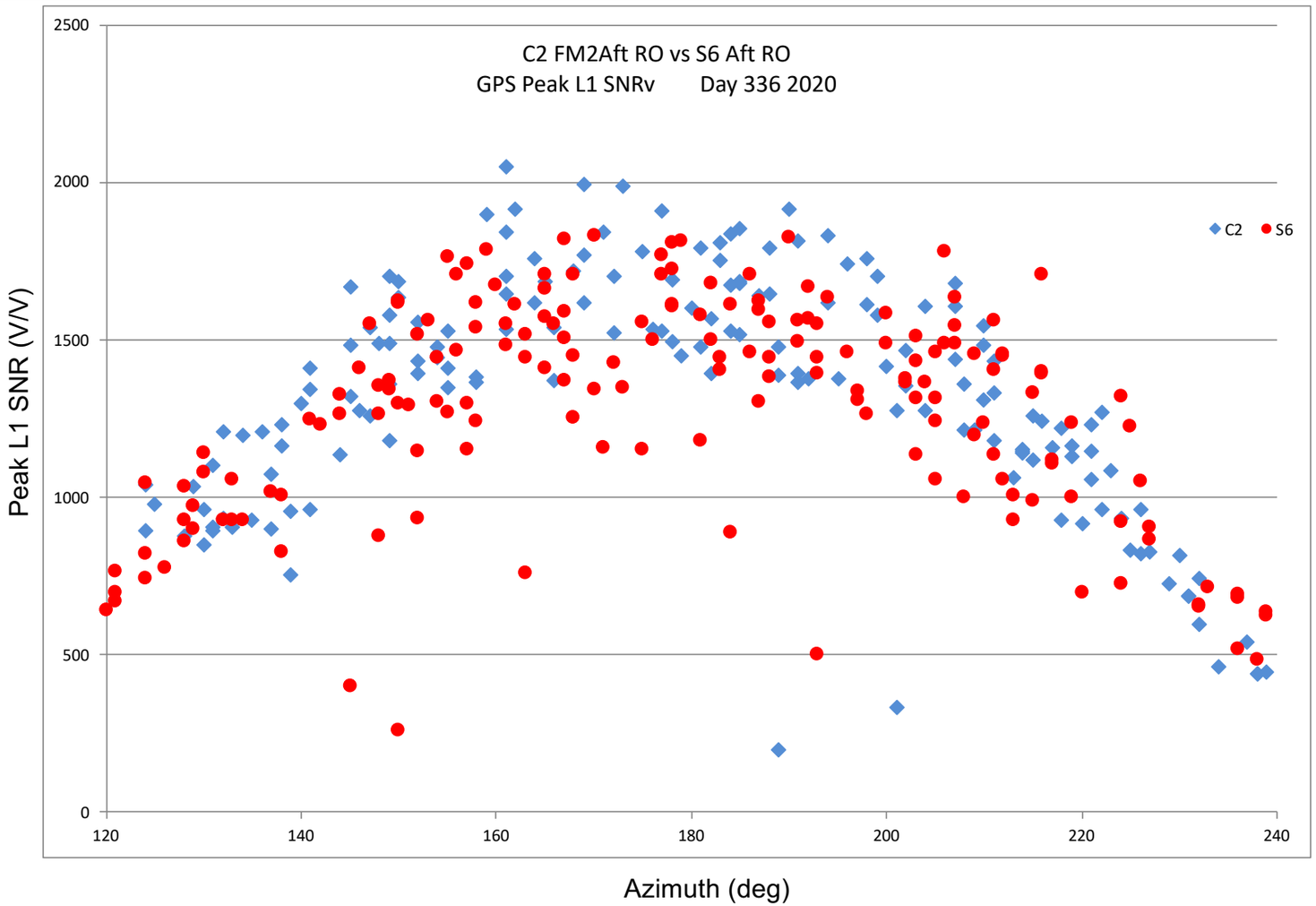


- **Setting RO SNRs are consistent with COSMIC-2.**
- **Rising RO SNRs lower due to lower-gain antenna.**

Instrument Performance: SNR

Azimuthal distribution of SNR from S-6 setting (aft-looking) occ matches COSMIC-2

(after adjusting for higher orbital altitude of S-6)



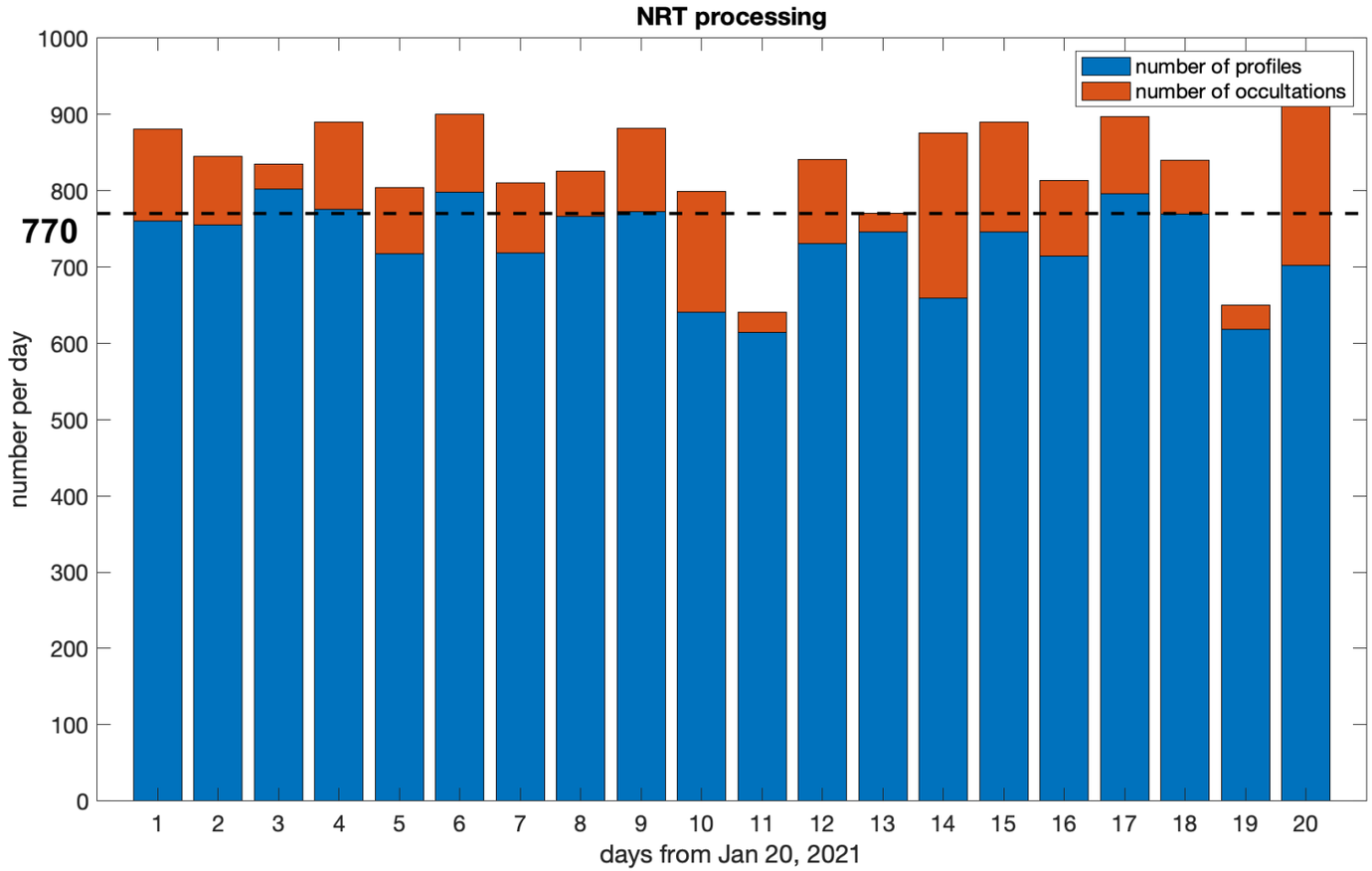
Number of Occultations & NRT Profiles

The average number of occultations tracked daily has been slightly lower than expected.

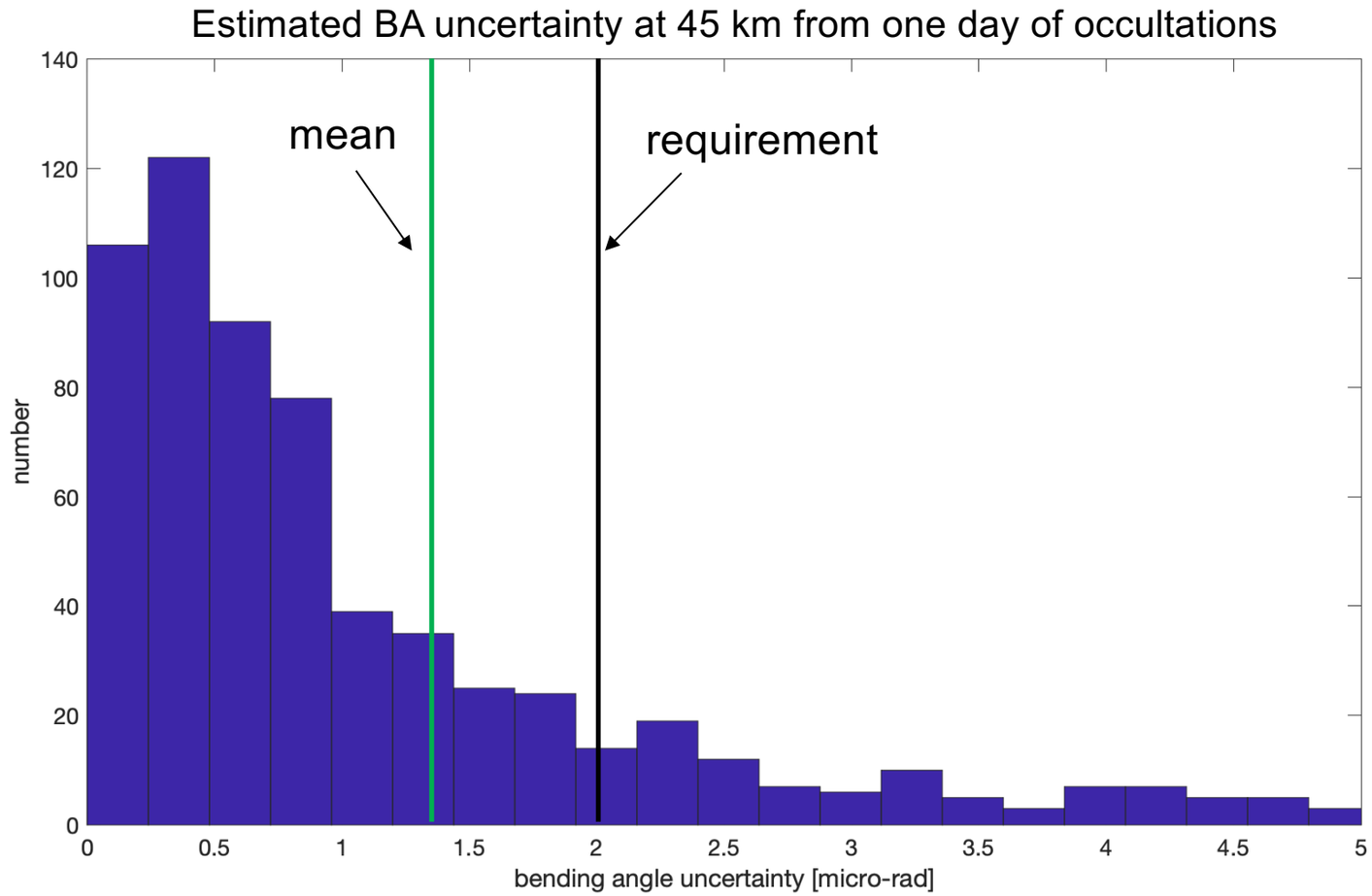
~ 831 occ/day acquired
~ 730 profiles/day retrieved

Requirement is 770 profiles/day

- Derived assuming full GPS and GLONASS constellation.
- Lower number is due largely to several unhealthy GLONASS satellites (~ 10% drop in total number).
- Some rising GLONASS occultations are not being tracked
  - Flight s/w update in progress to optimize GLONASS tracking that will increase number of occ.



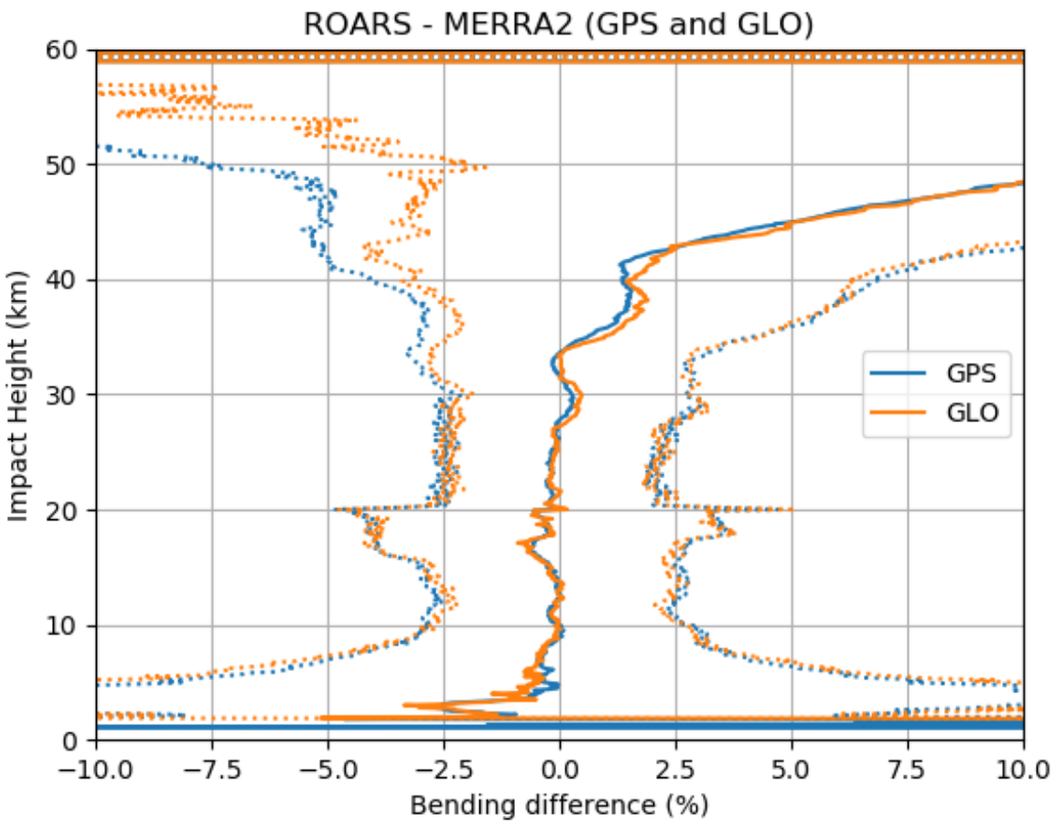
NRT Bending Angle Performance: Initial Assessments



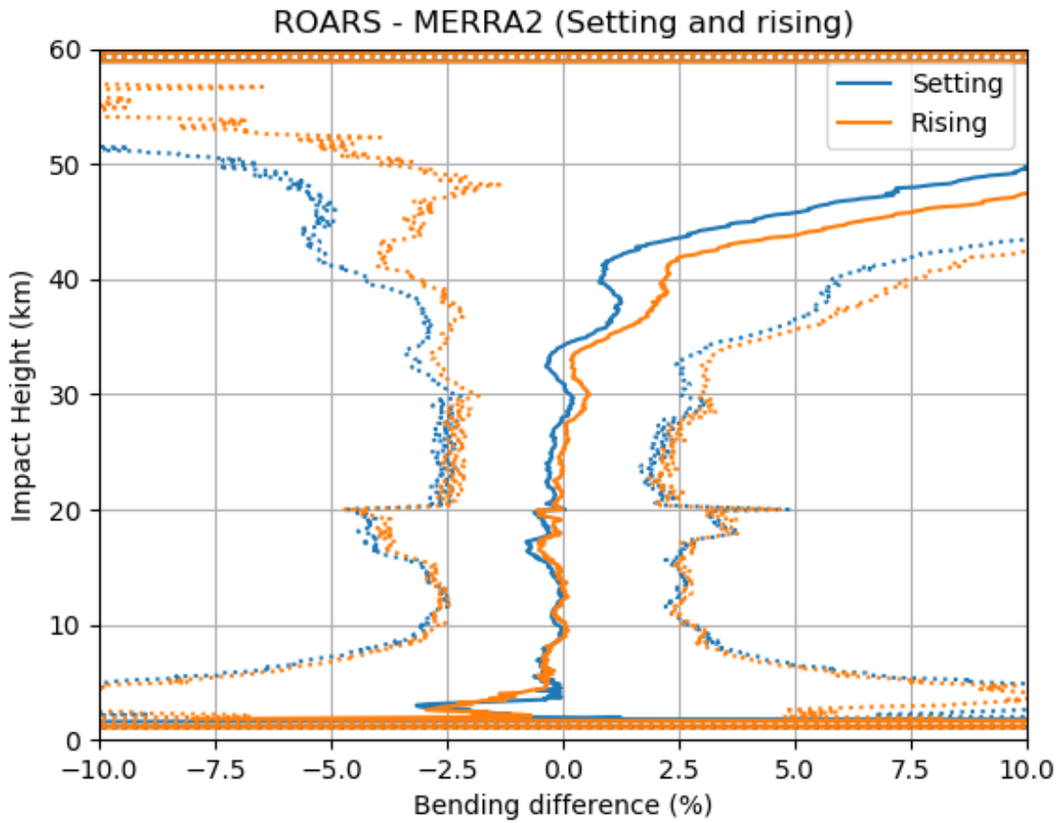
Mean BA accuracy was found to meet the mission requirement to better than 2 micro-rad above 30 km.

- Initial assessment focuses on high altitudes (easier to characterize noise).
- Assessment below 30 km ongoing.

Bending Angle vs Reanalysis



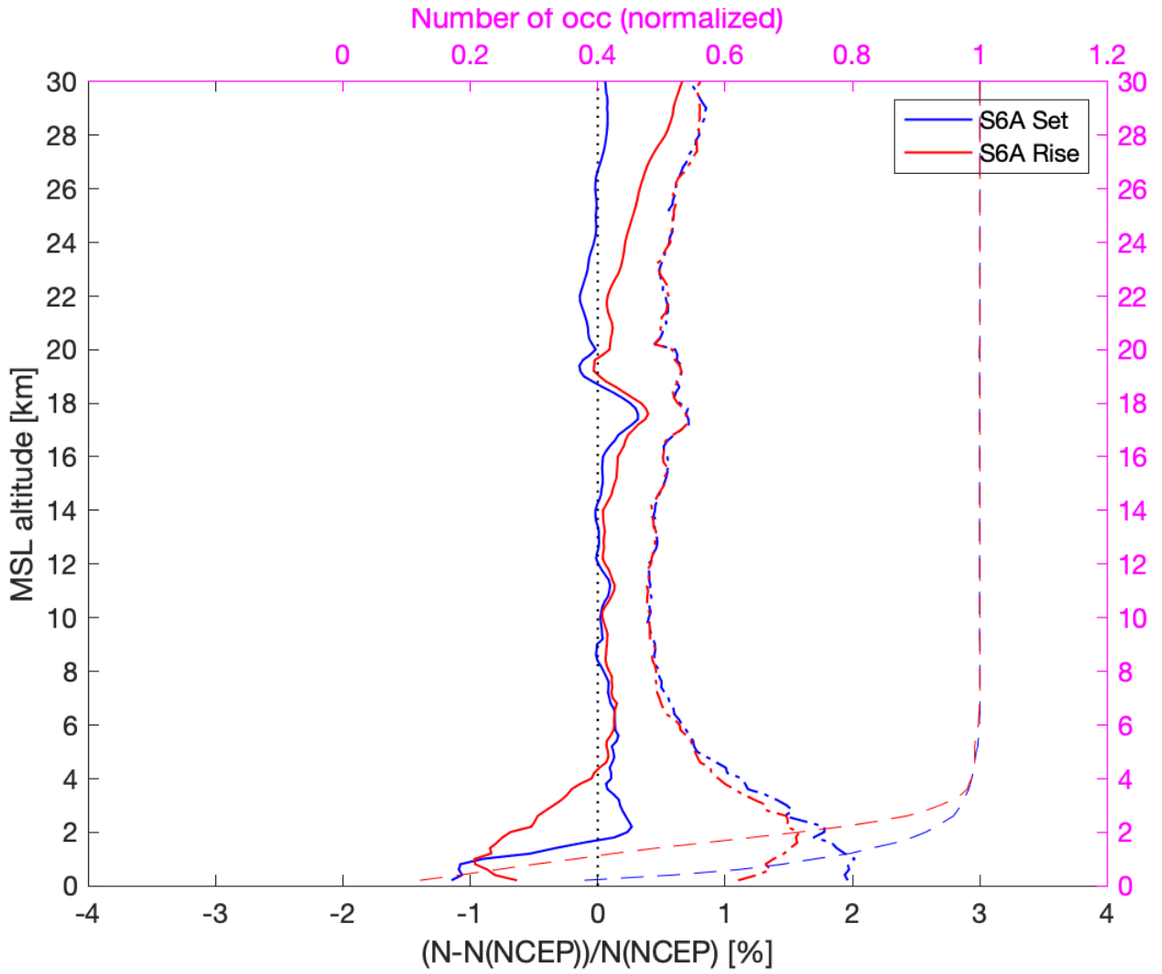
Similar mean/stdev for GPS vs GLO



Small bias between setting vs rising

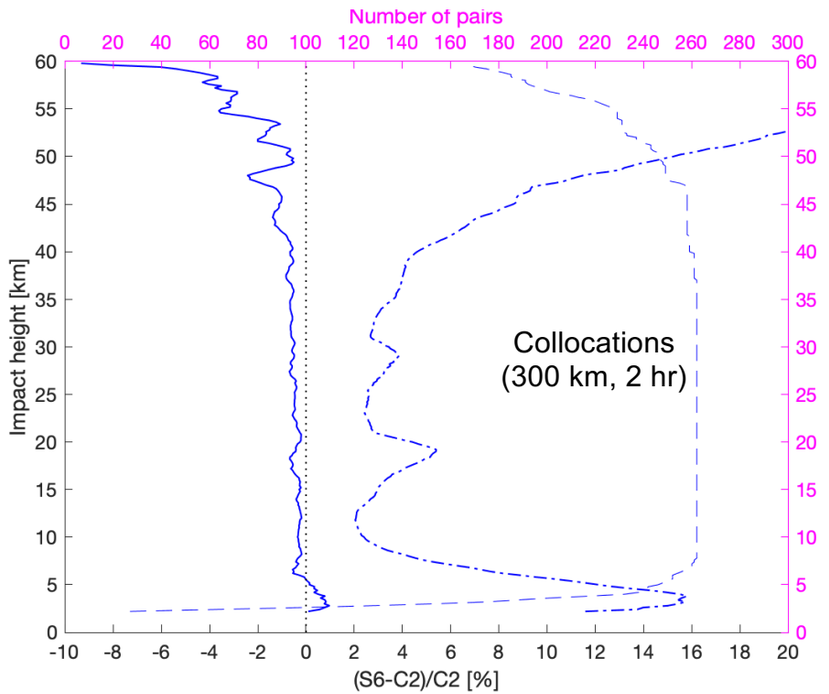
Setting vs Rising

- **S-6 rising occ retrievals have some issues that have been identified.**
  - A positive bias above 20 km (~ 0.5% at 30 km).
  - Worse profile penetration in the lowest ~ 4 km.
  - The issues with rising occultations are believed to be due to processing instead of the smaller SNRs of these measurements.

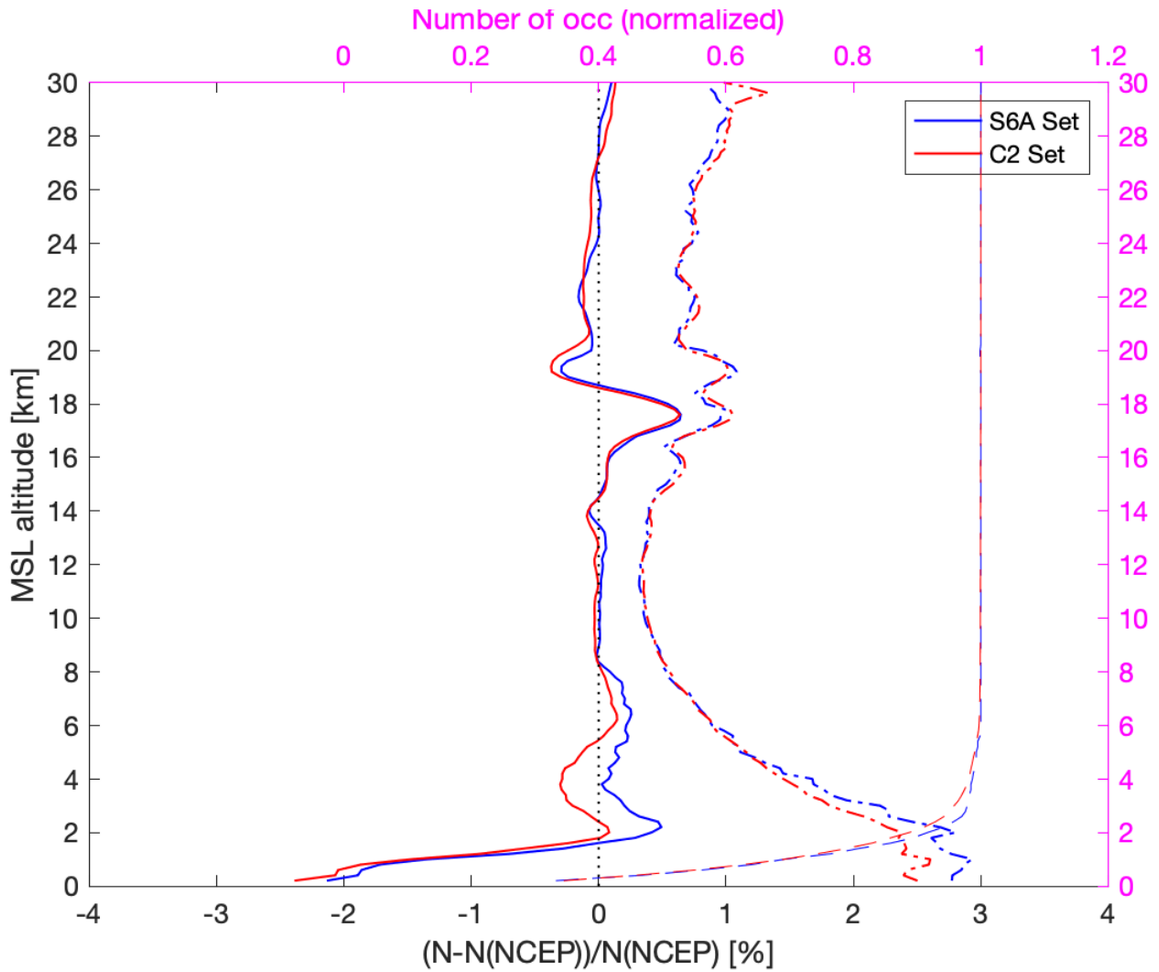


Tropics (30S-30N)

- **S-6 setting occ retrievals perform similarly to COSMIC-2.**



Bending angle difference between collocated S-6 & C-2 occultations



Product validation: NWP partners

- **NWP partners**:
  - European Centre for Medium-range Weather Forecasts (ECMWF)
  - U.K. Met Office (UKMO)
  - Joint Center for Satellite Data Assimilation (JCSDA)
  - Others: ROM SAF & NOAA STAR

- **Roles and responsibilities**:
  - Passive monitoring to compare Sentinel-6 RO observations to background models (results after about 1 month)
  - Impact of Sentinel-6 RO products on weather forecasts via trial experiments within 2-3 months

- **Status**:
  - Provided NRT BUFR products starting March 22, 2021
    - Products from first week in Feb, 2021 will be followed by a month of products starting from Feb 26, 2021
  - NTC products (generated by EUM) are made available as well.

Product Release Timeline

RP1 (Review Point #1): Release NRT data to NWP center partners for evaluation based on initial assessment of NRT data (minimum 2000 profiles).

RP2: Begin release NRT data to GTS and NASA DAAC based on extended assessment of NRT data (minimum 10000 profiles) and partner feedbacks. Routine operation begins.

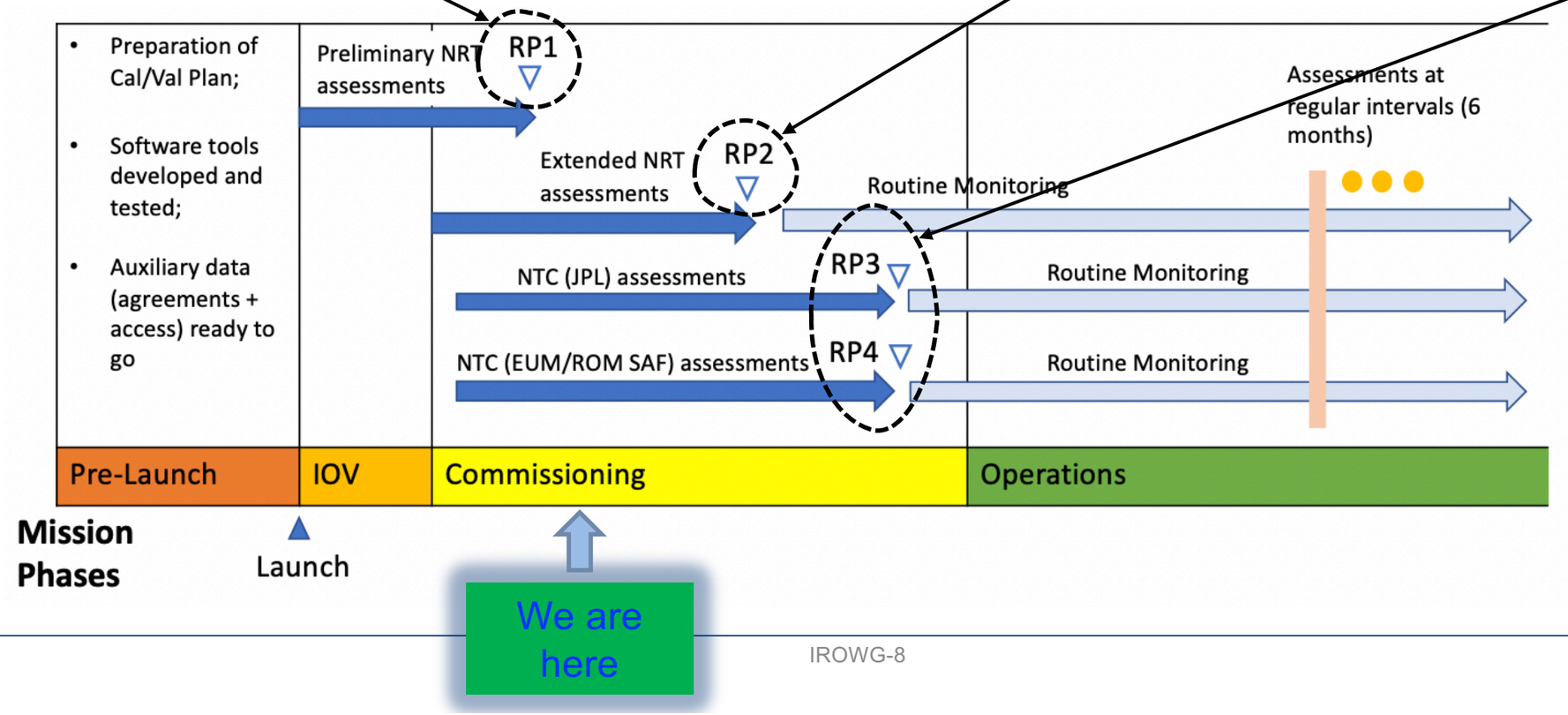
RP3: Begin release of NTC data (JPL) to NASA DAAC.

RP4: Begin release of NTC data (EUM/ROM SAF) to archive/public.

NRT L1B & L2 BUFR products ~ L+3 mos

NRT L1B & L2 BUFR products ~ L+6 mos

NTC L1B & L2 netCDF products ~ L+9 mos



Summary

- Sentinel-6 MF is expected to provide ~ 700-900 GNSS-RO profiles each day for at least 3 years (expected longer), with < 3 hr latency needed for NWP data assimilation.
- It will complement COSMIC-2 by providing global coverage with similar performance.
- Together with Sentinel-6B (2025 launch), Sentinel-6 will contribute towards long-term availability of RO measurements for climate monitoring.
- Initial evaluation shows good quality POD solutions and RO retrieved profiles, although some issues with rising occultations have been noted and are under investigations.
- RO data products are now available to our NWP partners for independent assessments of RO products. Public release is currently expected in ~ June 2021.