Sentinel-6 A GNSS-RO NTC Cal/Val Report

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Change Record

Version	Date	DCR* No. *if applicable*	Description of Changes
v1	15/09/2021		Initial version send for review and information.
v1A	04/10/2021		Inputs from review included, added NTC to title. Input to PVRB, with some sections outside of the PVRB scope identified to require updates.
v1B	15/10/2021		Included comments from co-authors on e.g. instrument re-boots, some editorial clarifications. Added Commissioning WBS/WP to traceability matrix in Section 7.3. Added limitation section, capturing possible future updates. Made read-only as input to IOCR, PVRB.
v1C	18/11/2021		Addressed PVRB comments. Included a 1 month GRAS PPF v5 comparison, included updated RO-NTC v3.4 vs 3.5 plot, included additional POD validations against CNES orbits. Updated instrument related information up to mid November. Limitations section addressed and removed.
v1D	11/03/2022		Updated general instrument and orbit related information, covering events that occurred after release of v1C (primarily updates to Executive Summary, Sections 2, 3, 7, 8). Scientific validation is not updated.
v1E	01/11/2022		Updated to cover recent yaw flips, processor updates, instrument issues and operations after release of v1D (primarily to Executive Summary, Sections 3, 7, 8), up to 31 October 2022. Signature table updated.

DCR = Document Change Request

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EXECUTIVE SUMMARY

A validation of EUMETSAT's Non Time Critical (NTC) bending angle products derived from observations taken by the GNSS-RO instrument on-board of the Sentinel-6 Michael-Freilich (S6A) satellite is presented. These NTC bending angles provide higher quality than the ones delivered by NASA/JPL in Near Real Time (NRT), as they make use of improved GPS and GLONASS orbits and clocks. The timeliness of NTC data is given in the End User Requirements Document (EURD), and is formally within 60 days. The improved GPS/GLONASS orbit and clock data though is delivered latest after 18 days, and thus timeliness does not exceed 3 weeks.

The GNSS-RO instrument can make use of GPS and GLONASS satellites for occultation measurements (the orbit determination though relies on GPS only). Generally, there are about 30 GPS satellites available, and 24 GLONASS ones, so the majority of the occultations are GPS based. In addition, processing of the initial GLONASS data showed that 3 of them are not providing data on the second frequency, making them unusable. Consequently, it was decided to block the tracking of these faulty satellites (by an on-board instrument s/w update in early June 2021), and only 21 GLONASS ones were tracked after the update. Additionally, another two GLONASS satellites dropped out of the available satellites for occultations mid-December 2021 and mid-June 2022 (albeit this satellite is again observed since 6th of October 2022).

The mentioned June 2021 s/w update also improved the autonomous monitoring of the instrument, that initiates re-boot commands to the science processor if issues are found within the occultation data. This is not unexpected for the high-radiation environment of the GNSS-RO. One major issue here was the occasional loss of all GLONASS data for longer periods. Within the early mission phase, this was resolved by a manual re-boot, the updated s/w now performs those autonomously.

From instrument switch-on, on the 28th of November 2020, up to 31st of October 2022, more than 710k occultations were recorded by the GNSS-RO instrument, about 61% from the GPS constellation, and about 39% from GLONASS. The number of daily occultations improved with the mentioned on-board s/w update, but also with an increase in the observed azimuth angles in May 2021, it is now generally above the 770 quality controlled profiles per day, fulfilling the EURD requirement (the number of functioning GLONASS satellites is though recently depleting, reducing the overall performance). Exceptions are found e.g. during yaw flip manoeuvres (this leads to lower data quality, as the antenna beam forming needs to be re-calibrated), if there are issues with the auxiliary data provided, or the instrument.

The actual NTC S6A orbit and bending angle quality is very high, similar to EPS/GRAS data, for bending angles this was also confirmed by independent assessments at ECMWF and MetOffice. E.g. assimilating the data into the ECMWF model yielded improved forecasts. These impact trial experiments included in addition the NRT data, confirming that the EUMETSAT NTC data has a larger impact – as expected since the data uses higher quality auxiliary inputs in the processing. There are three EURD requirements that capture the bending angle quality for different altitude regions. Within these investigations we could not fully confirm compliance to these requirements, as any data used for validation has its own uncertainly, adding to the overall uncertainty budget. Please note that similar issues are also observed for EPS/GRAS and COSMIC-2 assessment.

Overall, the EUMETSAT NTC data is compliant to the EURD requirement, and generally compliant to the EURD number of daily products and bending angle quality requirement. The daily number of products should increase further once the faulty GLONASS satellites are replaced. Several RO-NTC processor updates further improved the data quality and quantity further, compared to the results presented here (based primarily on processor v3.4). Most recent processor information, addressed anomalies, product notice information is available here.

1 INTRODUCTION

This report provides the results of the Calibration and Validation ("Cal/Val") activities carried out for the Non Time Critical (NTC) products of the GNSS-RO instrument on-board the Sentinel-6 Michael-Freilich (S6A) satellite; it is presented to a EUMETSAT validation board that determines whether the data can be provided with an operational status. NTC products are of higher quality than the Near Real Time (NRT) ones, since they use higher quality auxiliary data; they are made available in particular for climate and re-analysis applications. Several NTC products are produced within the mission, some can have a timeliness of up to 60 days; for the GNSS-RO data, timeliness is though about 2-3 weeks. It also includes instrument related updates that happened after November 2021 instrument commissioning.

The S6A satellite was launched into a Low Earth Orbit (LEO) on 21st November 2020 from the Space Launch Complex at Vandenberg Air Force Base in California, with the GNSS-RO instrument being switched on a week later. We demonstrate that the quality of the GNSS-RO level 1b NTC products obtained from the S6A satellite are of the same quality (and very consistent with) those of operational GRAS products from the Metop-A, -B and -C satellites, justifying the inclusion of S6A GNSS-RO L1B NTC products in the operational product portfolio of EUMETSAT. The validation is primarily based on a best effort reprocessing run of the version 3.4 of the RO-NTC processor, in order to have a longer data set available. Relevant differences with the v3.5 processor that is the base for operational data dissemination are discussed. In addition, updates from the v3.6 processor, deployed in April 2022, are also covered.

The activities described in this Cal/Val Report are partly based on the planning provided in [AD-01].

All validation results described in this report up to v1B/C were presented and discussed in several ROWG (Radio Occultation Working Group, a technical working group formed by the S6 partner project management team to coordinate RO related items throughout the project) meetings, as well as at the Product Validation Reviews (PVR) on 26th of October 2021. The PVR Board (PVRB) authorised the release of the GNSS-RO L1B NTC product as "operational", releasing them to the general public on the 29th of November 2021 (production date).

The PVR was followed by an Operational Readiness Review (ORR) of the ROM SAF for the L2 NTC products on 24th of November 2021, the validation reports are available at [RD 1, RD 2]. Data was released to the user on 16th December 2021 (production date).

1.1 Scope

This report at v1B was an input to the PVRB meeting and thus initially restricted to EUMETSAT, ROM SAF, NASA/JPL, and NWP Partner colleagues working on/with GNSS-RO data. After the PVRB meeting, and release of the NTC data operationally, it was updated to v1C and provided on the EUMETSAT website, available to the public. v1D covered only instrument related updates, released with the processor version 3.6, the validation was untouched. v1E covers instrument related updated with processor v3.7.

1.2 Applicable Documents

	Document Title	Reference*
AD-01	Sentinel-6 Project GNSS-RO Calibration and Validation Plan	JPL D-100955
AD-02	Sentinel-6 End-User Requirements Document	EUM/LEO-JASCS/REQ/12/0013

1.3 Reference Documents

	Document Title	Reference*
RD 1.	Validation Report for Sentinel-6 NTC Level 2 refractivity and dry temperature products (GRM-117, GRM-118)	SAF/ROM/DMI/REP/ATM/003
RD 2.	Validation Report for Sentinel-6 NTC Level 2 1D-Var products (GRM-119, GRM-120, GRM-121, GRM-122)	SAF/ROM/DMI/REP/1DVAR/003
RD 3.	Sentinel-6 Project GNSS-RO Level 0 Decoder Software Description Document	JPL D-101407
RD 4.	YAROS v2.0-rc7 Yet Another Radio Occultation Software - Release Notes	EUM/RSP/TEN/21/1219323
RD 5.	YAROS v2.0-rc11 Yet Another Radio Occultation Software - Release Notes	EUM/RSP/TEN/22/1285652
RD 6.	Sentinel-6 Project GNSS-RO Auxiliary File Specification	JPL D-100948
RD 7.	Jason-CS/Sentinel-6 RO Level 1B Auxiliary Data Specification	EUM/LEO-JASCS/SPE/16/882105
RD 8.	Jason-CS/Sentinel-6 RO Level 1B NTC Product Generation Specification	EUM/LEO-JASCS/SPE/17/899378
RD 9.	Jason-CS/Sentinel-6 RO Level 1B Product Format Specification	EUM/LEO-JASCS/SPE/16/882399
RD 10.	D. Hoaglin, F. Mosteller, and J. Tukey, Understanding Robust and Exploratory Data Analysis, John Wiley & Sons, 1983	
RD 11.	D. Klaes et al, The EUMETSAT Polar System: 13+ Successful Years of Global Observations for Operational Weather Prediction and Climate Monitoring, Bulletin of the American Meteorological Society	https://doi.org/10.1175/BAMS-D-20-0082.1
RD 12.	W.S. Schreiner et al, COSMIC-2 Radio Occultation Constellation: First Results, Geophysical Research Letters	https://doi.org/10.1029/2019GL086841
RD 13.	The Radio Occultation Processing Package (ROPP) Overview, Version 10.0	SAF/ROM/METO/UG/ROPP/001
RD 14.	Dach, R., S. Lutz, P. Walser, P. Fridez (Eds); 2015: Bernese GNSS Software Version 5.2. User manual, Astronomical Institute, University of Bern, Bern Open Publishing; ISBN: 978-3-906813-05-9	https://boris.unibe.ch/72297/
RD 15.	IGS Products	https://igs.org/products/
RD 16.	ESA/ESOC, NAPEOS Mathematical Models and Algorithms, 2009	DOPS-SYS-TN-0100-OPS-GN
RD 17.	Sentinel-6 Michael Freilich GNSS-RO Near-Real-Time Science Data Product Release, JPL D-103443 Initial, CL#21-3575, Aug 3, 2021	Available here (01 Sept 2021)
RD 18.	Jason-CS Commissioning Plan	EUM/LEO-JASCS/PLN/19/1114520
RD 19.	Sentinel-6 Michael Freilich Product Notice (Radio Occultation NTC)	EUM/LEO-JASCS/DOC/21/1253471 (also available on EUMETSAT website)

**Note that some Reference hyperlinks work only within EUMETSAT's intranet, some might have restricted access.*

1.4 Terminology

Acronyms and Abbreviations

Acronym/Abbr.	Explanation
AR	Anomaly Report
BUFR	Binary Universal Form for the Representation of meteorological data
CCSDS	Consultative Committee for Space Data Systems
CNES	Centre national d'études spatiales
CPF	Common Processing Facility
CSW	Central On-Board Flight S/W
ECMWF	European Centre for Medium Weather Forecast
EURD	End User Requirements Document
FDMA	Frequency Division Multiple Access
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema (Russian)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (US)
GRAS	GNSS Receiver for Atmospheric Sounding
GTS	Global Telecommunication System
IGS	International GNSS (Global Navigation Satellite Systems) Service (formerly International GPS Service)
JCSDA	Joint Center for Satellite Data Assimilation
L2TA	GPS L2P Tracking Altitude
LTA	Lowest Tracking Altitude
NAPEOS	NAvigation Package for Earth Orbiting Satellites
MOEG	Medium Orbit Ephemeris GNSS
NRT	Near Real Time
NTC	Non Time Critical
NWP	Numerical Weather Prediction
POD	Precise Orbit Determination
POE	Precise Orbit Ephemeris
PVR(B)	Product Validation Review (Board)
PRN	Pseudo Random Noise (identifying GNSS satellite, with G: GPS; R: GLONASS)
PUS	Packet Utilisation Standard
RaUn	Random Uncertainty (also called Standard Deviation)
RMS	Root Mean Square
RO	Radio Occultation
ROM SAF	Radio Occultation Meteorology Satellite Application Facility
ROPP	Radio Occultation Processing Package
RTH	Ray Tangent Height (aka SLTA)
S6(A)	Sentinel-6 (A)
SEU	Single Event Upset
SLTA	Straight Line Tangent Altitude (aka RTH)
SNR	Signal to Noise Ratio
STC	Short Time Critical
SyUn	Systematic Uncertainty (also called Bias)
TCE	Technical Computing Environment
UCAR	University Corporation for Atmospheric Research
WMO	World Meteorological Organization

Definitions

Definition/Term	Explanation
Level 0 Data	reconstructed raw sounding data at full time resolution with all available supplemental instrument information, to be used in subsequent processing
Level 0R Data	Level 0 occultation data, reconstructed to phase, SNR and amplitude
Level 1a Data	individual occultations full information such as phases and amplitudes, Signal to Noise Ratios (SNRs), as well as all other information e.g. from the Precise Orbit Determination (POD), needed to process it further to Level 1b
Level 1b Data	Level 1a sounding data that have been processed to bending angles and impact parameters, tangent point location, and quality information
Occultation (EURD)	The EURD [AD-02] uses the term occultation for all measurements prior to Level 1b data.
Profile (EURD)	The EURD [AD-02] uses the term profile for all nominal measurements at Level 1b. Note that within this Cal/Val report, this occultation / profile distinction is not made throughout.

1.5 Document Structure

Section 1 Introduction, document references, acronyms
Section 2 Overview of the processing setup, applied metrics
Section 3 Overview of the satellite and instrument
Section 4 Analysis of the Precise Orbit Determination
Section 5 Analysis of the level 0r data
Section 6 Analysis of the level 1b data
Section 7 Requirements, Anomalies, Cal/Val Task traceability
Section 8 Conclusion, Issues and Limitations

1.6 Acknowledgements

We are grateful to several internal and external colleagues for fruitful discussions. External special thanks go to Stig Syndergaard and Kent Lauritsen (DMI, Denmark), Chad Galley, Chi Ao, Tom Meehan, and Angie Dorsey (NASA/JPL, US), Shu-Peng (Ben) Ho (NOAA, US). Internal special ones go to Teoman Unal (EUMETSAT/SEP).

2 PROCESSING SETUP OVERVIEW

2.1 Sentinel-6 Data Sets and Processing

Most S6A data presented in this document is either output generated by the RO-NTC processor at level 0 (using the JPL L0Decoder v1.3 [RD 3]) or is generated with the RO-NTC processor version 3.4 (based on Yaros release 2.0rc7 [RD 4]). The latter is using a reprocessing setup in the Common Processing Facility (CPF) DEV environment to allow an assessment of all data since GNSS-RO start up. All available GNSS-RO level 0 data was used, both, regular and archive dumps, up to including 11th of September 2021; regarding level 1b, data up to including August 31st, 2021 was used. Exceptions to v3.4 data use are (1) for timeliness assessments, the first operationally deployed RO-NCT v3.4 processor output on the CPF was used, with all available data from the CPF up to the 31st of August 2021; (2) to show the improved agreement to GRAS PPF v5 data (which only became available after the main validation period used here), October 2021 data from the operational processing of GRAS and S6A were used. In addition, some instrument events info, such as yaw flips, as well as general occultation information, is included up to 31st of October 2022 (within Section 3).

The processor RO-NTC v3.4 did not reflect the latest processor and L0Decoder updates, as we used reprocessed data to cover the full period of the S6A mission. Thus first operational data is actually coming from processor version 3.5, running on the CPF OPE environment, using the L0Decoder v1.3, all included in the latest Docker delivery with the Yaros release 2.0rc11 [RD 5]. The differences between RO-NTC v3.4 and v3.5 processors are limited, and will be discussed further in the text (a direct comparison for a limited data set of v3.4 and v3.5 is provided in Figure 29). The v1.2 and v1.3 L0Decoder differences are small, where v1.2 occasionally does not fully reconstruct the occultation or RINEX data (related Anomaly Report: EUM/JasonCS/AR/1977), this is however irrelevant for the statistical analysis of a large data set presented here. Both processor versions, v3.4 and v3.5 (and later ones), use the same auxiliary data, with the GNSS orbits/clocks and other data provided by NASA/JPL [RD 6], these auxiliary data provide the highest quality GPS data, and GLONASS data available from the Real Time Stream.

The Processing Specifications for RO-NTC v3.5 and above are [RD 7, RD 8, RD 9].

Previous RO-NTC versions, and corresponding activation dates on the CPF are given in the table below. Most of the early RO-NTC processor developments, from instrument switch-on up to 18th of February 2021, was actually performed on the EUMETSAT offline Technical Computing Environment (TCE), to allow greater flexibility in particular during the instrument optimisation (see instrument activity Table 2).

Processor Version	Date activated	Comments
RO-NTC v3.1	25.09.2020	Processing GRAS MetOp-A L0 data in NTC mode, complete all the interfaces, use of NASA/JPL data
RO-NTC v3.2	18.02.2021	Processing Jason-CS data, using Bernese POD S/W
RO-NTC v3.3	25.03.2021	Updates on the L1A/L1B processors, updates on POD, addressing anomalies
RO-NTC v3.4	14.06.2021	Updates on the L1A/L1B processors, updates on POD, addressing anomalies
RO-NTC v3.5	25.10.2021	Updates on L1A/L1B processor, updates on POD, addressing anomalies (e.g. yaw flip). After PVRB

		meeting, providing operational data from 29th November 2021 production date onwards.
RO-NTC v3.6	07 April 2022	Addressing several anomalies. See also [RD 19].
RO-NTC v3.6.1	03 May 2022	Addressing several anomalies (EOP format, duplicated GLONASS orbit/clock entries).
RO-NTC v3.7	08 Dec 2022 (planned)	Addressing several anomalies. See also [RD 19].

A general overview of the input and output data of the processor is provided in Figure 1.

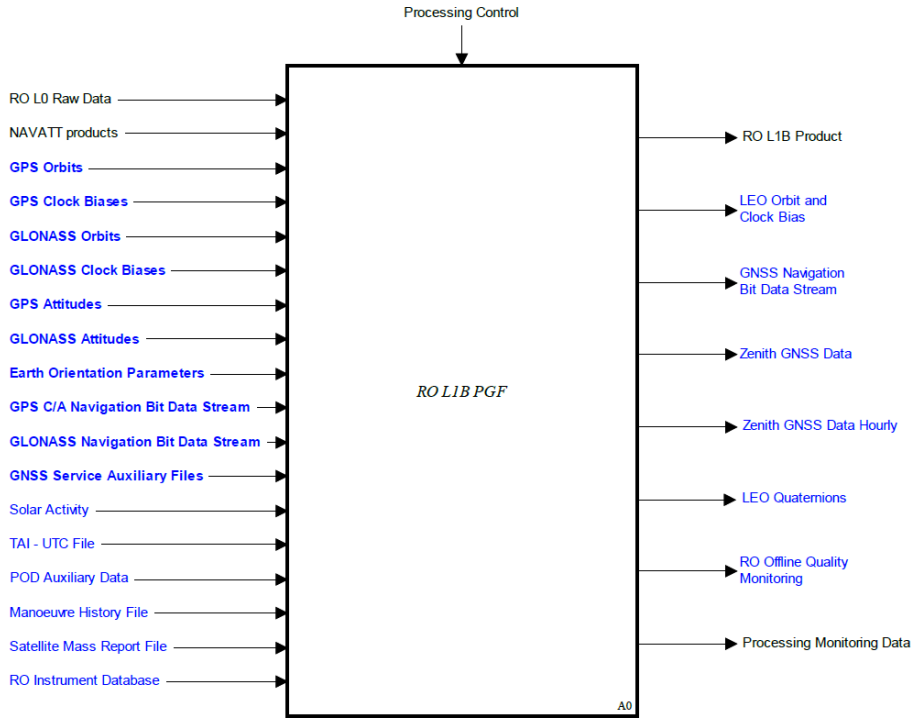

Figure 1 RO-NTC outer level context diagram. Auxiliary input and output files are shown in blue (input auxiliary data provided by NASA/JPL are shown in bold). Note that the L0 Raw and the NAVATT products cover also the archive dump data.

2.2 Validation Metrics

The following validation metrics are used throughout the document when comparing different data sets.

Statistics:

- *Observations minus background departures* - refers to departures that are derived using the *(O-B)/B* [%] quantity. *O* represents the observed (bending angle) profile, *B* the background (bending angle) profile (e.g. as taken from ECMWF data). This representation allows to better compare the exponentially varying bending angle profiles. *B* is sometimes not taken from the ECMWF re-analysis, but from a match of another bending angle observation; in this case we refer to $(O_1-O_2)/O_2$ where O_1 generally denotes the EUMETSAT data and O_2 the other bending-angle observation. All profile data validation is based on "thinned" data, meaning that the high resolution profile data (which has > 1000 data points per profile) is thinned to a resolution varying with altitude (higher resolution near the surface of about 150m, to about 300m near 60km). This thinned profile data is comprising 247 data points for the EUMETSAT

NTC data, all other data sets are interpolated to this resolution. However, the high-resolution data is also part of the S6A product [RD 9].

- *Robust estimator for statistics based on Tukey's bi-weight* - refers to an estimator that provides an effective tool to reduce weight for outliers from noisy distributions, returning systematic uncertainty (also called bias), random uncertainty (also called standard deviation and refers to the 1σ value) and percentage of data points falling into the ±2σ interval. This would be 95% for an ideal Gauss distribution, for e.g. GRAS it is around 92% at the upper troposphere. For more details on robust estimators, please refer to [RD 10].
- *Weight* - provides information on the number of outliers filtered out in the robust estimator (see above); at higher altitudes, for ideal Gauss distributions, it should be about 95% that are entering the statistics (and about 5% filtered out). In the lower part of the atmosphere, it also shows the penetration of the occultations, meaning how many occultations manage to reach down to a particular impact height level.
- *Random Uncertainty* - output of the robust estimator, represents the 1σ value of the data set once outliers are de-weighted, also called standard deviation.
- *Systematic uncertainty* – output of the robust estimator, represents the systematic difference of the two data set once outliers are de-weighted, also called bias.
- *Number of occultations* - the average number of occultations per day over the plotted or analysed time range. Taking into account all valid occultations processed (percentage of invalid occultations is given in failure rate, see next point).
- *Failure Rate* - Percentage of all occultations that do not provide valid neutral bending angles (e.g. because one of the frequencies is not tracked) or that are very short (covering less than 20km in impact height space). This information is though not for all processing streams or data separations available, as e.g. the data is not processed to a complete level 1b file, and thus cannot be used in the failure assessment. Also, for data generated from BUFR streams, this is unavailable as only valid data is disseminated.
- *Structural uncertainty* - a residual uncertainty that still persists between processing streams, even if the processing starts from the same level 0 / original data. It is caused by assumptions/implementations made in the processing, such as e.g. how to filter noisy data, how to interpolate them (linearly or exponentially).

Other:

- *Match up or Matches* - A sensor "point" measurement that is matched with another sensor's "point" measurement sufficiently close in space and time (usually 300km/3hours is used here). For radio occultation matching, the "point" measurement is taken at the reference tangent point location (which for RO-NTC S6 data is at 0 km SLTA).
- *Straight Line Tangent Altitude (SLTA)* - the tangent altitude of the direct LEO/GNSS satellite ray with respect to the Earth WGS84 Ellipsoid; it is generally >0km, but in the lower troposphere can reach values <-200km due to the bending of the ray. For EUMETSAT data, the reference tangent point corresponds to SLTA = 0km.
- *Impact Height* – altitude resulting from subtracting the radius of curvature (a fitted sphere at the tangent point) from the impact parameter (a in Figure 2), it is generally about 2km above the ground for rays close to the Earth surface, and is close to the actual height in the atmosphere from about mid-troposphere upwards.

- *Bending angle* - the actual geometry of the limb-sounding radio occultation measurement technique is shown in Figure 2. The figure shows the bending angle as the angle between the actual, measured, and the straight line propagation from the GNSS satellite to the LEO satellite. The SLTA altitude is also shown.

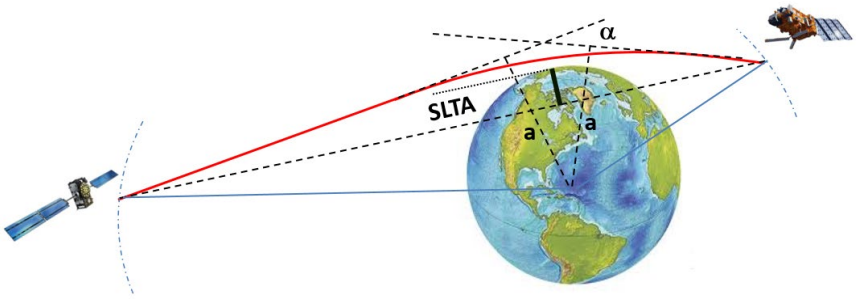

Figure 2 Radio occultation geometry, showing the bending angle α, the impact parameter a, and the straight line tangent altitude (SLTA or RTH). Note that α is generally below 1° and is measured in µrad, thus the figure is greatly exaggerated.

2.3 Validation Data Sets

Validation was performed against two operational RO missions, EUMETSAT Polar System (EPS) with its GNSS Receiver for Atmospheric Sounding (GRAS) instruments [RD 11], and FORMOSAT-7/COSMIC-2 [RD 12], which is flying TriG instruments very similar to the S6 one, but at a low inclination orbit. For both data sets, a thinned bending angle profile is used (247 vertical levels), and not the high resolution one.

Validation is also performed against operational forecasts from the European Centre for Medium Weather Forecast (ECMWF), these are available within EUMETSAT, as provided for the EPS mission.

Operational GRAS data, available from Metop-A, -B, and -C, is provided by the ground segment running at EUMETSAT and is obtained from the internal monitoring environment of the RO group, which has a data feed from the operational environment. In total, there are more than 0.5 million occultation available for the investigated period.

Operational COSMIC-2 data is obtained from the GTS BUFR data stream, as also available to Numerical Weather Prediction (NWP) centres for data assimilation. In total, there are about 1.4 million occultation observations available for the investigated period.

Validation against RO missions uses also collocation, generally based on a smaller than 300km and 3h criteria. Against ECMWF profiles, the validation is against a collocated profile, forward modelled to bending angles using the RO Processing Package (ROPP) [RD 13]. The forward modelling takes the temperature, humidity, pressure, and geopotential ECMWF data on 137 vertical levels at the reference occultation position (using a bi-linear interpolation to the reference location from the stored 0.5 degree resolution, and the nearest forecast data).

Note that we performed only a very limited validation against the NRT data stream provided by NASA/JPL, as this currently has several issues that need to be addressed [RD 17].

We also include contributions from two NWP Partners, the MetOffice and ECMWF [AD-01]. These also provide statistics of the NRT and NTC data, as well as outcomes of impact trials.

2.4 Monitoring and Validation Environment

Data analysis and validation was generally performed on EUMETSAT's offline infrastructure TCE, using analysis and plotting routines that have been developed for GRAS and adapted for S6A data. The monitoring environment also makes heavy use of ROPP, e.g. to convert BUFR GTS data to ROPP netCDF format, or to forward model ECMWF fields to bending angles.

ECMWF and MetOffice used their own monitoring / validation / plotting environments and provided those results directly.

3 SATELLITE AND INSTRUMENT OVERVIEW

The following sections give a brief overview of the satellite and the GNSS-RO instrument, the orbit, executed satellite and instrument activities, as well as providing more detailed information on some instrument issues and anomalies (covering the time frame up to document release date).

3.1 Jason-CS Satellite and GNSS-RO Instrument

Pictures of the Jason-CS satellite model outside of the EUMETSAT entrance are shown in Figure 3. The various instruments are indicated, including the three GNSS-RO antennas. The forward looking one is a 3x2 array, the backwards looking one a 3x4, thus in nominal flight direction, the 3x4 antenna, which has a higher gain, will observe setting occultations. The zenith looking one is a one patch antenna, observing GPS satellites for the orbit determination.

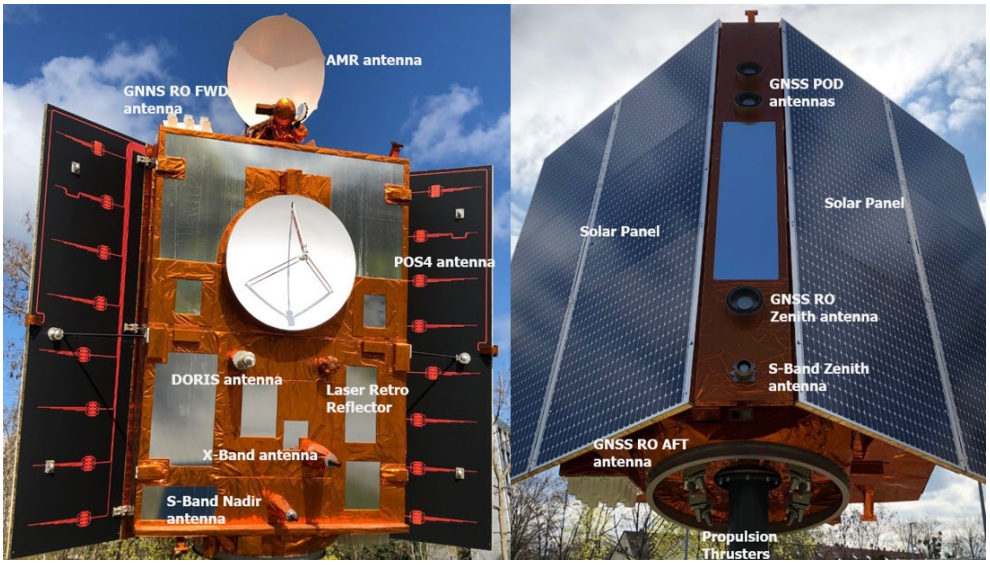

Figure 3 S6A satellite model pictures, taken outside of EUMETSAT premises.

The GNSS-RO instrument can track both available GPS signals on the second frequency, L2P and L2C. Where available, it will track L2C in occultation. On L1, it tracks the L1 C/A code as well as the L1P for codeless tracking when L2P is used. For GLONASS, it tracks the Frequency Division Multiple Access (FDMA) signals on L1 and L2.

3.2 Satellite and Instrument Activation

S6A was launched on 21st November 2020 from the Space Launch Complex at Vandenberg Air Force Base in California, USA on a Space-X Falcon 9 rocket. The GNSS-RO instrument was switched on a week later, 28th November 2020 at 09:19:52, first zenith antenna data was received at 09:25:31 and the first occultation data of GPS satellite G27 was observed at 13:39:43, the first GLONASS slightly later, at 13:50:00.

3.3 Satellite Orbit

The satellite is on a 1336 km non-Sun-synchronous orbit with an inclination of 66 degrees, it thus passes over locations at different times of the day and night, primarily to measure changes that may vary throughout 24-hours, like the tides. For RO, this translates into a different local solar

time coverage than other current EUMETSAT satellites carrying RO instruments. Examples of the distribution for the S6A and Metop-B satellites are given in Figure 4. Note that (1) the coverage for the Metop satellite does not change over time, while the S6A looks different for different time periods; (2) the strips of S6A coverage are due to the GLONASS orbit geometry (as noted by S. Syndergaard, DMI).

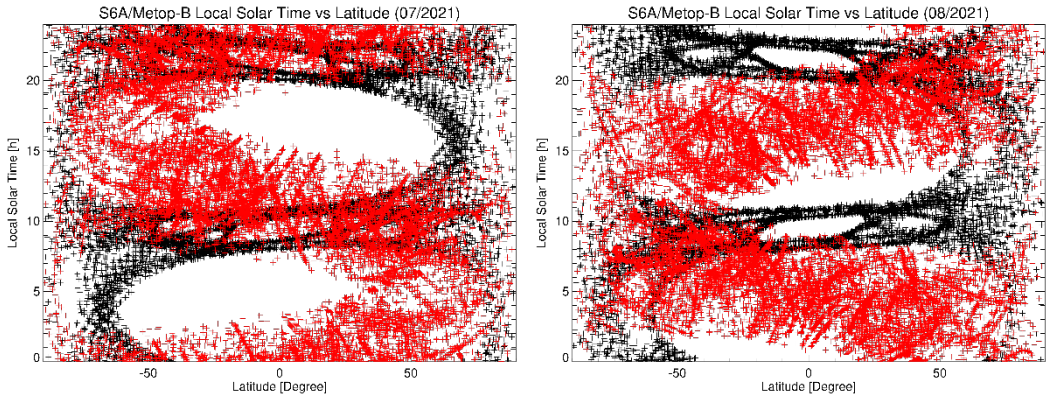

Figure 4 Examples of the local solar time coverage for S6A and Metop-B for the first 20 days in July 2021 (left), and August (right). Red symbols S6A, black Metop-B.

3.4 Satellite Manoeuvres

Several manoeuvres were performed for the S6A satellite, in particular during the first few weeks, in order to bring S6A into tandem flight with Jason-3. Table 1 below lists all manoeuvres as provided in the auxiliary Manoeuvre History File, plus all yaw slew manoeuvres – yaw flip ones are though listed in Section 3.5. This history file is an input to the RO-NTC processor [RD 8]. Note that the table includes dates prior to GNSS-RO instrument switch on.

Manoeuvre Start Time	Manoeuvre End Time
2020/11/23 02:37:50.000	2020/11/23 02:38:19.999
2020/11/23 09:49:41.709	2020/11/23 09:58:19.426
2020/11/24 01:38:00.000	2020/11/24 01:41:52.320
2020/11/27 05:22:12.403	2020/11/27 05:24:22.775
2020/12/10 05:00:35.480	2020/12/10 05:07:57.920
2020/12/14 05:15:05.448	2020/12/14 05:23:50.552
2020/12/16 06:27:00.710	2020/12/16 06:27:51.044
2020/12/18 00:38:14.206	2020/12/18 00:39:06.998
2021/02/18 01:44:59.789	2021/02/18 01:45:00.211
2021/04/27 07:42:00.000	2021/04/27 07:42:27.000
2021/04/27 07:50:00.000	2021/04/27 07:50:16.000
2021/04/27 08:10:00.000	2021/04/27 08:10:07.000
2021/04/29 00:54:51.097	2021/04/29 00:55:20.903
2021/04/30 10:38:33.806	2021/04/30 10:38:50.194
2021/08/16 00:20:44.845	2021/08/16 00:20:45.155
2021/11/19 03:52:45.000*	2021/11/19 04:38:20.000*
2021/11/19 16:13:21.000*	2021/11/19 16:59:00.000*
2021/11/25 02:59:59.827	2021/11/25 03:00:00.173
2022/01/17 15:42:57.000*	2022/01/17 16:18:55.000*

2022/01/18 04:03:34.000*	2022/01/18 04:39:32.000*
2022/03/08 02:59:59.737	2022/03/08 03:00:00.263
2022/06/22 07:29:59.699	2022/06/22 07:30:00.301
2022/10/13 06:49:59.747	2022/10/13 06:50:00.253

Table 1 Manoeuvre start and end time since the start of S6A mission, as listed in the Manoeuvre History File. Yaw slew maneouvres, where the satellite is only rotated by 90 Degrees are indicated by an * (Yaw flips ones are mention in Section 3.5).

3.5 Instrument Activities

Several instrument activities were performed during the SIOV and Commissioning Phase of the satellite/instrument. Some of these were identified in [AD-01], e.g. the beam forming activation, the GPS L2P tracking altitude (L2TA) optimisation, and the Lowest Tracking Altitude (LTA) activation for latitudes within the ±35 degrees. Table 2 provides an overview of these activities, it also e.g. includes the beam forming issues observed on the instrument (related Anomaly Report: EUM/JasonCS/AR/1413) as that required several command uploads.

Time	Activity
28/11/2021 09:19:52	Initial Switch On
Instrument Optimizations (Task 4 of AD-01)	
04/12/2020 14:42:12	Beam Forming Off
07/12/2020 15:31:58	Beam Forming On
11/01/2021 16:08:25	L2TA to -60km
12/01/2021 16:31:38	L2TA to for Rising Occs -20km
13/01/2021 14:57:55	LTA to 35deg (Deep Tracking for Setting Occs enabled)
18/01/2021 14:55:56	L2TA to -40km for Rising Occs (Default)
20/01/2021 15:41:01	L2C tracking enabled
25/01/2021 15:39:16	L2C tracking disabled
02/02/2021 12:55:44	Cal/Val Parameter Setting Upload, RTH to 90km
Instrument Beam Forming Issues (affecting data from 16 Feb to 9 Mar)	
24/02/2021 15:03:20	Beam Forming Off
26/02/2021 15:45:38	Beam Forming On Attempt (failed due to re-boot)
26/02/2021 12:13:44	Beam Forming On
Enable deep Tracking	
24/03/2021 10:00:00	Deep tracking to -350km for setting, low lat activated
Central On-Board Flight S/W (CSW Update)	
27/04/2021 07:32:03	Instrument Switch Off
27/04/2021 18:42:37	Instrument Switch On
27/04/2021 20:00:00	Hard Reboot
Update Azimuth Angle Configuration	
11/05/2021 16:13:00	Azimuth Angle Update to > 60 degree (failed)
18/05/2021 13:25:00	Azimuth Angle Update to > 60 degree
GNSS-RO On-Board s/w Update to v3.2	
07/06/2021 15:54:00	Navigation Processor Upload Part 1
07/06/2021 09:00:17	Navigation Processor Upload Part 2
07/06/2021 10:56:04	Navigation Processor Installation
08/06/2021 07:27:40	Science Processor Upload Part 1
08/06/2021 09:22:48	Science Processor Upload Part 2
08/06/2021 11:18:37	Science Processor Installation
08/06/2021 13:14:22	Return to normal operations

Instrument Configuration Updates for Yaw Flip Handling (with deep tracking)	
01/07/2021 13:07:38	Yaw Flip Backward Configuration
05/07/2021 12:55:38	Yaw Flip Forward Configuration
Instrument Configuration Updates for Yaw Flip Handling (without deep tracking)	
01/09/2021 05:01:30	Yaw Flip Backward Configuration
05/09/2021 06:33:00	Yaw Flip Forward Configuration
Instrument Configuration Updates for Yaw Flip Handling (without deep tracking)	
05/11/2021 16:24:28	Yaw Flip Backward Configuration
09/11/2021 17:28:38	Yaw Flip Forward Configuration
GNSS-RO Instrument Upload (to address AR 2132)	
16/11/2021 11:03:40	GNSS-RO Script Update Start Period
16/11/2021 11:23:01	GNSS-RO Script Update End Period
Instrument Configuration Updates for Yaw Flip Handling (without deep tracking)	
27/02/2022 15:54	Yaw Flip Backward Configuration
03/03/2022 17:12	Yaw Flip Forward Configuration
Instrument Configuration Updates for Yaw Flip Handling (without deep tracking)	
25/04/2022 16:45	Yaw Flip Backward Configuration
29/04/2022 16:36	Yaw Flip Forward Configuration
Script Update to improve GLONASS Acquisitions	
04/05/2022 11:50	GNSS-RO Script Update Start Period
04/05/2022 12:07	GNSS-RO Script Update End Period
Script Update to improve GLONASS Ephemeris Handling (4 short activities)	
07/09/2022 14:10	GNSS-RO Script Update Start Period
08/09/2022 16:32	GNSS-RO Script Update End Period

Table 2 GNSS-RO instrument activities.

3.6 Instrument Issues

The following sections outline the observed instrument issues.

3.6.1 Future Occultation

The instrument sometimes reports occultations that are in the future, sometimes by several days. This incorrect timing is being investigated by NASA/JPL (EUM/JasonCS/AR/1971), and is thought to be due to a loss of GNSS time synchronisation, likely caused by a Single Event Upset (SEU). These occultations are identified by a filter within the RO-NTC level 0 processing, that searches and removes all occultations that are more than 600s outside of the time interval covered by the corresponding level 0 dump (no past occultations were found so far). Table 3 lists all the future occultations so far identified along with the corresponding GNSS satellite PRN. No further future occultations were though observed for several months, after the last one in December 2021, so potentially this issue is resolved with one of the performed on-board s/w updates.

PRN	Future Occultation Start	Future Occultation End	Level 0 Data Dump End
G06	2020/12/06 00:39:43.10	2020/12/06 00:40:46.09	2020/12-05 20:21:25.00
G08	2020/12-06 00:39:13.11	2020/12-06 00:40:46.10	2020/12-05 20:21:25.00
R08	2021/04-04 07:04:13.09	2021/04-04 07:05:55.07	2021/03-23 04:16:05.00
R16	2021/04-04 07:04:59.11	2021/04-04 07:05:17.10	2021/03-23 04:16:05.00
R04	2021/06-02 10:07:19.08	2021/06-02 10:08:54.07	2021/04-14 21:29:16.00
R15	2021/05-22 01:46:47.10	2021/05-22 01:46:56.09	2021/05-20 13:48:56.00
R13	2021-09-04 17:07:45.10	2021-09-04 17:08:20.09	2021-09-04 13:02:49.00

R09	2021-09-09 14:51:48.10	2021-09-09 14:52:58.09	2021-09-09 10:45:33.00
G16	2021-10-29 21:55:08.10	2021-10-29 21:55:45.09	2021-10-05 14:42:49.00
G17	2021-12-07 06:50:16.12	2021-12-07 06:50:19.11	2021-12-06 22:14:34.00

Table 3 List of identified future occultations.

3.6.2 Data Gaps with single Orbit Dump Processing

The instrument communicates with the spacecraft via a 1553B bus interface. The GNSS-RO instrument produces two types of these telemetry packets (on separate 1553 sub-addresses): 640-byte Navigation/POD packets and 1024-byte Science/RO packets. The POD packets contain both housekeeping and science data, while the RO packets contain science data. The native packets produced by the instrument are CCSDS-formatted, but are not PUS compliant. The platform wraps both types of instrument packets into PUS packets.

As the package size is limited, and the platform dumps the level 0 data by complete PUS packets, it is possible that not all information to fully decode the instrument data is available to the L0Decoder for a particular level 0 packet. Such a situation appears at the start or the end of a level 0 dump. A more complete reconstruction in NRT is possible by providing also the previous level 0 data dump to the level 0 decoder, in NTC one can provide the entire level 0 data of the day being processed.

The RO-NTC v3.5 processed L0Decoder data was still affected by these data gaps, generally leading to 1 second of missing data in some occultations. In total though, this kind of issue occurred only about 1750 times from the start of the mission, thus affecting 0.42% of occultations (Anomaly Report tracking this is: EUM/JasonCS/AR/2137). Most gaps are 1s long (less than 30 events show gaps larger than 1s, and among those most are 2s long); v3.5 will process this data to level 1b, and mark the generated product as degraded.

With the RO-NTC v3.6 processor, these gaps are removed by running the L0Decoder with all the level 0 files of a particular day, once archive and regular dumps are available (thus with a delay of about 3 days). For NRT-like processing, only the previous orbit dump, if available, is used.

3.6.3 Incomplete Occultation Tracking

This issue has been observed only a few times, one recent and most severe occurrence was on the 31st of July and the 1st of August 2021 (the related Anomaly Report is: EUM/JasonCS/AR/2132, which now also includes the 24th of August and late on the 31st of August to early 1st of September where the issue re-appeared). For a few hours on these days, the GNSS-RO instrument was not tracking the occultations over the expected range in Straight Line Tangent Altitude (SLTA, a.k.a RTH). This lead to a reduced number of L1B occultations, violating the related EURD requirement R-U-00600 [AD-02] on some of the affected days. Figure 5 shows the lowest and highest SLTA observed per occultation for a few days around the identified higher occurrence in July/August 2021. The identified days clearly stick out, but a similar issue for fewer occultations appears also on the 30th of July, it is though under investigation if these are related.

Shortly before publication of this report, a script on the GNSS-RO instrument was updated (see Table 2), which was uploaded to address this AR. No further events have been observed since.

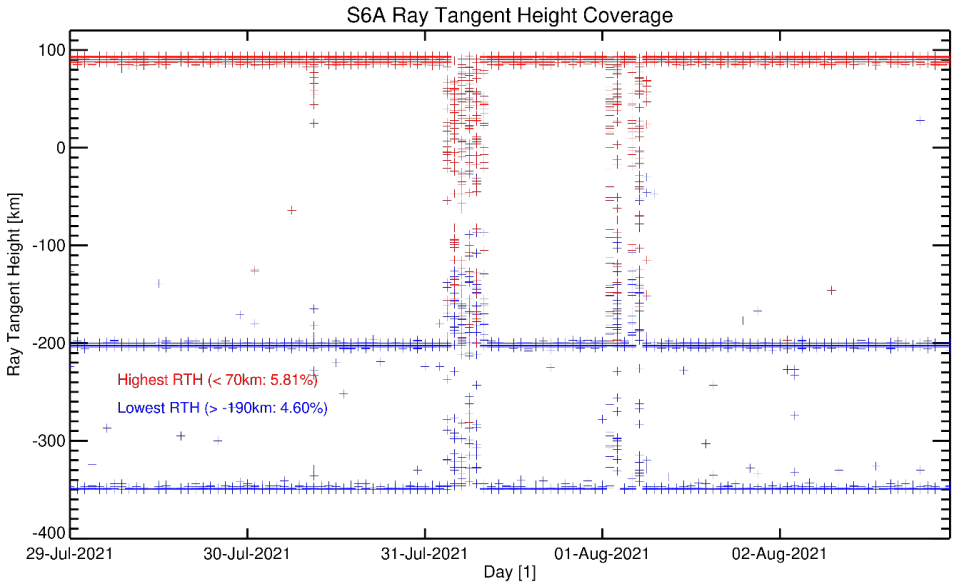

Figure 5 Lowest and highest Ray Tangent Height reached per occultation for the identified days. The legend also provides information on the percentage of occultations not reaching the identified threshold.

3.6.4 Instrument Re-boots and GPS Rising Reduction

During early operation of the GNSS-RO instrument, it was noted that the instrument performed several autonomous re-boots (relevant Anomaly Report: EUM/JasonCS/AR/1413), several issues also required a commanded re-boots, e.g., when the instrument stopped tracking GLONASS occultations. The loss of GLONASS occultations has been addressed by the June 2021 instrument on-board s/w update. There are however several watchdogs that can lead to false re-boots (Anomaly Report: EUM/JasonCS/AR/2041). NASA/JPL is working on a related s/w update.

Re-boots can occur on several levels, for the whole instrument or for a processor only. The instrument was re-booted about 254 times since the start of mission, almost every second day on average. More recently (10th of June onwards) about 0.4 re-boots per day are observed, generally taking < 30min (when not including the anomaly on GLONASS satellite tracking, see Section 3.6.7). An instrument re-boot leads to a downtime of the instrument and no data is collected. A processor or s/w re-boot leads to a downtime of that specific processor; some of these autonomous re-boots lead to an observable lower number of GPS rising occultations. From purely geometrical considerations, an RO instrument should see similar numbers of setting and rising occultations. There are however generally always more setting occultations available, as the signal is acquired at high SNRs, above the neutral atmosphere. GRAS on EPS e.g. has an “imbalance” of setting / rising of 52% / 48% at level 1b.

For the Sentinel-6 GNSS-RO instrument, it varies between GPS and GLONASS, and e.g. for both constellations setting / rising is 52.9% / 47.1% (GPS: 52.3% / 47.7%; GLONASS: 53.9% / 46.1%) already at level 0R. At level 1b (looking at data up to 31st of August 2021) it is similar to level 0 at about 53% / 47% generally (and about 55% / 45% for GLONASS, GPS 52.5% / 47.5%). Partly explaining the 1% difference in the overall numbers against GRAS could be the different setting and rising antennas of the GNSS-RO instrument (see also Section 3.1), where the higher gain antenna under nominal conditions observes setting occultations.

There is though another reason why rising occultations are under-represented, and this is connected to the mentioned (science) processor re-boots. The GNSS-RO instrument science processor re-boots once per day to remove any corrupted data (as the instrument flies in a high-radiation environment). These re-boots don't generally lead to a longer loss of any occultation data, albeit sometimes longer gaps with no occultation data are observed, e.g. when the instrument and not just the science processor re-boots. The instrument however actually requires more time to download the GPS ephemeris data on the zenith antenna to schedule upcoming rising occultations (GLONASS information is stored on-board). The impact is shown in Figure 6, using a 30 minute time windows to analyse the number of available occultations within this window.

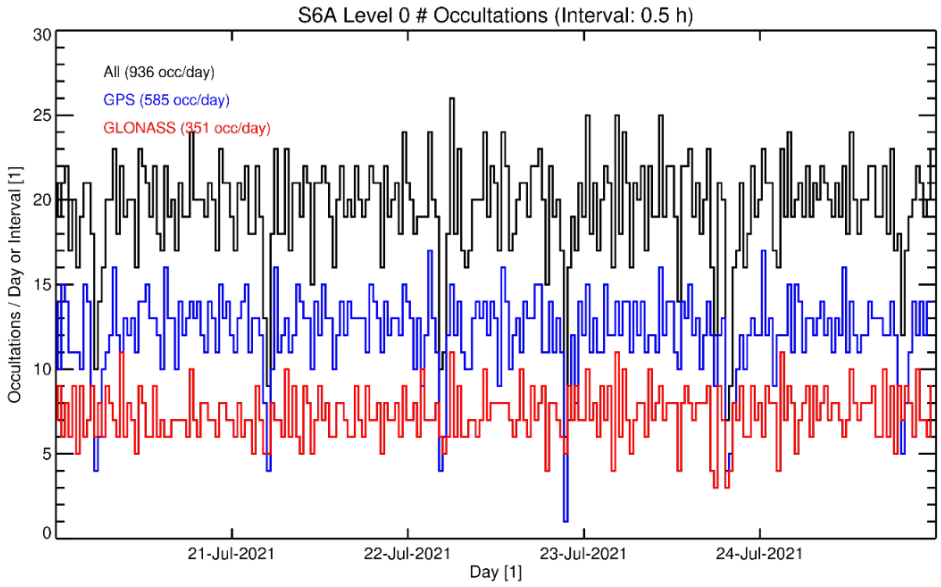

Figure 6 Number of GLONASS and GPS occultations tracked at level 0R within 30 minute intervals, for several days in July 2021.

For these 5 example days in July 2021, the regular drop in the number of GPS occultations can be observed, with roughly a daily frequency. Initially, the processor re-boots are earlier during the day, on the 22nd of July, an early processor and an instrument re-boot occurred, the instrument one around 21:21, shifting the daily processor re-boots to later during the day. On the 23rd of July, another, slightly earlier instrument re-boot occurs around 19:40, and on the 24th of July the processor re-boot follows the daily pattern again.

Figure 6 shows both occultation types, a further split up (not shown) reveals that the number of GPS rising occultations actually drops to zero within this time window, while the number of GPS setting occultations is almost unaffected. The number of occultations not acquired due to this s/w re-boots represents about 0.5% a day (approximately 5 occultations are lost per day), partly explaining the "imbalance", at least for GPS.

The ratio of setting vs. rising occultations per constellation is shown in Figure 7 for data in 2022, up to about mid-July. It shows that there are about 10% more setting occultations than rising ones for GPS, and this is found also for the full time series. GLONASS actually suffered from highly varying ratios up to the on-board s/w update in May 2022, this though clearly improves the ratio, and it is now even closer to 1 than GPS, as GPS still suffers from the above mentioned drop in rising occultation after a re-boot.

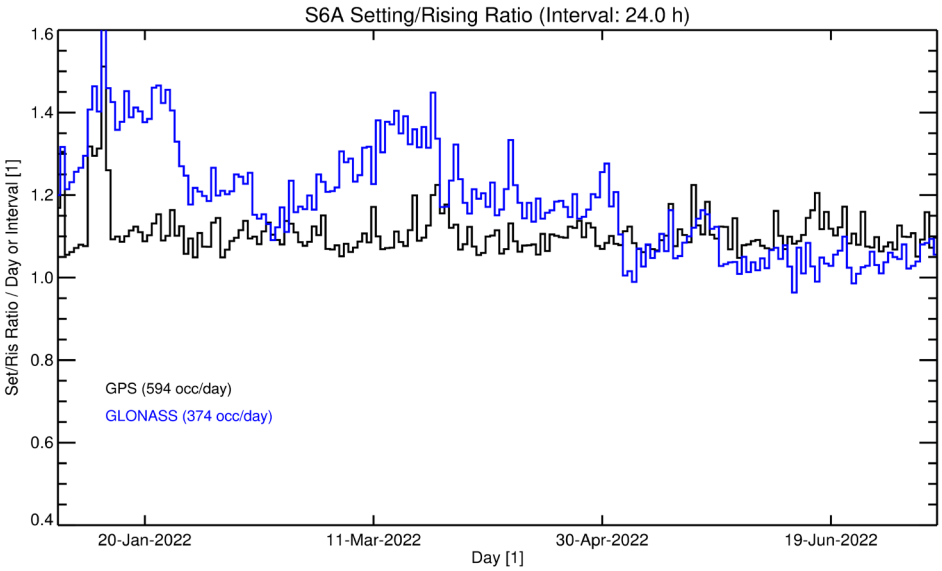

Figure 7 Setting to Rising ratio per constellation for occultations at level 0R for 1st of Jan 2022 to 12th of July 2022. The instrument s/w update and its impact on GLONASS rising occultation tracking in early May 2022 (see Table 2) is clearly visible.

3.6.5 Unphysical L2 Bending Angles

Analysis of the initial bending angle retrievals showed unphysical neutral bending angles close to the altitude where the L2 bending angle tracking was lost. Further analysis revealed that the L2 bending angles actually sometimes had a “kink” in the lowest part, which, via the ionospheric correction, impacted the neutral bending angle. This occurred for both, GPS and GLONASS occultations.

A simple filter that removes all L2 bending angles below a configurable altitude is one option to remove these unphysical data, the availability of the L2 bending angle though impacts the neutral bending angle quality. The aim should be to use all data that is physical, and remove only the unphysical part. We have thus developed a simple filter that checks the difference between the L1 and L2 bending angles in the lower atmosphere (the ionosphere is very similar on both frequencies at these altitudes), and removes all L2 data below an altitude where this difference first exceeds a configurable threshold. This approach assures that all physical L2 data is available for the retrieval.

An application of the L2 filter is shown in Figure 8 for a GLONASS occultation (R12). After the filter application, the difference between the L1 and neutral (ionosphere free) bending angle is very small and the lines overlap.

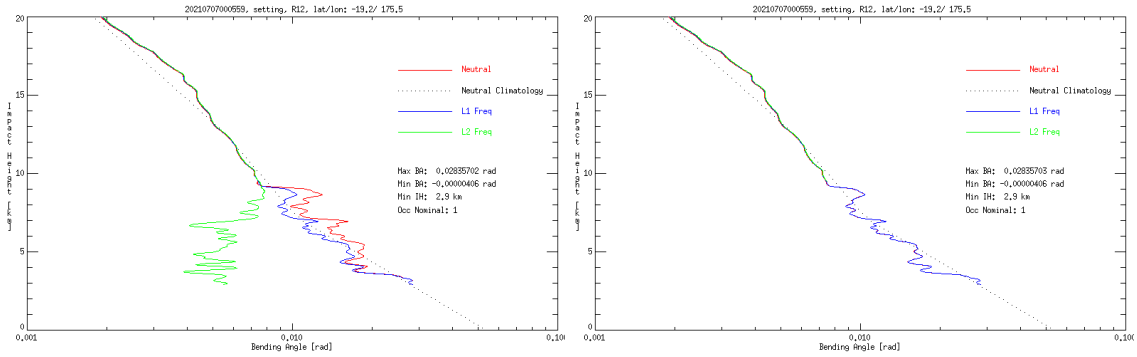

Figure 8 Bending angles at L1, L2 and neutral for an occultation that has no L2 filter applied (left) and applies it (right). The legend provides some further characteristics of this bending angle occultation, like minimum impact height (IH), and bending angle (BA), and whether the occultation is nominal.

The statistical impact of using or not using the L2 filter is shown in Figure 9 for one day. The improvement of the filter is clearly visible, the unphysical positive systematic uncertainties at lower altitudes are removed when applying the filter.

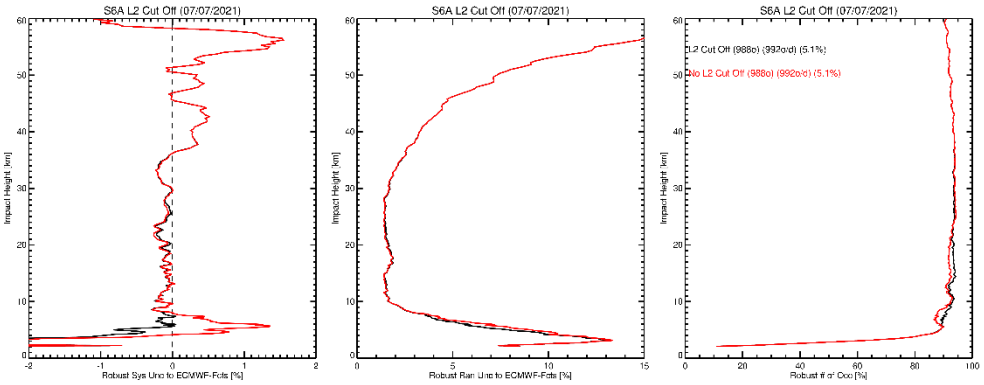

Figure 9 (O-B)/B statistics of EUMETSAT RO-NTC level 1b bending angle against ECMWF forward propagated bending angles with and without the L2 filter (07 July 2021). Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right). The legend provides in addition the total number of occultations, average occultations per day and the failure rate.

3.6.6 Occultation Data Gaps

Section 3.6.4 mentioned re-boots of the instrument (autonomous, commanded and /or due to losing GLONASS tracking), that are one cause of occultation data gaps. Table 4 shows an analysis of all data since start of mission, listing data gaps where no occultations were recorded for more than 30 minutes. The table includes every gap and not only those due to instrument issues, thus including instrument updates, downtimes of the data link or any other observed loss of level 0 data. It does though also include some gaps that are due to instrument re-boots (these usually take less than 30 minutes though). Note that the shorter downtime for e.g. the July 2021 yaw flip configuration upload is not visible here, since it took only about 15 minutes.

In total, since the start of the mission, the number of gaps correspond to an average of about 0.13 gaps/day, and a total loss of about 1.5% of data. As these numbers also include the early instrument activation, they are higher than during nominal operations; if taking only data from 10th of June 2021 on-wards, this improves to about 0.11 gaps/day and about 0.5% of data loss.

Gap Start Time	Gap End Time	Duration [min]
2020/11/29 20:56	2020/11/29 21:27	31
2020/12/13 04:02	2020/12/13 07:34	212
2020/12/20 14:00	2020/12/20 15:35	95
2020/12/20 19:23	2020/12/20 21:18	115
2020/12/21 19:21	2020/12/22 11:26	965
2020/12/23 07:23	2020/12/23 09:20	117
2020/12/29 18:29	2020/12/30 10:34	965
2021/01/01 05:40	2021/01/01 06:13	33
2021/01/06 08:31	2021/01/06 09:23	52
2021/01/12 16:30	2021/01/12 17:02	32
2021/01/14 22:41	2021/01/15 00:35	114
2021/01/30 23:00	2021/01/31 02:45	225
2021/02/02 12:46	2021/02/02 13:17	31
2021/02/06 01:51	2021/02/06 02:24	33
2021/02/12 12:49	2021/02/12 13:27	38
2021/02/24 16:54	2021/02/24 17:25	31
2021/03/02 17:57	2021/03/03 10:49	1012
2021/03/07 01:54	2021/03/07 16:48	894
2021/03/08 15:34	2021/03/08 16:07	33
2021/03/08 21:55	2021/03/09 11:01	786
2021/03/12 02:22	2021/03/12 03:39	77
2021/03/14 02:16	2021/03/14 02:49	33
2021/03/18 23:14	2021/03/18 23:57	43
2021/03/24 10:09	2021/03/24 10:42	33
2021/03/29 10:22	2021/03/29 10:58	36
2021/04/01 01:19	2021/04/01 11:35	616
2021/04/01 23:42	2021/04/02 08:09	507
2021/04/05 09:28	2021/04/06 09:33	1445
2021/04/08 19:32	2021/04/08 20:02	30
2021/04/12 09:31	2021/04/12 10:27	56
2021/04/13 06:38	2021/04/13 07:11	33
2021/04/15 16:03	2021/04/15 16:33	30
2021/04/27 07:26	2021/04/27 19:15	709
2021/04/29 18:50	2021/04/30 09:07	857
2021/05/11 16:10	2021/05/11 16:43	33
2021/05/18 13:02	2021/05/18 13:32	30
2021/05/19 02:11	2021/05/19 04:06	115
2021/05/21 08:27	2021/05/21 09:01	34
2021/06/07 07:04	2021/06/07 11:31	267
2021/06/08 07:26	2021/06/08 13:31	365
2021/06/09 07:48	2021/06/09 09:46	118
2021/06/15 15:32	2021/06/15 17:25	113
2021/06/16 16:40	2021/06/16 17:41	61
2021/07/02 18:02	2021/07/02 19:58	116
2021/07/12 15:57	2021/07/12 17:55	118
2021/07/19 15:03	2021/07/19 16:44	101
2021/08/07 19:19	2021/08/07 20:06	47
2021/08/27 04:59	2021/08/27 06:01	62
2021/09/03 05:07	2021/09/03 07:00	113

2021/09/09 13:22	2021/09/09 14:07	45
2021/10/08 09:41	2021/10/08 10:41	60
2021/10/19 07:59	2021/10/19 08:51	52
2021/10/25 08:18	2021/10/25 08:55	37
2021/11/05 16:18	2021/11/05 16:52	34
2021/11/16 11:00	2021/11/16 11:32	32
2021/11/25 16:48	2021/11/25 17:58	70
2021/12/26 17:00	2021/12/26 18:03	63
2021/12/28 19:15	2021/12/28 19:45	30
2021/12/30 15:29	2021/12/30 16:04	35
2022/01/01 01:58	2022/01/01 02:30	32
2022/01/02 05:04	2022/01/02 05:48	44
2022/01/02 06:11	2022/01/02 18:50	759
2022/01/12 11:45	2022/01/12 12:21	36
2022/01/12 14:41	2022/01/12 15:29	48
2022/01/22 00:47	2022/01/22 01:20	33
2022/02/03 07:10	2022/02/03 08:02	52
2022/02/04 15:13	2022/02/04 15:43	30
2022/02/11 08:16	2022/02/11 09:14	58
2022/02/14 09:25	2022/02/14 12:00	155
2022/02/27 15:45	2022/02/27 16:36	51
2022/03/21 01:57	2022/03/21 02:31	34
2022/03/24 20:38	2022/03/24 21:10	32
2022/03/25 08:45	2022/03/25 09:22	37
2022/04/01 19:18	2022/04/01 19:50	32
2022/04/14 05:23	2022/04/14 06:00	37
2022/04/25 16:38	2022/04/25 17:25	47
2022/04/29 16:30	2022/04/29 17:02	32
2022/05/15 15:31	2022/05/15 16:51	80
2022/06/14 05:35	2022/06/14 06:49	74
2022/06/14 15:17	2022/06/14 16:13	56
2022/06/15 08:45	2022/06/15 09:15	30
2022/06/22 13:11	2022/06/22 14:26	75
2022/07/16 06:09	2022/07/16 08:04	115
2022/07/31 18:43	2022/07/31 19:26	43
2022/08/03 16:14	2022/08/03 17:20	66
2022/08/11 07:07	2022/08/11 07:38	31
2022/09/01 00:30	2022/09/01 01:02	32
2022/09/03 00:11	2022/09/03 00:51	40
2022/09/07 14:07	2022/09/07 14:48	41
2022/09/20 13:13	2022/09/20 14:03	50
2022/10/05 08:55	2022/10/05 09:59	64
2022/10/08 06:00	2022/10/08 07:08	68

Table 4 List of data gaps since the start of mission. A data gap is identified when no occultation data is observed for > 30 minutes.

The availability of occultation data can also be analysed per constellation. Taking only GPS, since the start of the mission, there are on average 0.5 gaps per day, and 2.5% of data is lost. Restricting this to 10th of June onwards yields 0.5 gaps per day, and 1.6% data loss. For GLONASS, the numbers are on average 0.2 gaps per day and 2.8% data low for the whole mission, and for 10th of

June onwards about 0.2 gaps per day, and 0.7% data loss. These latter GLONASS numbers show the improvement with tracking GLONASS data after the instrument on-board s/w update. Also, these numbers indicate that the GLONASS tracking is more robust, having fewer gaps or data losses within the recent period.

3.6.7 Partial Loss of GLONASS Tracking

On 23rd December 2021, at about 13:23:20, the GNSS-RO instrument didn't track all possible occultations of the GLONASS constellation any longer (affecting all GLONASS PRNs > 06). The total number of GLONASS occultations dropped by about 50%. The behavior continued up to 2nd of January, at about 18:36:19 the instrument performed a reset (there was also a long outage prior, see Table 4).

The instrument continued to function normally up to the 8th of January, when the issue occurred again. It continued up to the 11th of January, and was resolved with an instrument rebooted at 10:37:29. An updated watchdog behavior was also introduced to the instrument, at a series of uploads during the period of 12th January 2022 (14:45) up through 13th January 2022 (00:06).

Additional events occurred on:

- 2022-03-25 08:46, starting after a reboot, the anomaly cleared itself following an autonomous reboot at 2022-03-28 12:27
- 2022-06-11 19:22, it was cleared with SOR on the 2022-06-14 at about 15:40
- 2022-09-15 about 02:00, it was cleared with SOR on 2022-09-20 at 13:18

The possible cause is that several stored GLONASS ephemeris are no longer being updated and becoming outdated. The relevant Anomaly raised at EUMETSAT was: EUM/JasonCS/AR/2272. An initial script update to further monitor this was performed in September 2022 (see Table 2).

3.6.8 Events under Investigation

The following bullet points provide a brief overview of recent events that are still under investigation:

- On 14th of February 2022, the instrument had a longer outage (see Table 4);
- On 21st of February 2022, the instrument wasn't tracking all available GPS occultations for several hours (duration about 12h-16h, EUM/JasonCS/AR/2397);
- On 9th of March 2022, the instrument was not tracking all available occultations, leading to reduced occultation counts on that day (EUM/JasonCS/AR/2397);
- On 12th to 13th of September 2022, occultation data was degraded for about 5h, an autonomous science processor re-boot resolved this. There was also a noticeable reduction in the overall SNR of the occultations;
- On 24th to 25th of September 2022, several GPS satellites were no longer tracked for about 15h, reducing the GPS occultations by about 15%.
- Evaluations of the covered SLTA (RTH) range, as reported in the level 1b processing, showed that contrary to Figure 15, which shows the instrument reported coverage, real coverage can extend several 100km higher in rare cases.
- On 13th to 19th of October 2022, the instrument was frequently loosing tracking in the lower atmosphere, leading to data gaps and more degraded occultations (about 10% to 20% more)

The first 3 events are thought to be cause by higher solar activity, daily sun spot numbers actually had maxima on or near those days. The others are currently considered SEUs (Single Event Upset).

4 PRECISE ORBIT DETERMINATION DATA VALIDATION

4.1 Comparison of the RO-NTC POD to other POD Solutions

The POD s/w used within the RO-NTC v3.5 processor is Bernese [RD 14], which is triggered by the availability of RINEX instrument data, GNSS orbits, clocks, attitude, Earth Orientation Parameters, as well as by data provided for the Bernese s/w [RD 7]. The availability of these data have a timeliness of about 2 to 3 weeks, similar to "final" orbits provided by the International GNSS Service (IGS) [RD 15], and drives the overall timeliness of the RO-NTC product provision.

A validation of the POD LEO orbit and clock solution of the Bernese s/w has been performed within the altimetry activities, where different centres provided an orbit solution for the first few months of the S6A mission based on the GNSS-POD[1] receiver data on-board of S6A. In the results shown in Figure 10, two different POD s/w processed the GNSS-RO instrument data, NAPEOS [RD 16] and Bernese. The NAPEOS POD (EUMN, black data) was only provided for a short period, while the Bernese (EUMB, red data) one covers the investigated period fully, providing a 3D RMS (Root Mean Square) solution very similar to other centres processing the GNSS-POD data.

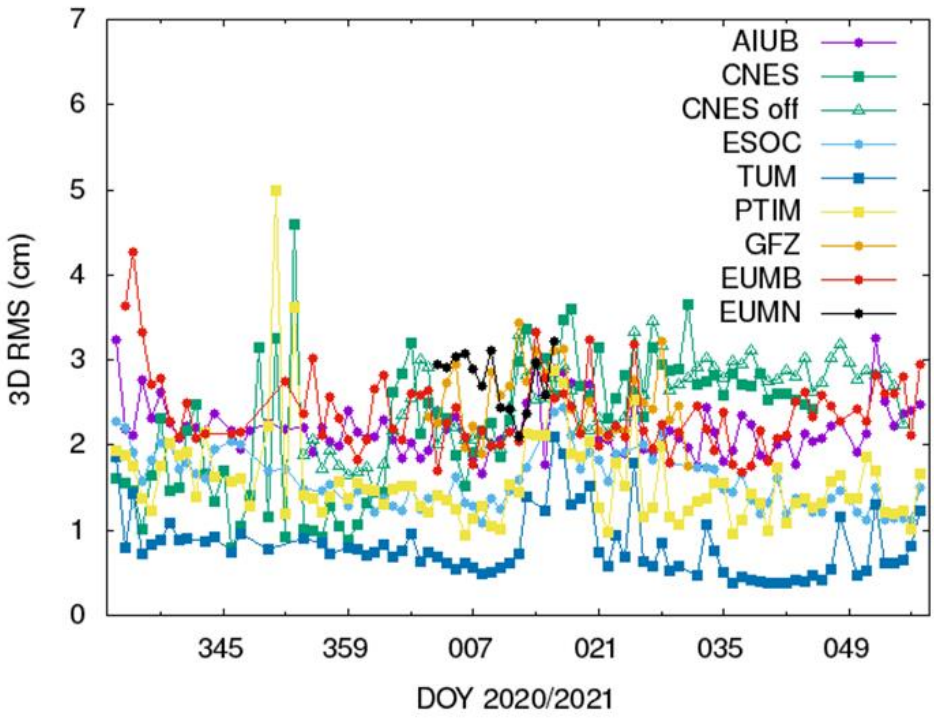

Figure 10 3D RMS of different POD solutions, generally using GNSS-POD RINEX, against DLR reference solution for data up to Feb 2021. EUMN / EUMB are using GNSS-RO RINEX data, running NAPEOS / Bernese.

Another comparison, covering about 3 months of data, against two POD solutions provided by CNES (Centre national d'études spatiales), is shown in Figure 11. It includes the most precise orbit POE (Precise Orbit Ephemeris) and the medium precise orbit MOEG (Medium Orbit Ephemeris, based on preliminary GNSS orbits). As expected, the MOEG has slightly higher 3D RMS values, but both solutions agree to within 3.2 cm with the RO-NTC one.

[1] GNSS-POD is a POD only receiver, used for altimetry processing of S6A, it observes GPS and Galileo signals.

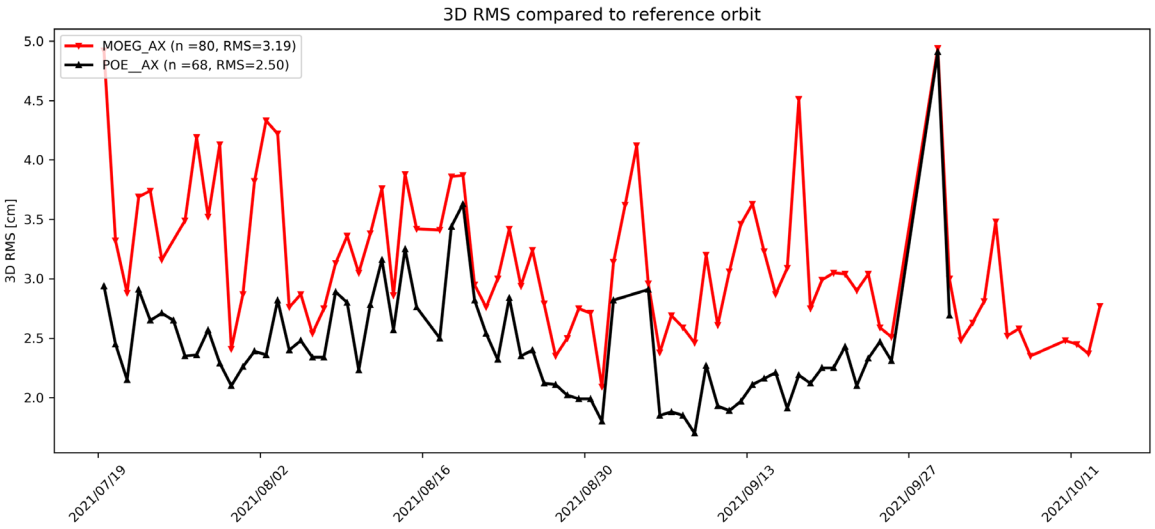

Figure 11 3D RMS of 2 CNES POD solutions (MOEG and POE) against Bernese 5.3 for about 3 months from mid-July 2021 on-wards. POE ends a bit earlier.

4.2 POD Impact on Bending Angles

A comparison of the impact of the POD on the bending angles is shown in Figure 12. Three POD solutions are used here: (1) Bernese v5.2; (2) Bernese v5.3; (3) NAPEOS v3.5. This analysis is based on EUMETSAT's internal monitoring data, where an STC like processing for the last complete day is performed, using IGS rapid GNSS data as input.

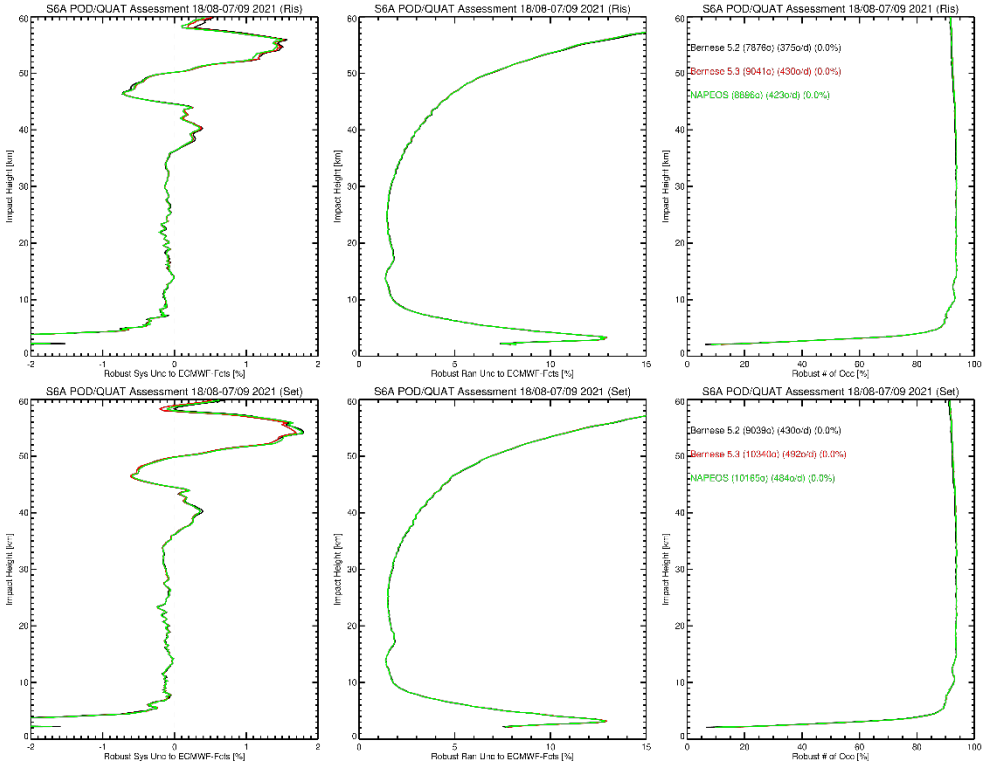

Figure 12 (O-B)/B statistics of EUMETSAT RO-NTC level 1b bending angle against ECMWF forward propagated bending angles for different POD s/w used (18 Aug – 07 Sep 2021). Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right); rising (top), setting (bottom). Otherwise as Figure 9.

The figure shows only small differences in the overall bending angle statistics against ECMWF forecast data. The main difference is observed regarding the number of total processed occultations (and thus also the ones processed per day), this varies between the 3 POD solutions, where Bernese 5.3 – the one used within the RO-NTC processor – is most robust towards providing a LEO POD solution and thus also towards providing most occultations. The failure rates for setting/rising combined are also showing slightly lower numbers for Bernese 5.3 (5.9%), while Bernese 5.2 has 6.2% and NAPEOS 6%.

5 LEVEL 0 DATA ANALYSIS

The following analysis is generally based on processing the raw level 0 data (both regular and archive dump) to level 0R, using the NASA/JPL Level 0 Decoder [RD 3], and analysing the output within the TCE environment. The analysis in this section covers data up to 11th of September 2021.

5.1 Daily Occultations

Figure 13 shows the number of occultations available at level 0r per day. Early data shows several longer outages due to instrument commissioning.

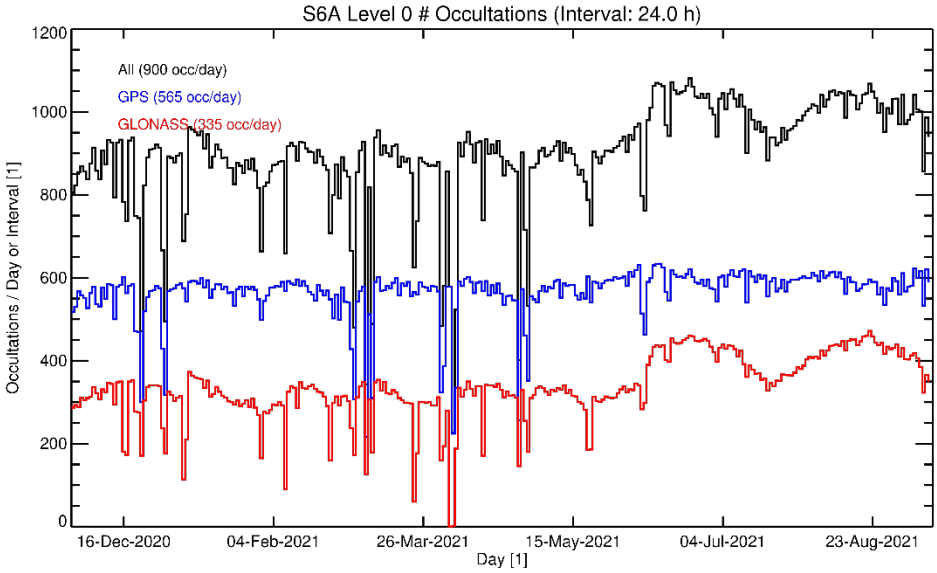

Figure 13 Daily number of occultations at level 0r, total, and per constellation; average number of occultations per day is given in legend.

Within the analysed period, almost 260.000 occultations were recorded by the instrument at level 0R, about 63% from GPS occultations, and about 37% from GLONASS. About 53% are setting ones, the rest is in rising geometry.

On average, about 900 occultations are observed per day; GPS contributes 565 occultations per day, GLONASS only 335. From early June 2021 onwards, the daily numbers increased with the on-board instrument s/w update (Table 2), which, among other improvements, also addresses issues where the instrument would stop to track GLONASS occultations (visible in the figure where only the total and the GLONASS daily counts drop). Taking only data from the 10th of June 2021 onwards yields 1007 occultations per day (593 GPS, 414 GLONASS). With this s/w update, the contributions to the total number of occultations per day per constellation is also now aligned with the number of available GNSS satellites in that constellation (as the faulty GLONASS satellites are no longer tracked).

Figure 13 also shows the impact of three versus six GNSS orbit planes on the daily occultation numbers; with three GLONASS ones, the instrument shows variations over weeks due to the varying visibility of GLONASS satellites from the LEO orbit plane – seen more clearly in particular after the instrument update. GPS does not show this variation.

5.2 Occultations per PRN

The two observed GNSS constellations have either up to 32 (GPS) or up to 24 (GLONASS) active satellites, that can provide occultation measurements. Over a longer timeframe, such as the data set observed here, all available satellites should have contributed a similar amount of occultations.

Figure 14 shows such an analysis. At level 0R, the different GPS satellites have all contributed fairly evenly to the total numbers of occultations, each slightly more than 3% (except for G28, which was removed from the GPS constellation during the investigated time period, see also Section 5.5). The GLONASS contributions already point to some issues in the constellation for PRNs R06, R10, R23; these provide notably fewer occultations at level 0R. In addition, e.g. R13 also shows a lower contribution.

The contributions at level 1b for the RO-NTC v3.4 reprocessing are shown at the bottom of Figure 13, further separated into nominal and non-nominal occultations (this info is taken from the file name; it is thus not fully aligned to the bending angle analysis in Section 6, which uses all occultations, not just profiles, even if it is set to non-nominal). The above mentioned R06, R10, R23 do not contribute at all to the overall number of occultations (a further analysis of the SNRs showed issues with the second frequency, see also Section 5.4, these issues are also confirmed by stations on the ground - an independent confirmation that it is no instrument issue). In addition, R11 very rarely contributes. For the GPS constellation, the contribution also does depend on whether the L2C or L2P signal is available (see also the SNR analysis, Figure 16, right).

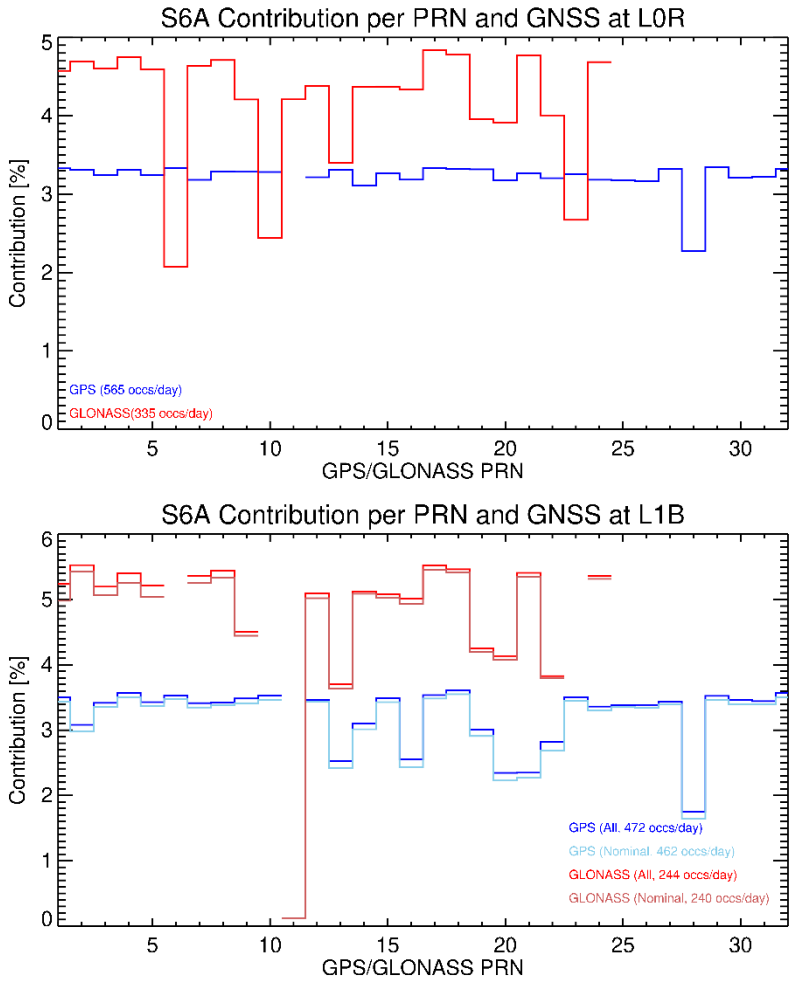

Figure 14 Percentage of occultations observed per PRN at level 0R (top) and level 1b (bottom). Level 1b further splits up the occultations in nominal and degraded.

5.3 SLTA (RTH) Coverage

The respective lowest and highest SLTA has been extracted per occultation, and plotted over the timeline since instrument switch on. Actual values are shown in Figure 15. These SLTA values are configurable, and e.g. from the 13th to the 18th of January, the deep tracking was assessed (LTA activity [AD 01]), on the 2nd February, the upper SLTA value was increased, to be always compliant with the requirement (which states 80km, R-U-00660 [AD 02]), and on 24th of March, the deep tracking for setting occultations that fall within about 40 Degree South/North latitude was re-enabled.

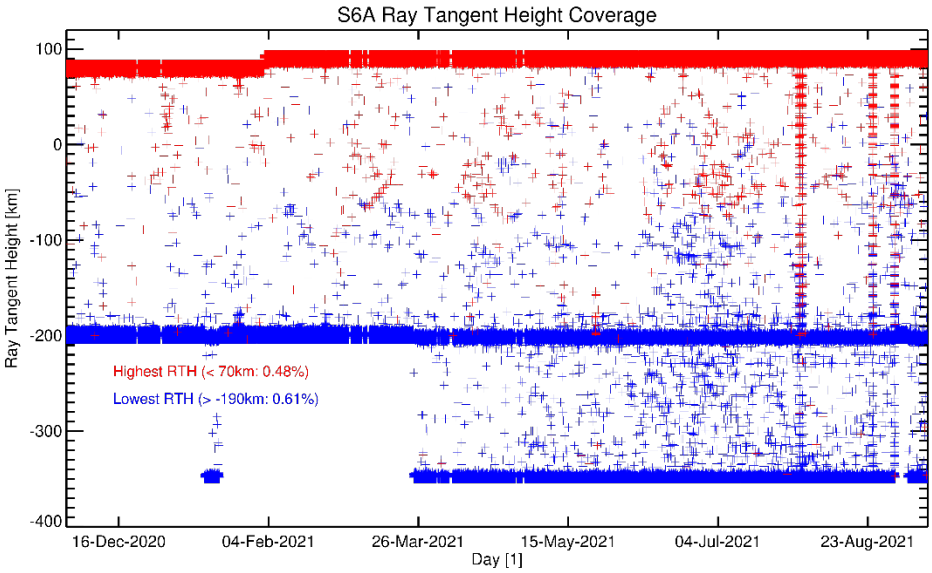

Figure 15 Lowest and highest SLTA (RTH) per occultation, since start of GNSS-RO switch on. The legend also includes some information on the percentage of occultations not reaching the given upper or lower threshold.

The figure does include the percentage of occultations that did not reach these upper/lower values in the legend, this is affecting about 0.5% of the occultations. Also visible in Figure 15 is the already discussed incomplete occultation tracking issue (Section 3.6.3). GLONASS occultations are four times more frequently not reaching these upper/lower limits; during the incomplete tracking, GPS and GLONASS are though very similar (not shown). Note that the plotted values are taken from the L0Decoder output, which reports the SLTA calculated on-board of the instrument. Note that data processed to level 1b sometimes shows upper SLTA values that can be much higher than those reported by the instrument.

5.4 SNR Analysis

An analysis of the Signal to Noise Ratio of data at level 0R was performed on several levels. First, histograms of the distribution of the maximum SNR found per occultation and GNSS signal tracked were plotted. Results are shown in Figure 16 (left). Both GLONASS frequencies can be tracked with higher SNRs of up to 2000 V/V for L1 and 1500 V/V for L2 than their respective GPS frequency, as GLONASS does not require codeless tracking. The L2 GPS SNRs show a bi-modal distribution, resulting from the two different GPS codes available: L2C (peak around 800 V/V) and L2P (which requires codeless tracking and has a peal around 200 V/V). In addition, GLONASS already shows an issue here, a fairly high number of satellites are being tracked with very low SNR, up to almost 10% for L2.

Figure 16 (right) analysis further the maximum SNRs per PRN, plotting the mean over the maximum SNRs found for the respective PRN. For GPS (top), it also splits the data up into whether it was tracked with GPS L2C or L2P, clearly showing the SNR improvement when using the L2C signal. For some GPS satellites, the L2 tracking changed over the mission time, in this case both mean SNRs are shown (e.g. G14), and the mean over all L2 signals is included as a dotted line. The bottom right panel of Figure 16 shows the GLONASS mean SNRs, and problematic PRNs can here again be identified, which do not contribute useful occultation data as the L2 tracking is showing very low SNRs (for R06, R12, R23; those that were excluded from being tracked in the on-board instrument s/w update in early June 2021).

The GLONASS analysis per PRN also reveals that these satellites are highly variable, some even having higher L2 SNRs than L1 (R19, R20), or showing fairly low SNR (R13, R22).

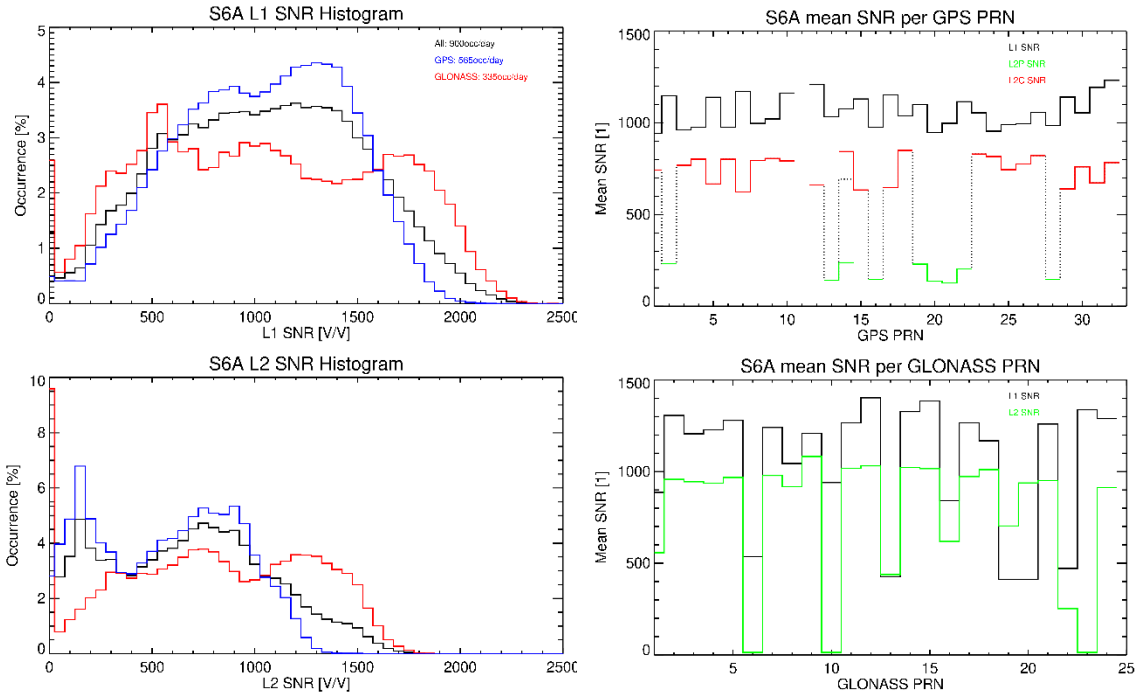

Figure 16 Left: Histogram of the maximum SNR per occultation, for the L1 frequency (top), L2 (bottom). Right: Mean of maximum SNR per GNSS PRN for GPS (top) and GLONASS (bottom).

An additional analysis on the maximum and mean SNRs observed per occultation was done by calculating the daily mean SNR for either the maximum or the mean SNRs, performed for both constellations as well as for setting and rising. Results are shown in Figure 17 for GPS and GLONASS. The time series clearly shows the GNSS-RO underperformance during the Instrument Beam Forming Issues for both constellations (February/March time frame, see also Table 2). Also, the first yaw flip in early July 2021 caused a bigger reduction in the mean SNR values, as the instrument needed to re-calibrate the beam forming. These reductions show up independent of whether the maximum or the mean SNR per occultation enters the calculation. The second yaw flip in early September 2021 shows a slightly better SNR performance than the first one (it however also did not perform the deep tracking). A general reduction in SNR can be observed for the L1 GLONASS frequency over the mission time line (up to the most recent dates), while L2 SNR remains essentially constant.

Using the mean SNR reveals some additional impact of the deep tracking activation on GPS (see Table 2), when the difference between L1 setting and rising disappears (Figure 17, right).

Some SNR dips can actually be traced to small issues in the beam forming calibration (which uses a GNSS satellite if it is tracked within a configurable, small angle around velocity / anti-velocity direction). These dips are then generally removed when a new GNSS satellite is tracked.

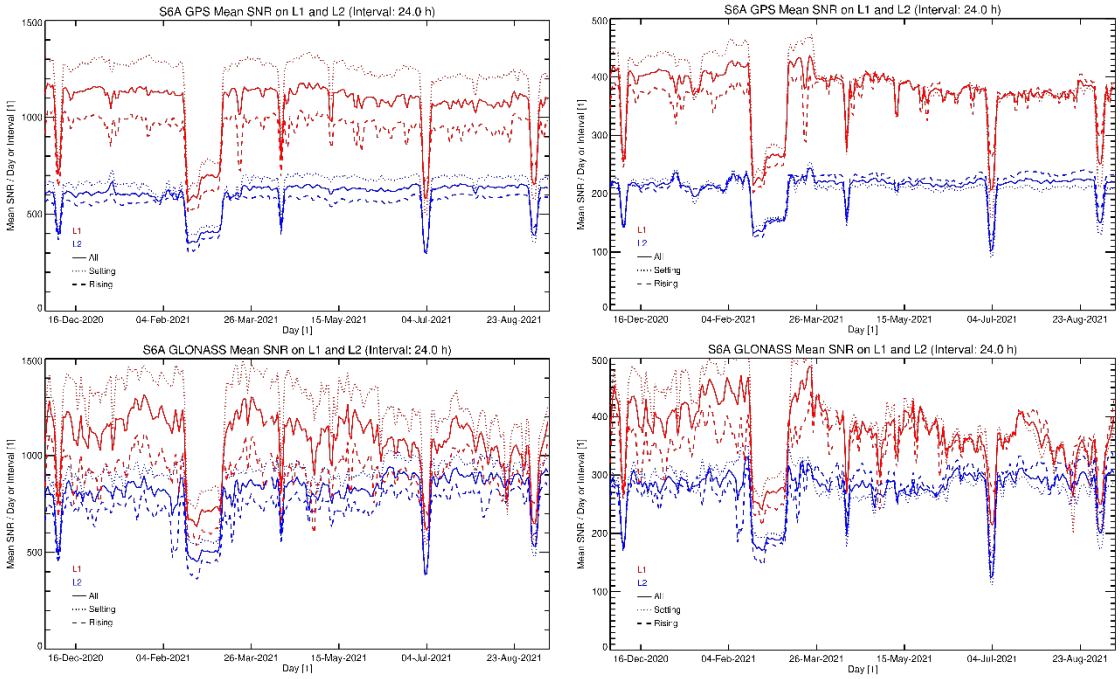

Figure 17 Time series of mean daily SNR values on the L1 and L2 frequency, further separated for setting and rising. Top: GPS, bottom: GLONASS, right: using maximum SNRs, left: using mean SNRs.

5.5 GNSS Constellation Assessment

The GNSS-RO instrument depends on the availability of signals of the GNSS constellations observed, which in turn have an impact on the performance of the instrument.

Figure 18 analyses the daily availability of the GNSS satellites over time since start of mission. Whether a certain PRN is tracked by the instrument depends primarily on the status of that satellite in the constellation almanac and ephemeris, this is an autonomous process and is e.g. visible for GPS PRN G28, which was removed from the GPS constellation on 23rd July 2021 (GPS NANU 2021035).

Two other mechanisms are though also impacting the performance: (1) the instrument can be configured to not track certain PRNs, this was performed with the instrument on-board s/w update (Table 2) early June 2021, when GLONASS PRNs/satellites R06, R10, R23 were no longer tracked; (2) due to instrument issues, as e.g. visible on 4th and 5th of April 2021 when no GLONASS occultations were observed for more than a day.

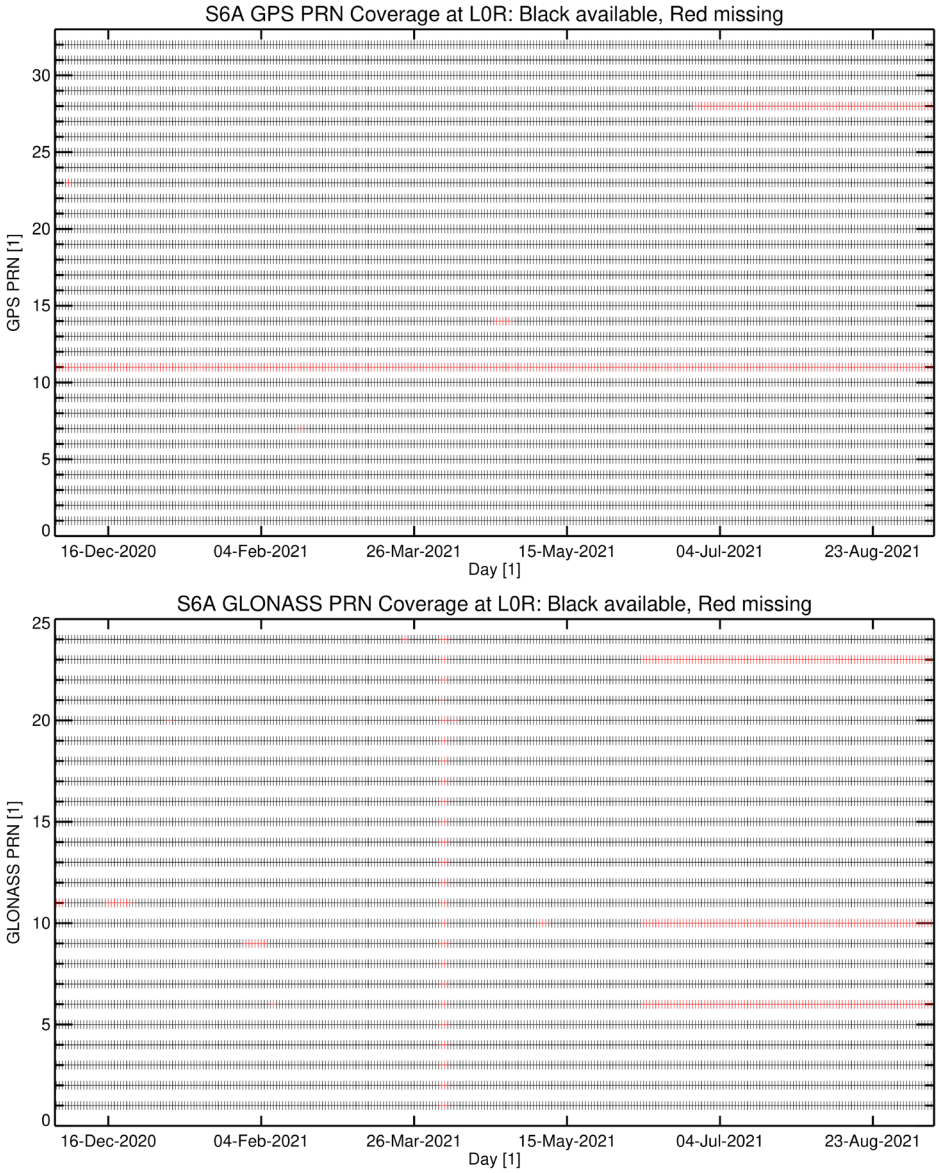

Figure 18 Daily GNSS availability at level 0R, top GPS, bottom GLONASS, black cross indicates PRN occultations observed on that day, red indicates none observed.

5.6 Occultation Duration

The occultation duration is shown in Figure 19. The majority of occultations are about 100s long; calculating the average finds about 110s due to the long tail. There are quite a few occultations that can take 5min or longer, in particular if the SLTA range goes down to -350km, in total more than 1500 are found at level 0R, 63% are GPS ones. The figure also includes the duration at level 1b, representing a quality control that removes occultations that are e.g., too short for processing. At level 1b, no occultations <50s are found; the number of long occultations >5min is also reduced to about 1100 (GPS still representing about 63%).

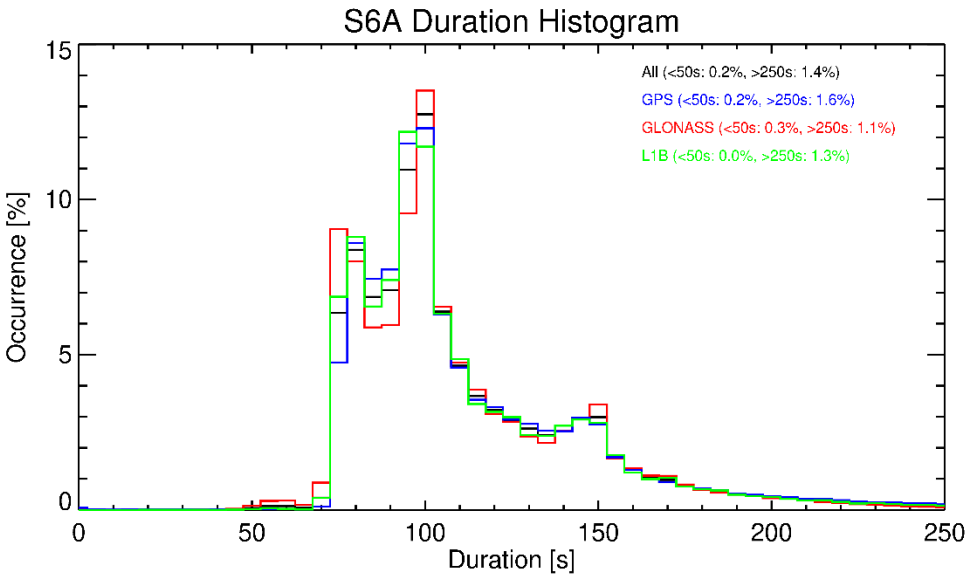

Figure 19 Occultation duration, total, per constellation and at level 1b. Legend provides additional info on very short or long occultations.

6 BENDING ANGLE DATA VALIDATION

6.1 Introduction

The following sections first show an internal analysis of the full record of S6A reprocessed bending angle products, validating them against ECMWF, as well as against collocated data from GRAS and the COSMIC-2 constellation. Selected results from NWP Partners, that analysed the S6A NRT data, as provided by NASA/JPL, and the NTC data, as provided by EUMETSAT, within their monitoring and assimilation system, is also shown.

Generally, processor v3.4 products are entering the validation, except for the yaw flip periods included, here v3.5 data was used as v3.4 had an issue with the yaw flip satellite configuration, leading to systematic uncertainties (see also relevant Anomaly Report EUM/JasonCS/AR/2059 and Section 6.9). Data analysed in this section is up to 11th of September 2021 for level 0R, and generally up to end of August 2021 for level 1b.

6.2 Number of Daily Products

The number of available occultations at level 0R was already shown in Figure 13; Figure 20 shows the number of occultations (the RO-NTC products) that were successfully processed to level 1b.

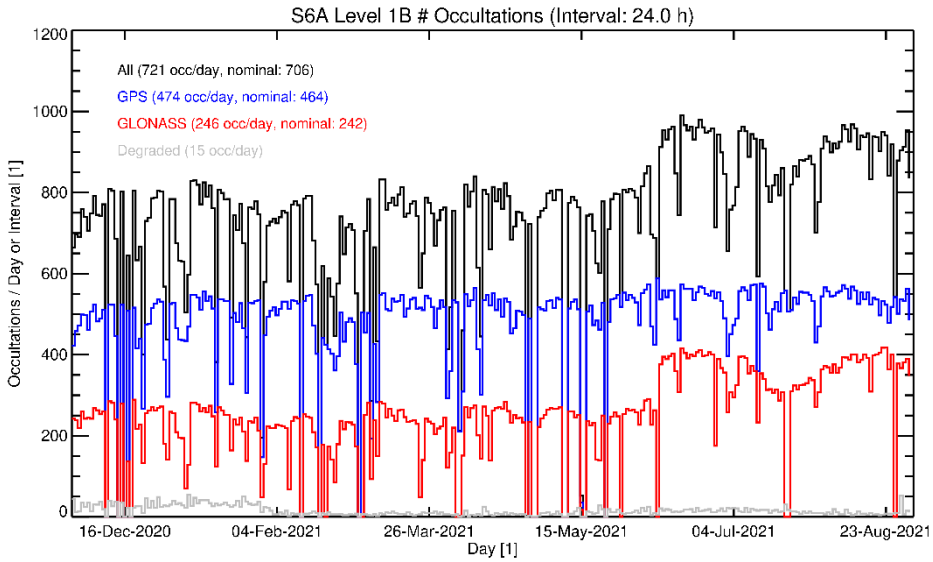

Figure 20 Daily number of occultations/products at level 1b, total, per constellation, non-nominal (degraded); average number of occultations per day is given in legend for total, and nominal ones.

Figure 20 again shows the improvement in the overall number of daily occultations with the on-board instrument s/w update in early June 2021. It does include however also some strong drops in these numbers after this update, e.g. on 21st and 22nd of July, no GLONASS occultations were processed, as the JPL provided GNSS orbit data had a gap (relevant Anomaly Report is EUM/JasonCS/AR/2105; it happened again after the investigated time period here, on 3rd and 4th of September 2021). A general lower number of occultations is also visible for the 1st to 5th of July yaw flip period, as expected since the SNR is lower during this period, see Figure 17. The about 15% reduction around the 31st of July and the 1st of August is also visible, caused by the already mentioned incomplete occultation tracking; a smaller reduction is visible for the 24th and 31st of August (see Section 3.6.3).

If analysing data since the on-board s/w update, there are on average 879 occultations per day, with 531 contributions from GPS, and 347 from GLONASS since 10th of June 2021. Nominal are 866 on average (GPS: 522; GLONASS: 343), thus providing an average exceeding the respective EURD requirement.

Figure 20 also includes some information about the number of nominal occultations over the full period. Generally, a degraded product (indicated by a DD or ND in the file name, [RD 9]) is caused by e.g., to low SNRs found on either the L1 and/or the L2 frequency, issues with the ionospheric correction, or the occultation is not spanning the expected altitude range. Degraded products can thus also provide valuable atmospheric information, even though they need to be handled with care.

For EURD assessments on daily numbers, only nominal products are considered. About 98% of all occultations that could be processed, were processed nominally, when looking at the total. For GPS, it is slightly below this number, for GLONASS slightly above, potentially due to the fact that GLONASS generally provides higher SNR on the second frequency and/or more problematic occultations are already failing prior to the level 1b generation (see Figure 14 and Figure 16). Removal of more problematic occultations is evident when comparing Figure 13 with Figure 20, noting that overall, about 78% of the level 0R occultations can be processed to level 1b, while this is 82% for GPS, and only 71% for GLONASS. This is the result of the quality control at level 1a, where the processing terminates.

6.3 GNSS Constellation Assessment at Level 1b

Similar to Figure 20, giving the available GNSS satellites at level 0R, it is also instructive to look at the availability at level 1b, which is shown in Figure 21.

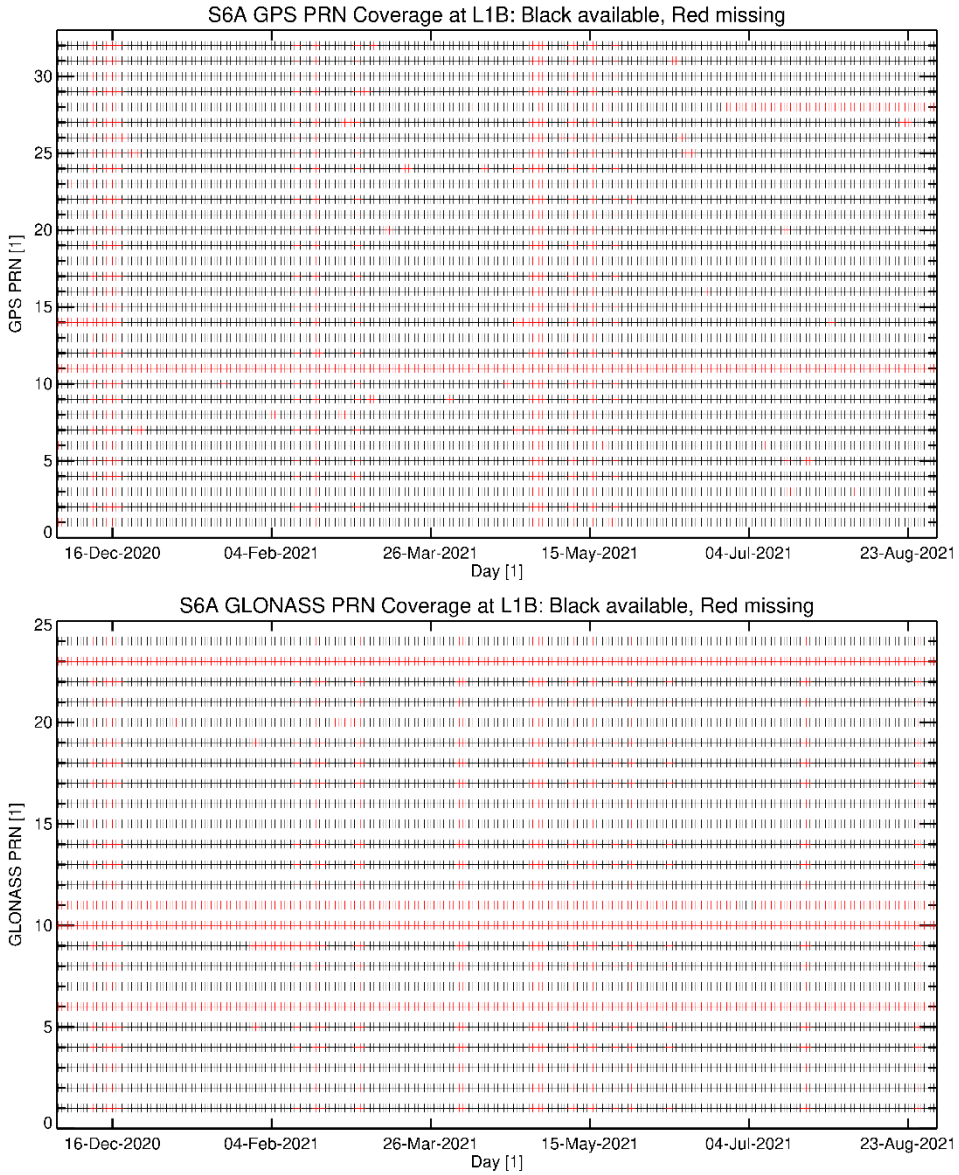

Figure 21 Daily GNSS availability at level 1b, top GPS, bottom GLONASS, black cross indicates PRN occultations observed on that day, red indicates none observed.

The availability of a PRN at level 1b depends on (1) whether the instrument observed it; (2) whether the auxiliary orbit/clock/other data for this PRN is available; (3) whether the LEO POD was able to provide an orbit and clock solution; (4) whether the occultation data had sufficient quality to process it to level 1b.

All of these factors are visible in Figure 21. E.g., that no GLONASS occultations for PRNs R06, R10, R23 were processed, indicates issues in the occultation quality, as already mentioned above (e.g., Section 5.5). These satellites are however generally not available in the auxiliary data, as the ground stations experience the same issues with the L2 frequency. R11, which is marked for testing in the constellation status by the Russian authorities, also generally has not auxiliary data, but is continued to be observed at level 0R. Days where no occultations are processed, neither for GPS nor for GLONASS, primarily indicate issues in the LEO POD s/w, which is e.g. for version v3.4 not capable to process days with a manoeuvre (see Table 1, relevant Anomaly Report is

EUM/JasonCS/AR/1646). In addition, as mentioned above, on 21st and 22nd of July 2021 a corrupted GLONASS file was provided by JPL, thus no GLONASS occultations were processed. Short outages of GNSS satellites are also visible, e.g. when they are set unhealthy by the relevant authority.

A short summary of relevant outages/reductions with further information is given in Table 5. As the v3.4 reprocessing was best effort, some days are missing where the cause is not known. Some days with issues in reprocessing actually worked fine in the CPF, on the OPE environment.

Day	Issue	Comment
2020/12/10	No products	Manoeuvre, v3.4 limitation
2020/12/14	No products	Manoeuvre, v3.4 limitation
2020/12/16	No products	Manoeuvre, v3.4 limitation
2020/12/18	No products	Manoeuvre, v3.4 limitation
2021/02/12	No products	
2021/02/18	No products	Manoeuvre, v3.4 limitation
2021/03/03	No products	
2021/04/04	No GLONASS	Instrument issue
2021/04/05	No GLONASS	Instrument issue
2021/04/27	No products	Manoeuvre, v3.4 limitation
2021/04/29	No products	Manoeuvre, v3.4 limitation
2021/04/30	No products	Manoeuvre, v3.4 limitation
2021/05/09	No products	Worked on CPF/OPE
2021/05/10	No products	Worked on CPF/OPE
2021/05/16	No products	GPS orbit data missing
2021/05/23	No products	Worked on CPF/OPE
2021/05/28	No GLONASS	
2021/06/09	No GLONASS	
2021/07/21	No GLONASS	Corrupted GLONASS data
2021/07/22	No GLONASS	Corrupted GLONASS data
2021/07/31	Fewer products	Incomplete tracking (see Section 3.6.3)
2021/08/01	Fewer products	Incomplete tracking (see Section 3.6.3)
2021/08/16	No products	Manoeuvre, v3.4 limitation
2021/08/26	Fewer products	Late GLONASS data
2021/08/31	Fewer products	Incomplete tracking (see Section 3.6.3)

Table 5 Outages/Reductions of L1B product production in RO-NTC v3.4 reprocessed data.

6.4 Instrument Activities and their Impact on Level 1b

Table 2 lists the instrument activities, where several early ones were tasks identified in the Cal/Val Plan [AD-01]. An analysis at level 1b of those in the Cal/Val Plan is shown in Figure 22, in the order they were actually activated.

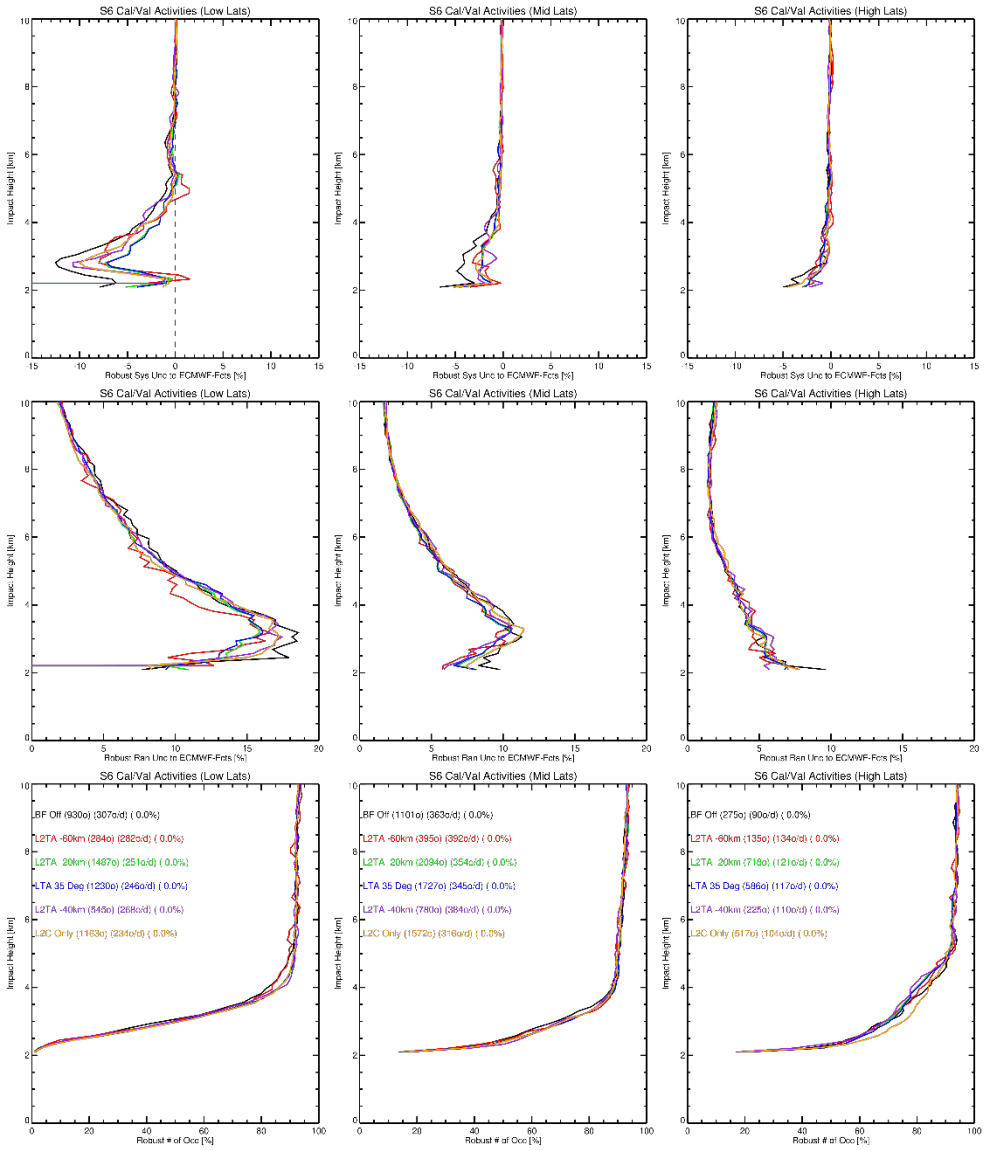

Figure 22 (O-B)/B statistics of EUMETSAT RO-NTC level 1b bending angles against ECMWF forward propagated bending angles for different instrument activities. Robust systematic uncertainties (top), random uncertainties (middle), outlier distribution (bottom); low latitudes (left), mid latitudes (middle), high latitudes (right). Otherwise as Figure 9.

The actual length of the instrument activities was fairly short, and also occurred in the early mission timeframe. The on-board s/w was thus not yet the optimal one. Hence these kind of analysis needs to be taken with a grain of salt. There are however several indicators that data improves with certain settings in Figure 22. E.g., the LTA 35 Degree period yielded lower systematic uncertainties for low latitude setting occultations, as expected; random uncertainties are also low for low latitudes. This setting, were data is tracked down to about -350km, was then also chosen as default.

Tracking the L2P signals for rising occultations down to -60km (L2TA -60km) appears to increase the systematic uncertainty, while the activity down to -20km (L2TA -20km) agrees very well in systematic and random uncertainty with the LTA 35 Degree assessment. The default for the L2P rising signal tracking is actually -40km SLTA (L2TA -40km), and here the situation is less clear cut and the short timeframe mentioned above are impacting the results; in the shown figure, -40km seems to have a higher bias for low latitudes. Splitting this further up into GPS rising occultations,

where this instrument setting is relevant, actually shows that -40km and -20km L2TA are very similar (not shown).

As expected, the deactivation of beam forming (BF Off), which reduces the SNR (see also Section 5.4), increases the systematic uncertainty in the low altitudes and increases the random ones.

6.5 Timeliness of L1b Products

The timeliness (meaning the time between the observation being made and it being available for users) is assessed by analysing individual occultation start times and processing times, as available from the file name of data processed on the CPF OPE environment in mid September 2021. The processing time is only a proxy for the data being available to the user, as it still needs to be made available via the EUMETSAT archive. This does however only add a small overhead onto the overall timeliness. Results are shown in Figure 23 for all products, nominal and non-nominal (there is though no distinguishable timeliness difference between the two). The driver of the timeliness is the availability of higher quality auxiliary GNSS orbit and clock data, which usually arrives after about 12 days. The maximum allowed timeliness of these auxiliary data is 18 days [RD 6]. There was though one anomaly, where auxiliary data was delivered late by NASA/JPL, resulting in the maximum found timeliness in the figure (relevant, closed anomaly report is EUM/JasonCS/AR/2023).

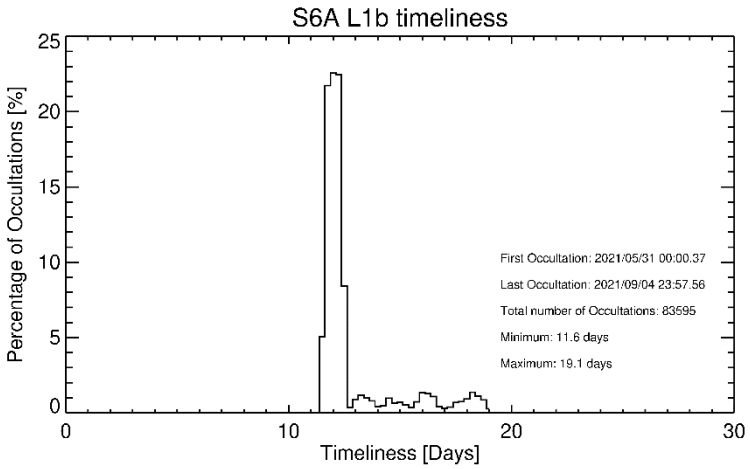

Figure 23 Level 1b product timeliness, as measured from file names. First, last, total number of occultations entering, minimum and maximum timeliness found, given in legend.

6.6 Validation against ECMWF Forecasts

Figure 24 and Figure 25 show a validation of the RO-NTC bending angle data against ECMWF forecasts, the first figure showing setting and rising occultations separately, the second different latitude bands. Regarding the setting and rising systematic and random uncertainties, they are very similar for the two occultation types, as can be expected when the orbit is accurate, and no processing issues introduce a split of these two occultation geometries.

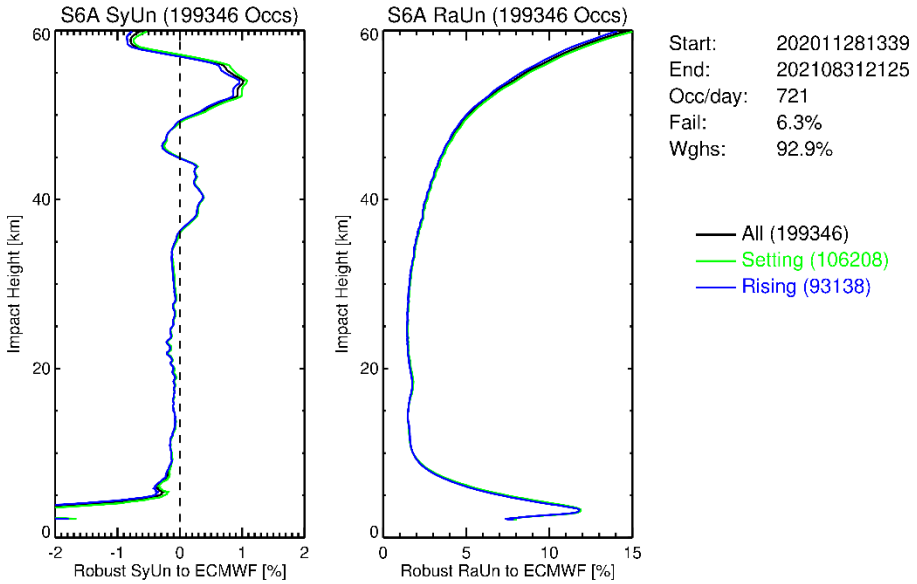

Figure 24 (O-B)/B statistics of EUMETSAT S6A RO-NTC level 1b bending angle against ECMWF forecasts for setting and rising occultations; (left) systematic uncertainty, (right) random uncertainty (1 sigma); legend gives further information on the data coverage, the average number of included occultations per day, the number of failures, as well as the robustness/weight of the statistics. The total number of occultations entering, as well as per data set, are given in brackets in title and legend.

The latitudinal assessment in Figure 25 (using 30º latitude steps), shows different systematic uncertainty structures from 17km upwards. This is thought to come from the ECMWF model, as the GRAS instruments show very similar structures (see Figure 28 or Section 6.7 which both confirm that these 2 RO instruments agree very well in the core region, up to about 50km). The random uncertainties vary for the different latitude bands, as e.g. gravity wave in the tropics, around 18km, are observed with S6A data, but are underrepresented in the ECMWF model. The RMS uncertainty, as given by the EURD [AD-02] is also included, showing that the random uncertainty (assuming this represents also the RMS, as RO is a bias free observation technique) is smaller than the EURD requirement for altitudes above about 40km, even though two error sources are included in the total budget of the random uncertainty: one from the model, and one from the GNSS-RO (which the EURD covers). Below about 40km, the random uncertainties are larger than the EURD RMS values, but we plot data in the standard vertical resolution as given to NWP centres. The relevant requirements gives a general lower vertical resolution of 1.5km for the interval from 20km to 30km.

Note that issues in confirming an RO instrument uncertainty budget are generally found when performing a validation, and were already observed for e.g., Metop/GRAS, or the COSMIC-2 constellation. The factors contributing to the difficulty in confirming such requirements are that the overall uncertainty budget will be the uncertainty combination of the two or more included data sets. This can be the NWP model uncertainty, or the space and time collocation uncertainty when comparing to another RO instrument. Also, the data coverage is usually only a few months, during commissioning. Hence, such requirements should be seen as actually driving the instrument performance. This way they assure that the best available data is also recorded for climate applications, which will make use of decades old RO data. E.g., the first long term RO instrument CHAMP, providing observations from 2001 to 2008, was reprocessed several times over the last 15 years, and each reprocessing run improved the data quality and agreement with re-analysis data.

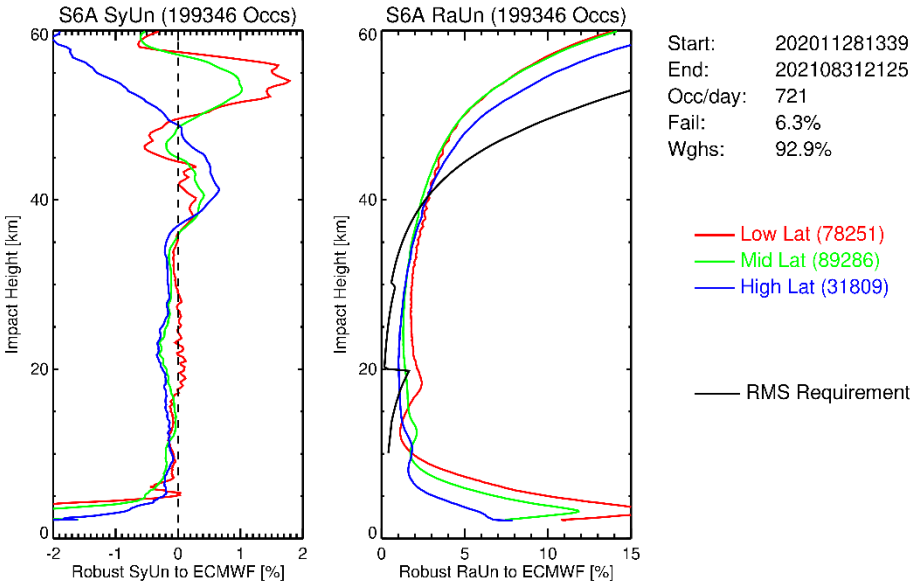

Figure 25 (O-B)/B statistics of EUMETSAT S6A RO-NTC level 1b bending angles against ECMWF forecasts for different latitude bands using robust statistics; (left) systematic uncertainty, (right) random uncertainty (1 sigma). The EURD RMS requirement is also shown; otherwise as Figure 24.

Time series of the uncertainties, evaluated against ECMWF forecasts, from the start of the mission are shown in Figure 26. Again, the setting rising difference is small, except for the very early data period, or where only limited data is available (2 top plot). The latitudinal plot appears to show a different behaviour of the systematic uncertainties for high latitudes, after the on-board instrument s/w update (3rd plot). This is also visible when splitting up by constellation (not shown). The cause for this change is currently unknown, it could also be a change introduced at ECMWF, with cycle update 47r2 that happened in May 2021. Assessing all GRAS data of this period against ECMWF also shows this high latitude bias evolving from about May/June 2021 onwards, and reducing again towards the end of August (not shown). The yaw flip increase in random uncertainty is clearly visible in early July 2021, affecting all data, setting, rising, all latitudes, as expected.

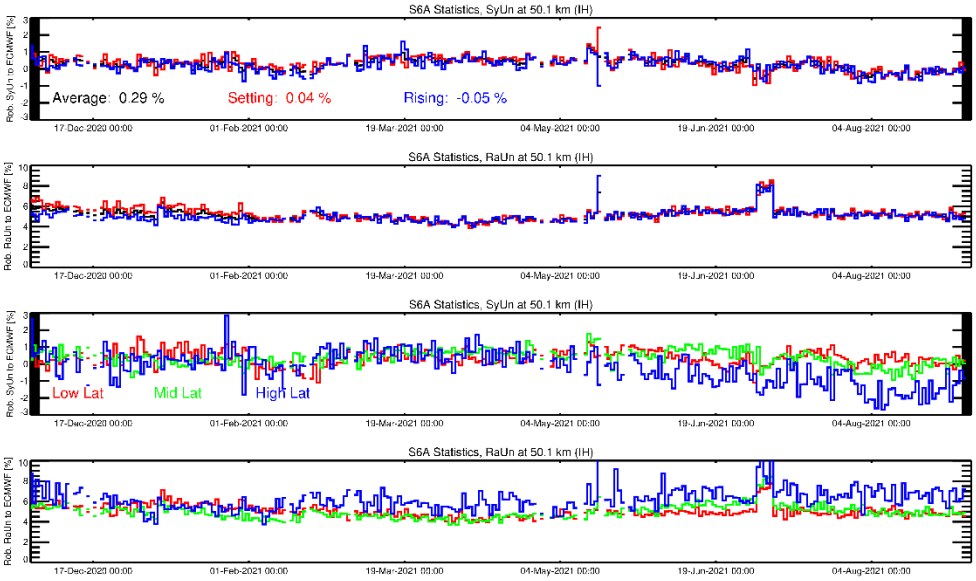

Figure 26 (O-B)/B time series of EUMETSAT RO level 1b bending angles against ECMWF forward propagated bending angles around 50km, daily averaged using robust statistics; (top) systematic uncertainty, (middle top) random uncertainty (1 sigma) for all/setting/rising; (middle bottom) systematic uncertainty, (bottom) random uncertainty (1 sigma) for different latitude bands. Average systematic uncertainty is also given, separated for setting/rising/all.

The GNSS-RO instrument on S6A observes two constellations, GPS and GLONASS. It is also instructive to split occultations by constellation, as done in Figure 27. The overall statistics are very similar, small differences exist for systematic uncertainties, where GLONASS data shows slightly higher values around 60km, including a very small setting vs. rising difference. The random uncertainties show slightly better GLONASS performance, even though GLONASS data is currently not using high quality final orbits, as these are not provided by NASA/JPL. However, the clock resolution of GLONASS data is higher, and, as already discussed in Section 6.2, there are more problematic GLONASS occultations not reaching level 1b; this might also contribute to the even better GLONASS performance for setting occultations, as the more problematic rising ones are removed. The failure rates for GPS and GLONASS are 6.8% and 5.3% respectively, for setting and rising combined.

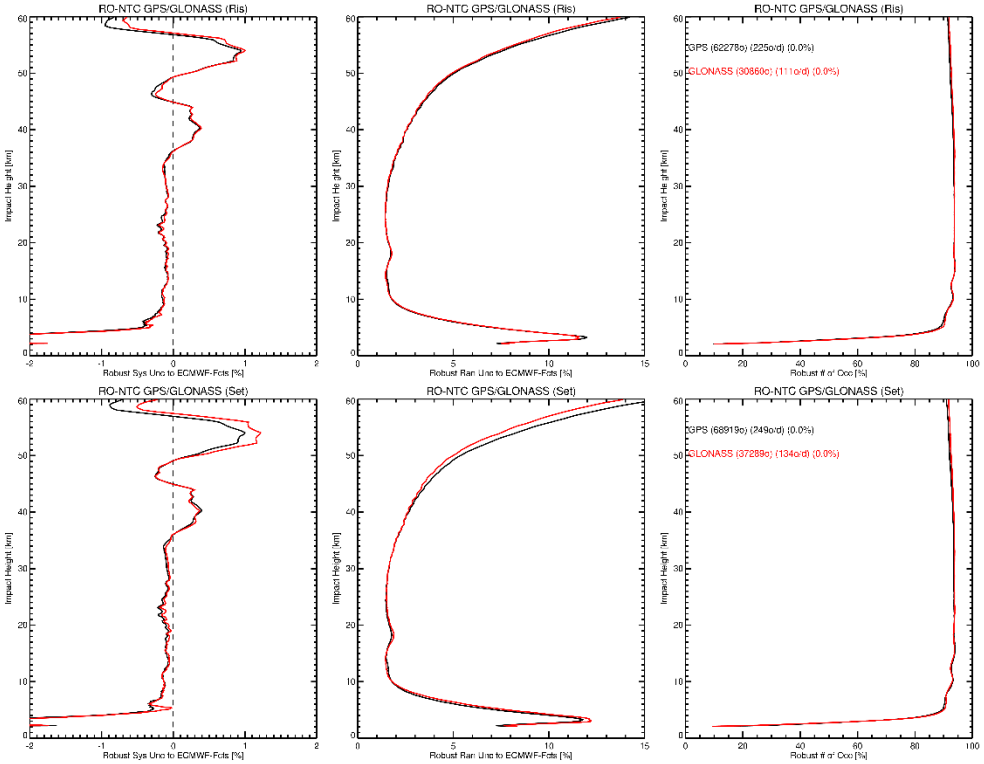

Figure 27 (O-B)/B statistics of EUMETSAT RO-NTC level 1b bending angles against ECMWF forward propagated bending angles for GPS and GLONASS. Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right); rising (top), setting (bottom). Otherwise as Figure 9.

Figure 28 shows a global validation of all S6A and all GRAS setting and rising occultations versus ECMWF. The overall systematic uncertainty is very similar from about 8km to about 50km. Above, the impact of the POD is visible and leads to differences that are generally small in comparison to the random uncertainty. Below about 8km, the operational GRAS data shows a large setting rising difference, this has now been corrected with an update of the GRAS processor to v5.0 (14 September 2021), S6A data is very similar to v5.0 (not shown). The random uncertainties show generally higher values for GRAS, which is another issue resolved with the PPF 5.0 installation; GRAS, using an ultra-stable oscillator for clock measurements, has lower uncertainties. The penetration to lower altitudes is very similar for both instruments, as seen in the right plots. The failure rate for S6A, setting and rising combined, is 6.3%, as also visible in e.g. Figure 24, thus higher than the GRAS one. This is e.g. due to the already mentioned instrument issues (see Section 3.6) or issues with the observed GNSS constellation (see e.g. Section 5.2). There were also more failures observed during the beam forming issue and during the yaw flip periods (see Table 2). On average, about 5% of failures are observed for nominal periods after the instrument on-board s/w update.

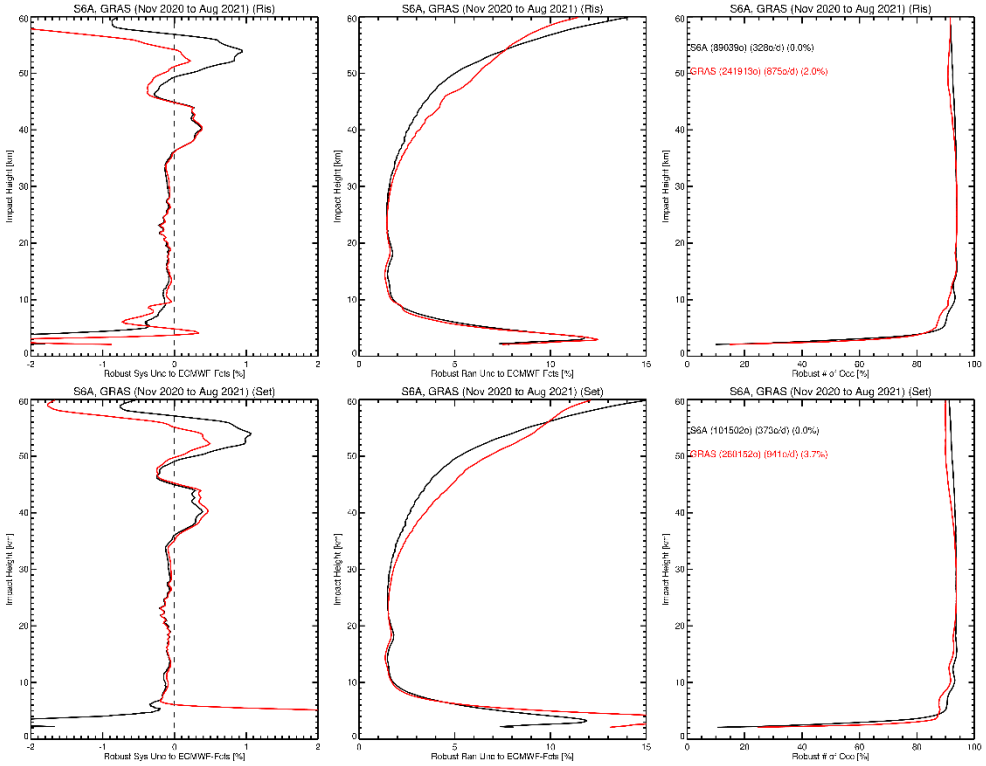

Figure 28 (O-B)/B statistics of EUMETSAT RO-NTC and GRAS level 1b bending angles against ECMWF forward propagated bending angles. Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right); rising (top), setting (bottom). Otherwise as Figure 9.

Figure 29 shows a comparison of the RO-NTC v3.4 and v3.5 bending angles for a few days (10th of June to 30 June 2021), confirming that both processors yield very similar results, v3.5 though leading to higher number of occultations processed per day and slightly lower number of failures.

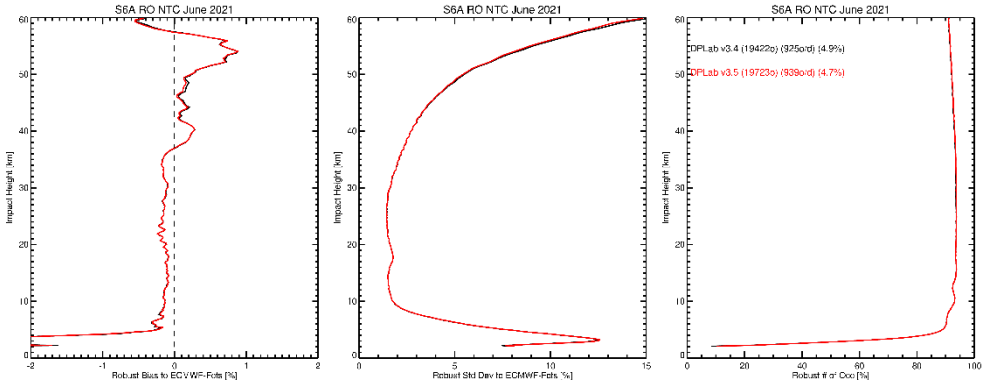

Figure 29 (O-B)/B statistics of RO-NTC processor v3.4 and v3.5 level 1b bending angles against ECMWF forward propagated bending angles for a few days in June 2021. Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right). Otherwise as Figure 9.

6.7 Validation against GRAS Occultations

Primarily, the operational GRAS data, generated with the GRAS processor version v4.7, was used for the collocation against S6A bending angles; all three Metop satellites were included [RD 11]. v4.7 does have some issues in the lower troposphere, were a positive bias is found against NWP

models; this is corrected with an update of the PPF to v5.0. Nevertheless, v4.7 was run operationally through the investigated period, and thus covers the full main validation period.

Matches were performed by searching for collocations that happen within 300km and 3h, latitudinal results are shown in Figure 30. In addition, a more stringent criterion of 100km and 1h was applied. Results for the collocation impact are shown in Figure 31.

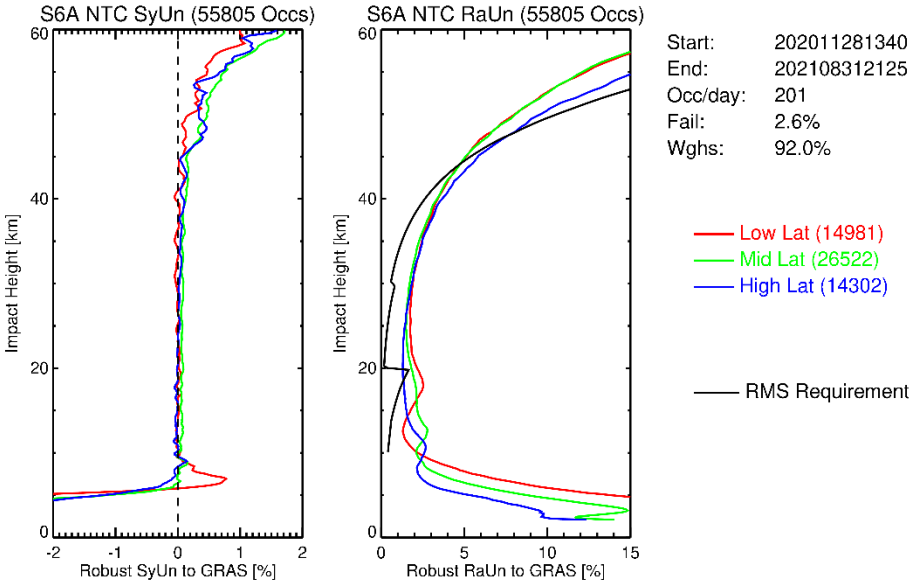

Figure 30 (O_1-O_2)/O_1 statistics of EUMETSAT S6A RO-NTC level 1b bending angles against collocated Metop GRAS bending angles using robust statistics; (left) systematic uncertainty, (right) random uncertainty (1 sigma). The EURD RMS requirement is also shown; otherwise as Figure 24. Note: Failures are accounted for only in GRAS v4.7 data; if one of the 2 occultations entering the match is invalid, the match is failed.

Figure 30 shows the already mentioned low altitude bias against collocated S6A data, for low latitudes it even shows a positive bias for some altitudes. Otherwise, the systematic uncertainty is very close to zero for altitudes from about 10km to about 45km. Above, S6A is positively biased when comparing to GRAS data. The bias is though (1) not significant when comparing the size to the random uncertainty at these altitudes, with the random uncertainty about a factor 15 higher at 55km., and (2), it is partly due to Metop-A rising occultations; in August 2019, Metop-A rising occultations suddenly showed a bias shift when compared to setting. This might have been caused by a shifted antenna phase centre, e.g. when some antenna patches stopped working. Investigations are on-going, but removing Metop-A rising occultations from the collocation about halves the found bias (not shown).

The figure again also includes the EURD [AD-02] RMS requirements, showing that this is archived from altitudes above 40km, but generally not fulfilled below (see also the related discussion along with Figure 25). The collocation criteria does impact the found random uncertainty. To assess this impact, we have also selected more stringent collocations, results are shown in Figure 31. The random uncertainty decreases with the more stringent requirement; even more stringent requirements do however find only limited matches and are thus very similar to the 100km / 1h results (not shown).

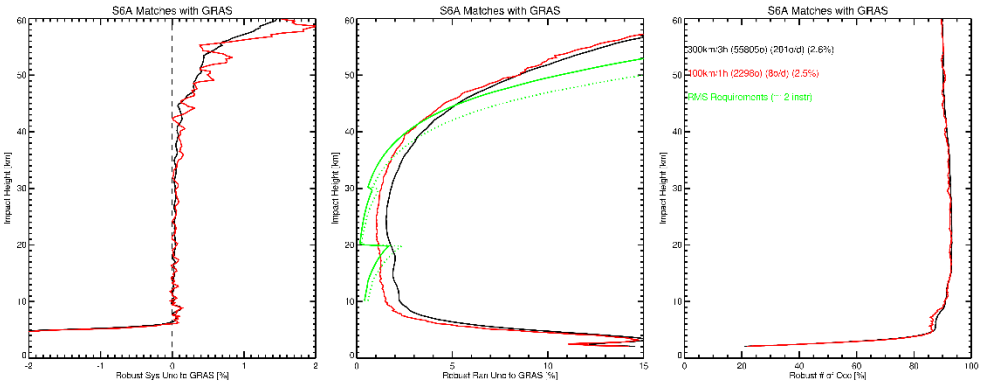

Figure 31 $(O_1\text{-}O_2)/O_1$ statistics of EUMETSAT RO-NTC level 1b bending angles against collocated Metop GRAS PPF 4.7 bending angles. Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right). Collocation criteria given in legend, the EURD RMS requirement for one and two instruments is also shown. Otherwise as Figure 9.

The validation is though again impacted by different error sources, here the collocation and the 2 instrument uncertainties (disregarding processing induced uncertainties). A rough estimate of the collocation uncertainty is given in Figure 31, by reducing the collocation criteria from 300km and 3h to 100km and 1h. In addition the figure also assumes that we have two instruments with the same uncorrelated uncertainty (leading to the green dotted line). This assumption likely represents a slight overestimation of the Metop GRAS uncertainties, but serves to show that the found uncertainties are compliant to the EURD requirement down to 35km, and around 20km.

Concerning the updated GRAS PPF 5.0 data characteristics, a one month period (October 2021) where RO-NTC v3.5 and PPF 5.0 were run in parallel on the operational platforms was used for comparison. Results are show in Figure 32, including comparisons of both data sets to ECMWF forecasts too. Clear improvements in the collocated data are visible in the lower troposphere and in the upper stratosphere, when compared against Figure 31.

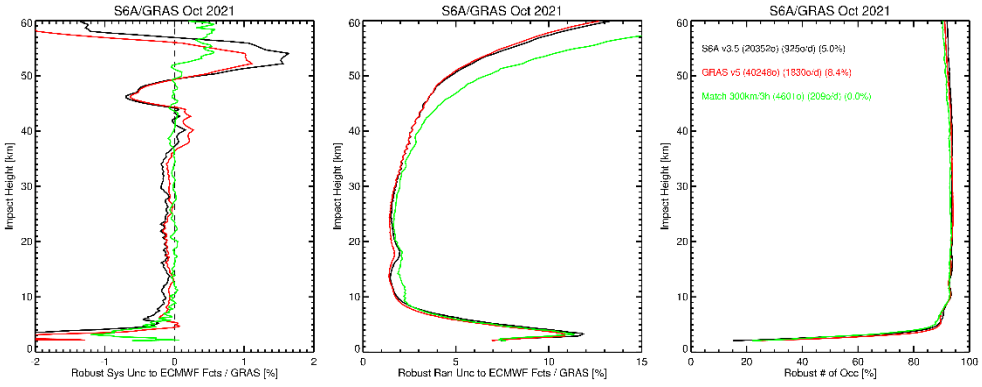

Figure 32 (O-B)/B or $(O_1\text{-}O_2)/O_1$ statistics of EUMETSAT RO-NTC and PPF v5 level 1b bending angles against ECMWF forward propagated bending angles or collocated Metop GRAS PFF 5.0 bending angles. Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right). Collocation criteria given in legend, the EURD RMS requirement for one and two instruments is also shown. Otherwise as Figure 9.

6.8 Validation against COSMIC-2 Occultations

A similar analysis as versus GRAS (see Section 6.7) was also performed against COSMIC-2 [RD 12], whose results are shown in Figure 33. Again, collocation criteria more stringent than the one shown yield only negligible improvements in the random uncertainties. But there is also a notable bias (systematic uncertainty) when collocating COSMIC-2 data against S6A one, almost for all altitudes above about 5km, which is not impacted by the collocation criteria. This bias is also observed on the ROM SAF NRT monitoring pages, when doing matches of GRAS and COSMIC-2. The root cause of this bias is unknown, NWP centres do not report any issues with assimilating COSMIC-2 data. It might be due to collocation, as e.g. reported in the IROWG 2019 workshop by B. Schreiner. Also within that presentation, it was noted that the COSMIC-2 refractivity requirements are difficult to verify, as all assessments ultimately include other uncertainty sources that are not very well known.

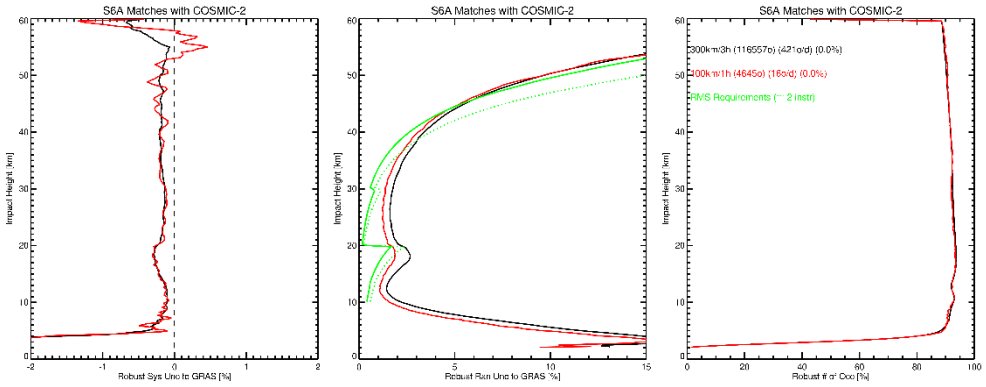

Figure 33 (O_1-O_2)/O_1 statistics of EUMETSAT RO-NTC level 1b bending angles against collocated COSMIC-2 bending angles. Robust systematic uncertainties (left), random uncertainties (middle), outlier distribution (right). Collocation criteria given in legend, the EURD RMS requirement for one and two instruments is also shown. Otherwise as Figure 9.

6.9 Yaw Flip Data Validation

RO-NTC processor v3.4 did not process occultations obtained during the yaw flip periods of 1st to 5th of July and September correctly (relevant Anomaly Report is EUM/JasonCS/AR/2059). In addition, it is evident from Figure 17 that the instrument SNR performance is degraded during these periods. For the general validation shown above, we used a corrected processor version internally, and included it in the data set. Here, we also look more in detail at the level 1b performance during the first yaw flip, using v3.5 data, as generated during testing on the development platform DPLab. Figure 34 shows the performance around 50km against ECMWF forecasts. The plot also includes a few days prior and after the yaw flip manoeuvre.

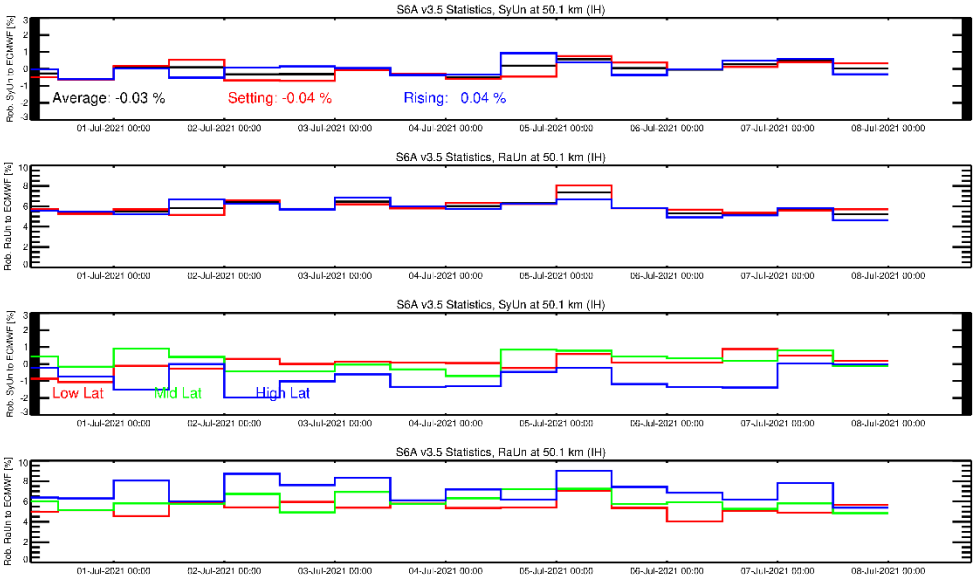

Figure 34 (O-B)/B time series of EUMETSAT RO level 1b bending angles, around the July 2021 yaw flip, against ECMWF forward propagated bending angles around 50km, 12h averaged using robust statistics; (top) systematic uncertainty, (middle top) random uncertainty (1 sigma) for all/setting/rising; (middle bottom) systematic uncertainty, (bottom) random uncertainty (1 sigma) for different latitude bands. Average systematic uncertainty is also given, separated for setting/rising/all.

Generally, the systematic uncertainty remains fairly similar during the yaw flip period, it is though noticeable that the random uncertainty increases slightly, and here primarily for the high latitude data.

6.10 Validation against NASA/JPL NRT

NASA/JPL NRT data was validated during the commissioning period, involving several NWP centres (MetOffice, UK; ECMWF, UK; JCSDA, US). Commissioning data was provided by NASA/JPL on a dedicated secure ftp server, covering the period from 2021/02/26 to 2021/05/25.

A comparison of these 3 months of data against the EUMETSAT RO-NTC v3.4 data is shown in Figure 35. Several of the bending angle issues identified in [RD 17] for the NRT data are visible, e.g. (1) a bias between setting and rising at high altitudes; (2) a positive bias at low altitudes.

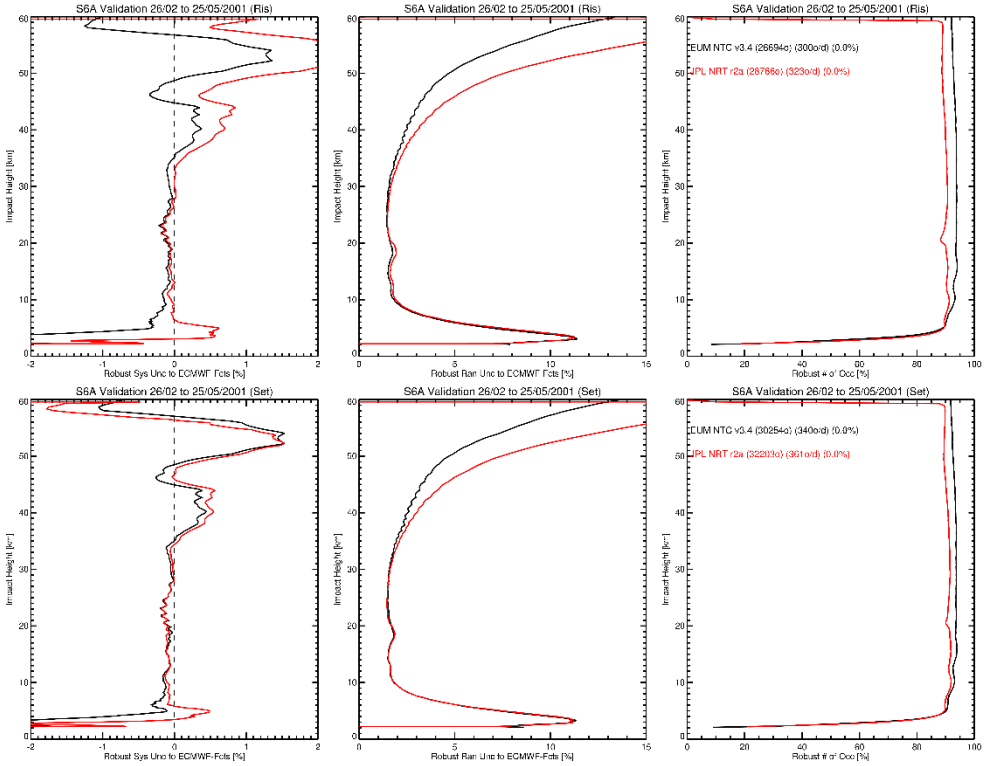

Figure 35 (O-B)/B statistics of EUMETSAT RO-NTC and NASA/JPL NRT level 1b bending angles against ECMWF forward propagated bending angles (Feb-May 2021). Robust systematic uncertainty (left), random uncertainty (middle), outlier distribution (right), rising (top), setting (bottom), otherwise as Figure 9.

6.11 Validation at NWP Partners

6.11.1 ECMWF Validation

ECMWF validated the data quality by performing assimilation trials. The setup for these trials is show in Table 6.

ITEM	SETUP
Bending angle operator	2D
Observation error model	Global bending angle error statistic
Bias correction	No
Usage of data	From surface to 50 km
Model	CY47R1 Tco399 (25 km spacing)
Data assimilation cycle	12h
Experiment period	From 26 Feb 2021 to 25 May 2021

Table 6 ECMWF assimilation trial setup.

The following three trials were run:

- **Control** Operational data available for the period, including the GNSS-RO data (3*Metop), KOMPSAT-5, TSX, TND, 6*COSMIC-2
- **NRT** Operational data available for the period, including the GNSS-RO data (3*Metop), KOMPSAT-5, TSX, TND, 6*COSMIC-2 + SENTINEL6-A/JPL (NRT)

- **NTC** Operational data available for the period, including the GNSS-RO data (3*Metop), KOMPSAT-5, TSX, TND, 6*COSMIC-2 + SENTINEL6-A /EUMETSAT (NTC)

Figure 36 shows the first guess departure statistics for the JPL NRT and the EUMETSAT NTC data sets. Similar to Figure 35, a higher systematic uncertainty is observed for the JPL data at high altitudes when comparing to EUMESAT's NTC data; the random uncertainty (STD) is higher at all altitudes. An analysis by constellation shows that the random uncertainly increase is as expected higher for both, GPS and GLONASS, but for GLONASS, the difference to the EUMETSAT data set is smaller (not shown).

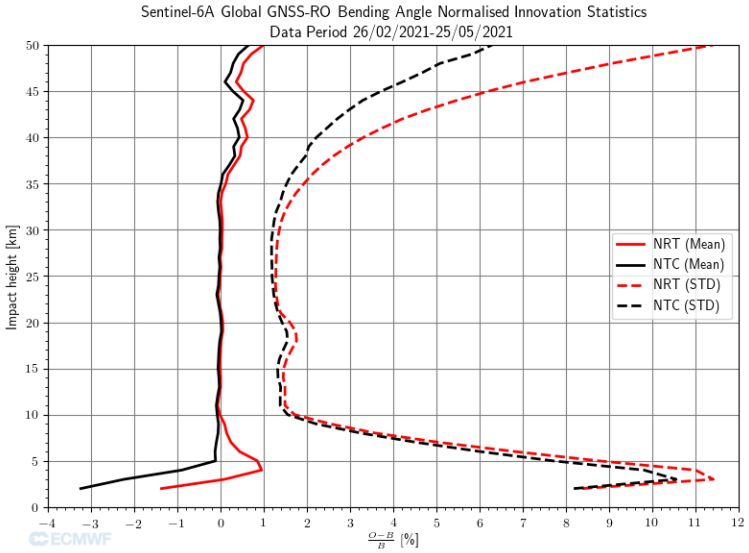

Figure 36 First guess departure statistics of the JPL NRT and EUMETSAT NTC data.

Figure 37 shows the improvements over the control run (which marks the 100% vertical line) for all RO measurements; both data sets improve the forecast, the EUMETSAT NTC data actually slightly higher.

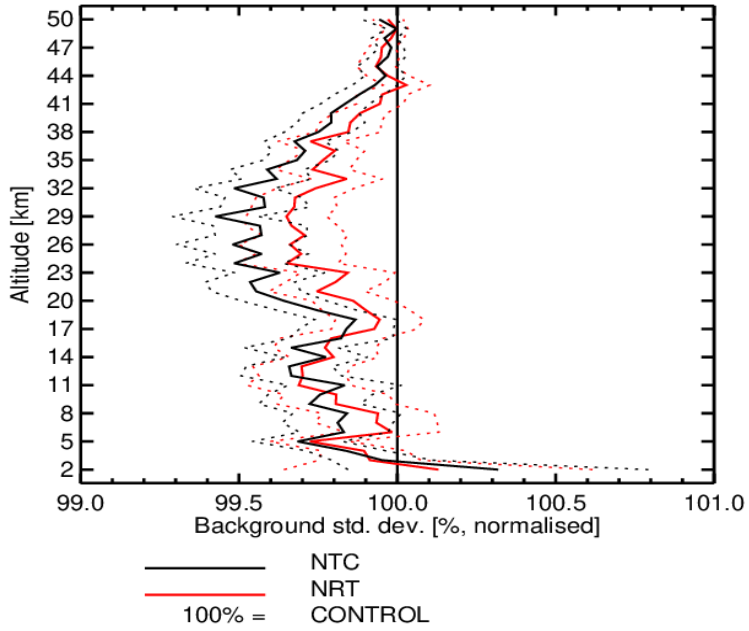

Figure 37 Fit to operational GNSS-RO data after assimilating either JPL NRT or EUMETSAT's NTC data. Dotted lines indicate the uncertainly margin.

Figure 38Figure 37 shows the improvement for radio sonde temperatures. Again, the NTC data by EUMETSAT leads to slightly better results. Note that several other plots on improvement were provided, e.g. fits to AMSU-A and ATMS satellite data, and all show the improvements in fits, with higher ones for the NTC data. These plots are not included here for the sake of brevity.

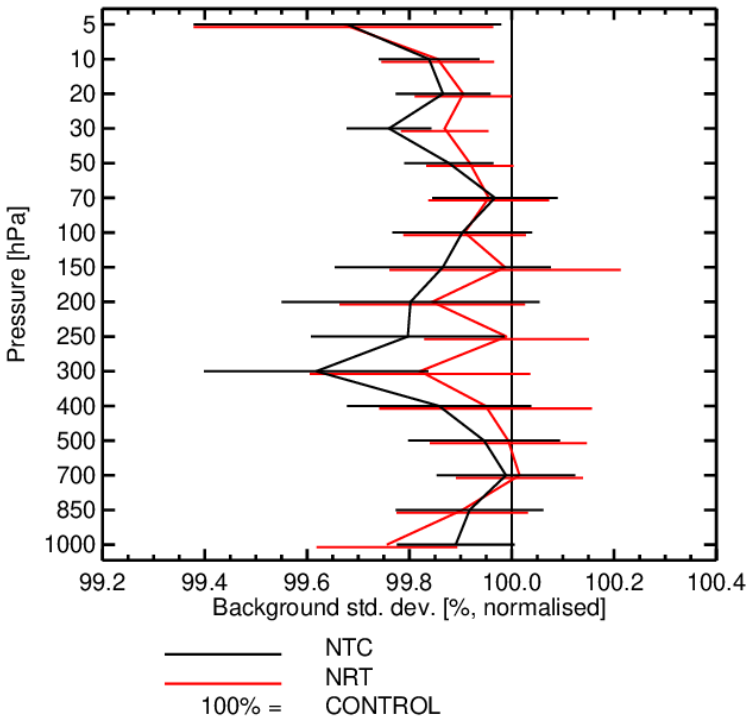

Figure 38 Fit to radio sonde temperatures after assimilating either JPL NRT or EUMETSAT's NTC data. Horizontal lines indicate the uncertainly margin.

6.11.2 MetOffice Validation

The Met Office routinely calculates monitoring statistics of GNSS-RO observations from a variety of satellites on behalf of the ROM SAF. That software has been used to produce the same set of statistics for Sentinel-6 observations, both using the NRT processing of JPL and the NTC processing of EUMETSAT.

The monitoring statistics have been calculated for the period of 1 January to 1 March 2021 for the NTC observations. These are compared with observations from the NRT processing between 26 February and 26 March 2021. This is version 2 of the NRT processing, after addressing issues which were noted in version 1. These can also be compared to GRAS observations from the latest three months (1 July to 30 September 2021). Although the periods do not match, these comparisons can still provide useful information.

The statistics focus on the difference between the observation and a short-range forecast (6h) of the observation, made from the Met Office's operational system. The plotted values are often the mean or standard deviation of

$$\frac{O-B}{B}$$

where O is the observed value and B is the simulated value from the model forecast. The normalisation by B helps to make the statistics clearer over a range of altitudes.

Figure 39 shows the mean and standard deviation of $(O-B)/B$ for the NRT and NTC processing of Sentinel-6 observations, and GRAS observations from Metop-B. The mean differences (solid lines) are generally very similar between 10 and 45 km impact height. In the troposphere the

biases are small for the NRT processing. For the NTC processing there is a consistent negative bias throughout the troposphere. The observations from Metop-B have a negative and positive bias since much of the data is derived from before the recent upgrade to the EUMETSAT processing. Since the NWP model may contain biases in the troposphere, it is not known which bias signature is "correct".

The standard deviations are generally similar for both sets of Sentinel-6 observations below around 35 km, with the NRT standard deviations being slightly smaller in the lower troposphere. Above 35 km the standard deviations for the NTC processing are smaller. They are both larger than the standard deviations for Metop-B above 45 km, but this is expected since the GRAS instrument on-board Metop-B is very accurate at these altitudes.

The counterpart for the standard deviations of *((O-B)/B)* is the vertical correlation of the same quantity. Increased vertical smoothing of the same data can lead to smaller standard deviations but increased vertical correlations. This is shown in Figure 40 for the NRT and NTC observations for Sentinel-6. The vertical correlations are very similar between the two sets of data. Near the top of the profile the NTC observations appear to have a slightly shorter correlation length-scale and do not have the small positive correlations at long range. On the other hand, the NTC observations appear to have very slightly longer correlation length-scales in the troposphere. Thus, unexpectedly, the NTC appears to have shorter correlations where the standard deviation is smaller, and vice-versa.

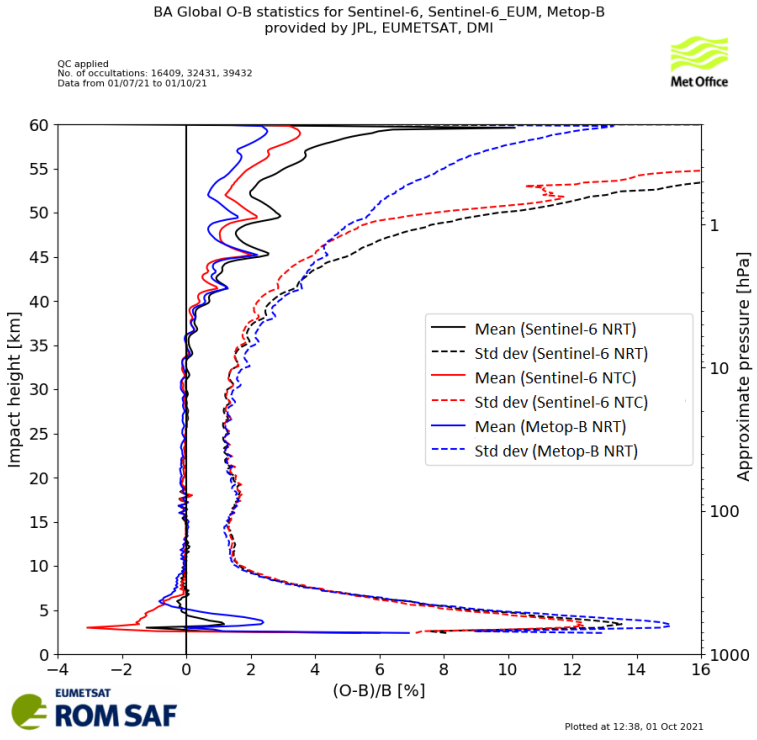

Figure 39 Mean and standard deviation of the normalised differences between the observations and the forecast. The data for Sentinel-6 (black, NRT processing), Sentinel-6 (red, NTC processing) and Metop-B (blue) are over different periods.

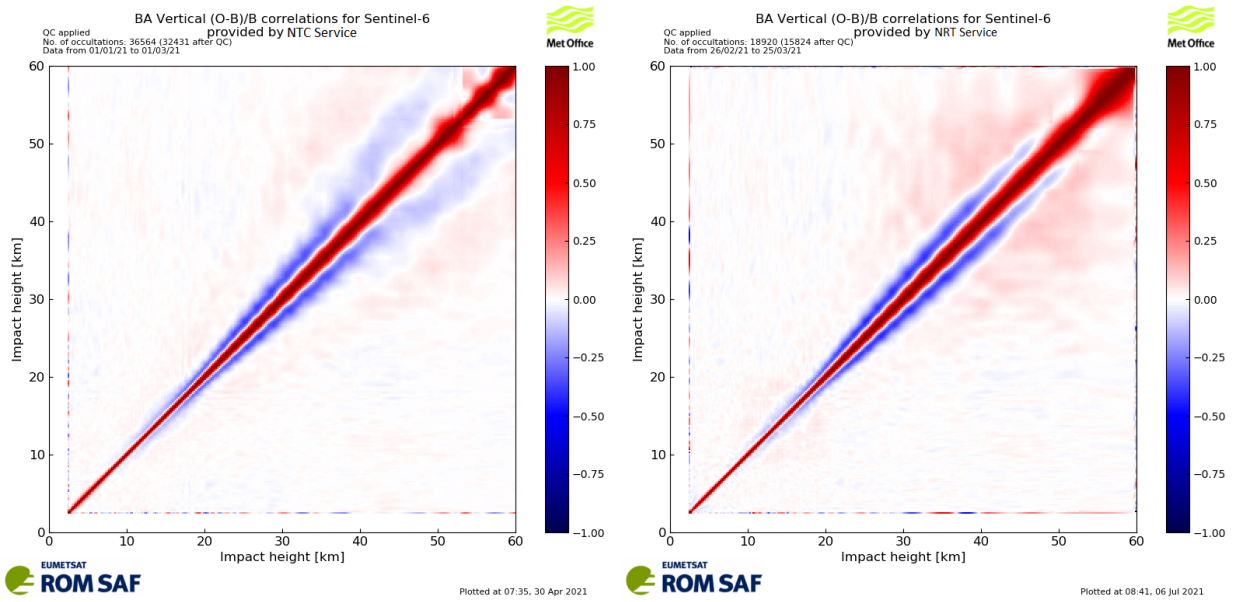

Figure 40 Vertical correlations of normalised observation departures for (left) NTC observations and (right) NRT observations.

Another interesting statistic is to consider the observations at different stages throughout the quality control (QC). Figure 41 shows the mean and standard deviation of (*(O-B)/B*) before any QC, after EUMETSAT QC and finally after Met Office QC. The mean observation departure in all three cases is very similar, indicating that all observations which have successfully been inverted are unbiased. A relatively small number of observations are removed by EUMETSAT QC (<5%) with the rest being removed by Met Office QC.

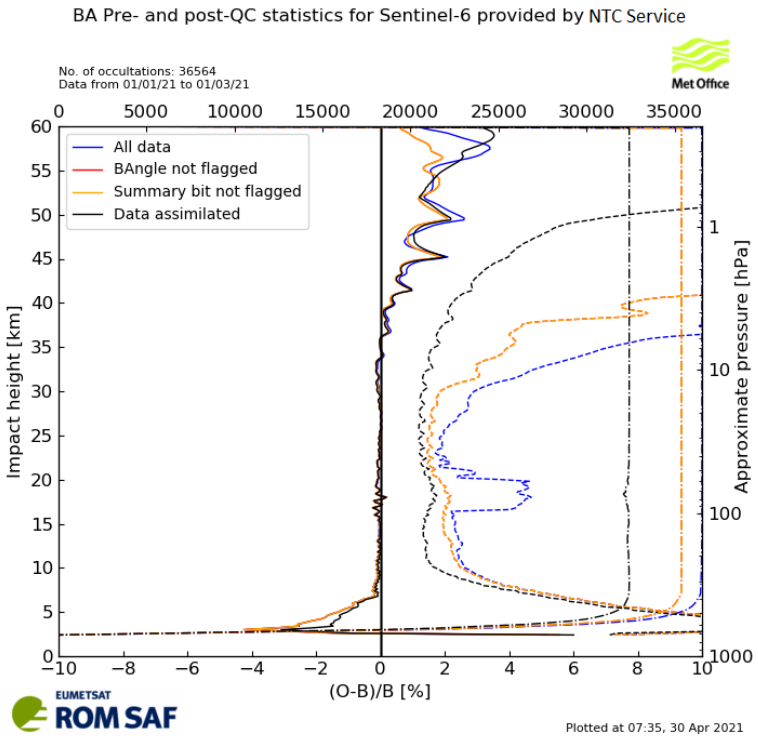

Figure 41 Mean and standard deviation of normalised observation departures at various stages of the quality control (QC) process for NTC data. (blue) Before any QC, (yellow) after EUMETSAT NTC QC and (black) after Met Office QC.

7 REQUIREMENT, ANOMALY STATUS, CAL/VAL TASKS

The following sections lists the EURD requirements and points to relevant figures or analysis performed in this report to show the compliance. It also includes a status of all relevant Anomalies that are currently on the GNSS-RO instrument, the processor, or the auxiliary data. The last section traces the Cal/Val Tasks, as identified in the Cal/Val Plan, to relevant figures and analysis performed in this report.

7.1 Requirements

All GNSS-RO EURD [AD-02] processing relevant requirements are listed below, along with their responsibility and compliance status. Where needed, additional information is provided. It is generally assumed, that NRT requirements are also applicable for the NTC service.

[EURD] R-U-00580:
The GNSS-RO shall track radio occultations from at least two of the following constellations: GPS; GLONASS; Galileo.
Responsibility: NASA/JPL and EUMETSAT
Status: Compliant
Further information: see e.g. Figure 20.

[EURD] R-U-00600:
The RO-NRT service shall be capable to provide 770 profiles per day.
Status: Compliant
Responsibility: NASA/JPL (and EUMETSAT for NTC cross-check)
Further information: The service is capable, e.g. shown with the GNSS-RO instrument s/w update early June `21, that lead to daily numbers safely above 770 (there are on average already 866 profiles per day for v3.4, see Figure 20 and related text in Section 5.1). The occasional, incomplete occultation tracking (see Section 3.6.3) can lead to reductions for single days; here the investigation at NASA/JPL regarding the root cause is ongoing. In addition, issues with the provision of auxiliary data can impact the daily numbers for the NTC service (see Table 5).

[EURD] R-U-00620:
The set of parameters in each record of the RO Level 1b products shall include, as a minimum: the time of measurement; bending angles over impact parameter; the geolocation of the tangent point.
Responsibility: NASA/JPL and EUMETSAT
Status: Compliant
Further information: see [RD 9].

[EURD] R-U-00640:
The set of parameters in each record of the RO Level 2 products shall include, as a minimum: the time of measurement; refractivity over geopotential/geometric height; the geolocation of the tangent point.
Responsibility: NASA/JPL and ROM SAF
Status: Compliant
Further information: Level 2 data provided by the ROM SAF uses a standard ROPP based format, which includes this information.

[EURD] R-U-00660

The Radio Occultation instrument shall make occultation measurements for ray path tangent heights between the Earth's surface and 80 km altitude.
Responsibility: NASA/JPL
Status: Compliant
Further information: see Figure 15.

[EURD] R-U-00680:

The Radio Occultation instrument shall be capable to make occultation measurements with ray path tangent height extending up to at least 500 km altitude.
Responsibility: NASA/JPL
Status: Compliant
Further information: the GNSS-RO instrument can be configured to make observations up to 500 km, thus the requirement is fulfilled; this configuration was though not exercised. The TriG instrument is able to do this, as shown on other missions (e.g. COSMIC-2).

[EURD] R-U-00720:

RO-NRT Level 1b products shall be made available within 3 hours after sensing time, with an operational availability of 90% over any 1-month period.
Responsibility: NASA/JPL
Status: Compliant
Further information: NASA/JPL assessed timeliness and found sufficient margin to be compliant, results were e.g. shown during the relevant reviews.

[EURD] R-U-00740:

RO-NRT Level 2 products shall be made available within 3 hours after sensing time, with an operational availability of 90% over any 1-month period.
Responsibility: NASA/JPL
Status: Compliant
Further information: This is assessed along with Level 1b data, thus see [EURD] R-U-00720.

[EURD] R-U-00760

The RMS measurement uncertainty of the neutral bending angle for altitudes between 30 km and 60 km shall be below 2 µrad, with a vertical resolution of 1.5 km.
Status: Generally compliant
Responsibility: NASA/JPL and EUMETSAT
Further information: See Figure 25, Figure 30, Figure 31, Figure 33 and related discussions.

[EURD] R-U-00780

The RMS measurement uncertainty of the neutral bending angle for altitudes between 20 km and < 30 km shall be below 3 µrad, with a vertical resolution of 1.5 km.
Status: Generally compliant
Responsibility: NASA/JPL and EUMETSAT
Further information: See Figure 25, Figure 30, Figure 31, Figure 33 and related discussions.

[EURD] R-U-00800

The RMS measurement uncertainty of the neutral bending angle for altitudes between 10 km and < 20 km shall be below 30 µrad, with a vertical resolution of 0.15 km.
Status: Generally compliant

Responsibility: NASA/JPL and EUMETSAT
Further information: See Figure 25, Figure 30, Figure 31, Figure 33 and related discussions.

[EURD] R-U-00820

RO-NRT products shall be made available to WMO users using WMO identified dedicated networks and formats.
Status: Compliant
Responsibility: NASA/JPL
Further information: RO-NRT products are available on GTS, in BUFR format [RD 17].

[EURD] R-U-00840

RO-NTC Level 1b products shall be made available within 60 days after sensing time, with an operational availability of 95% over any 1-year period.
Status: Expected to be compliant
Responsibility: EUMETSAT
Further information: We do not have a one year period to evaluate the requirement, but the timeliness of products produced so far never exceeded 20 days (see Figure 23).

[EURD] R-U-00860

RO-NTC Level 2 products shall be made available within 60 days after sensing time, with an operational availability of 95% over any 1-year period.
Status: Expected to be compliant
Responsibility: ROM SAF
Further information: We do not have a one year period to evaluate the requirement, [RD 1, RD 2] shows though that timeliness is well within requirements.

7.2 Anomalies

The following table lists the anomaly with title and the status with processor version RO-NTC v3.5 / v3.6. Some are already resolved and included here only for information. Also, relevant anomalies that occurred after the v1C release of this document, and are not covered here, are summarized in the Product Notice, publically available [RD 19].

Anomaly ID	Anomaly Title	Status with v3.5
EUM/JasonCS/AR/1167	Some GEMS warning events didn't have any impact on the operations	Resolved
EUM/JasonCS/AR/1413	GNSS-RO autonomous reboots	Information only. Instrument related, improved with s/w update, accepted as limitation.
EUM/JasonCS/AR/1580	JPL L0Decoder s/w Issue: GPS Fractional Seconds in Occultation Data greater than 1 or negative	Resolved with Decoder v1.3.
EUM/JasonCS/AR/1646	The RO-NTC doesn't support the generation of POD when a maneuvers is performed on the satellite	Resolved
EUM/JasonCS/AR/1715	The RO-NTC failed on the generation of POD	Resolved
EUM/JasonCS/AR/1746	GNSS-RO loss of occultation	Resolved

EUM/JasonCS/AR/1769	SEU Effects on Science Products	Open JPL action. Instrument related, did improve with s/w update, monitoring on-going.
EUM/JasonCS/AR/1971	GNSS-RO Instrument reporting Future Occultations	Accepted as instrument limitation, mitigated with v3.5 filter.
EUM/JasonCS/AR/2041	GNSS-RO false trigger of SciP watchdog	Resolved
EUM/JasonCS/AR/2059	RO-NTC Processor not handling Yaw Flip Data correctly	Resolved
EUM/JasonCS/AR/2105	Gap in GLONASS orbit and clock causes low number of L1B occultations	Incorrect format of NASA/JPL auxiliary data (4 days so far affected). EUM action resolved, impact reduced.
EUM/JasonCS/AR/2132	GNSS-RO occultation packets not being output consistently	Instrument related, script update uploaded, monitoring on-going (see Section 3.6.3).
EUM/JasonCS/AR/2137	Data Gap Handling in Occultation Time Series of single Level 0 Dumps	Resolved with v3.6.
EUM/JasonCS/AR/2143	S6 RO-NTC Docker Container core dumps and restarts	Resolved
EUM/JasonCS/AR/2159	RO-NTC late delivery of JPL ADF (GLONASS orbits) file leads to lower number of occultations	Resolved
EUM/JasonCS/AR/2206	RO-NTC failure on Bernese POD S/W	Resolved with v3.6. Affected v3.5 data of 26 Oct 2021, 06 Jan 2022.
EUM/JasonCS/AR/2306	L2 Cut Off impacted by Solar Activity	Resolved with v3.6. Affected v3.5 data, with occasional reduced L2 data use.
EUM/JasonCS/AR/2272	Significant increase in rate of GNSS-RO auto reboots	Monitoring on-going.

7.3 Cal/Val Tasks

The table below lists the tasks identified in the Cal/Val Plan in Table A.1 [AD-01], and points to relevant sections and figures within this report, where theses analysis were performed. The Cal/Val Plan priorities are also included, where I: high; II: medium; III: low.

The table also traces the Cal/Val Tasks to the relevant WBS/WP numbers, as defined in the Jason-CS Commissioning Plan [RD 18]. Notes: (1) 14/2 of the commissioning plan is covered by the PVRB and ORR reviews; (2) 55/1 covers only the execution of the instrument commanding, the actual trace to the analysis performed is included below; (3) some WBS are formally only NASA/JPL NRT responsibility, but where NRT and NTC activities overlap, are included in the table in grey.

Cal/Val Task	Priority	Relevant Cal/Val Report Part / Info	WBS/WP
1 Bending Angle Assessment	I	Sections 6.6, 6.7, 6.8 (6.10, 6.11)	75/1, 75/2
2 Refractivity Assessment	II	ROM SAF Activity [RD 1, RD 2]	75/2
3 POD Validation	I	Sections 4, 6.6	74/1, 75/2
4 Instrument Optimizations:			
4.1 Beam-Forming (BF) Calibration	I	Sections 5.4, 6.4	55/1, 75/1
4.2 L2P Tracking Altitude	I	Section 6.4	55/1, 75/1

4.3 Lowest Tracking Altitude	II	Section 3.6.5, 6.4	55/1, 75/1
5 Tracking Multiple GNSS Constellations	I	Sections 5.1, 5.2, 5.5, 6.3, 6.6	75/1
6 Number of Occultations	I	Sections 5.1, 6.2, Table 5	75/1
7 Vertical Coverage	I	Sections 3.6.3, 5.3, 6.6	75/1
8 Level 1b Products	II	Product Format Specification [RD 9]	75/1, 75/2
9 Level 2 Products	II	ROM SAF Activity [RD 1, RD 2]	75/2
10 Tracking Capability for Ionosphere	III	N/A; Optional activity, not executed	
11 Ionosphere Measurement Capability	III	N/A; Optional activity, not executed	
12 ROWG findings and recommendations		This RO NTC Cal/Val Report	83/1

8 CONCLUSIONS, ISSUES AND LIMITATIONS

The GNSS-RO instrument on-board of the Sentinel-6 Michael-Freilich (S6A) satellite has been measuring occultation measurements from instrument switch on, on the 28th of November 2020, one week after launch. Several instrument optimisation activities were performed during the first weeks in orbit, and in early February 2021 the instrument configuration was finalized.

The GNSS-RO instrument itself can make use of GPS and GLONASS satellites for occultation measurements (the orbit determination though relies on GPS only). Generally, there are about 30 GPS satellites available, but only 24 GLONASS ones, so the major part of the occultations are GPS based. In addition, processing of the initial GLONASS data showed that 3 of these satellites are not providing data on the second frequency, and are thus unusable for occultation processing. Consequently, it was decided to block the tracking of these faulty satellites (PRN 06, 10, 23), and only 21 GLONASS were tracked afterwards. The blocking was performed with an on-board instrument s/w update in early June 2021. Additionally, another GLONASS satellite (PRN 16) dropped out of the available satellites for occultations on the 16th of December 2021 and PRN 22 on 4th of June 2022 (albeit, this is providing data again since 6th of October 2022).

The early data assessment though did show another issues with tracking GLONASS occultations: the instrument occasionally lost the tracking of all GLONASS occultations, and required a manual re-boot to remove this issue. This second issue was also resolved with the on-board s/w update in early June 2021, by re-booting the on-board science processor automatically when no GLONASS data was found.

Validation of the complete EUMETSAT's Non Time Critical (NTC) bending angle products based on observations of GNSS-RO S6A satellite is shown. These NTC bending angles provide higher quality than the ones delivered by NASA/JPL in Near Real Time (NRT), as they make use of improved GPS orbits and clocks data (including GLONASS NTC data is being evaluated). The timeliness of NTC data is determined in the EURD, and is formally within 60 days. The improved GPS/GLONASS orbit and clock data though is delivered at the latest after 18 days, and thus timeliness does not exceed 3 weeks.

In order to have more robust statistics, data from a best-effort reprocessing run was used, that ran all available data from start of instrument operation to end of August 2021, based on processor version 3.4. The first operationally deployed processor was at v3.5, it had several improvements over the 3.4 version, e.g. providing slightly more occultations per day and also allowing to provide products during manoeuvres. Products are otherwise though very similar, thus v3.4 is sufficient to show the high data quality, and to assess compliance with EURD requirements.

From start of instrument switch-on, up to the 31st of October 2022, more than 710k occultations were recorded by the GNSS-RO instrument, about 61% from the GPS, and about 39% from GLONASS. The number of daily occultations improved with the mentioned on-board s/w update, but also with the azimuth angle update in May 2021, it is now generally above the 770 quality controlled profiles per day, fulfilling the EURD requirement. Exceptions are e.g. found during yaw flip manoeuvres (this leads to lower quality data, as the antenna beam forming needs to be re-calibrated), when there are issues with the auxiliary data provided, or with the instrument.

The actual NTC bending angle quality is very high, similar to EPS/GRAS data; actually GLONASS data shows slightly lower random uncertainties. This might be due to several satellites of this constellation not being tracked any longer, and/or due to higher resolution clock data.

Overall high quality was also confirmed by independent assessments at ECMWF and the MetOffice. Assimilating the data into the ECMWF model yielded improved forecasts. These impact trial experiments included in addition the NRT data, confirming that the EUMETSAT NTC data has a larger impact – as expected since the data uses higher quality auxiliary inputs in the processing. Assessments at the MetOffice also showed the higher quality of the NTC products.

There are three EURD requirements that capture the bending angle quality for different altitude regions. Within the validation investigation shown here, we could not fully confirm compliance to these requirements, as the data pool is limited (< 1 year), and all data used for validation also add to the overall uncertainty budget. No evidence was found that points to a possible violation of these requirements. Note that similar issues are also observed in general for RO instruments, e.g. also for the EPS/GRAS and COSMIC-2 assessments.

Overall, the EUMETSAT NTC data is compliant to the EURD requirement, and generally compliant to the EURD number of daily products and bending angle quality requirement. The daily number of products improved with the on-board s/w update, and should increase further once the faulty GLONASS satellites are replace. Users confirmed the high data quality of the EUMETSAT processing.

The following list discusses issues that can be improved with the next processor version, or on the instrument/GNSS side:

- **GLONASS final Orbits/Clocks**: NASA/JPL currently provide GLONASS data as provided by their real-time stream, thus the data quality could be improved by making final orbits available, after about 2 weeks. This is though not a major concern right now, as GLONASS occultation quality is actually slightly better than GPS.
- **GLONASS late Delivery**: The auxiliary GLONASS orbits and clocks data from NASA/JPL were provided late a few times. The v3.4 processor itself was triggered when the GPS data is delivered, and in these cases did not process GLONASS occultations. Although this is a non-compliance in the GLONASS delivery, the RO-NTC processor could act even more robustly (v3.5 now waits 12h) by processing the available GNSS constellations when they arrive and not together, or use the provided backup solutions after a configurable waiting time.
- **Manoeuvre Handling**: Currently, the manoeuvre is not estimated during the processing, instead 2 or more orbit arcs are calculated independently.
- **GLONASS Constellation Status**: Several GLONASS satellites are non-functioning and are blocked from being tracked by the GNSS-RO instrument at the moment. As the Russian authorities plan to launch new satellites, a regular status of the constellation, and possible updates of the satellites blocked, needs to be performed at NASA/JPL.
- **Galileo Occultations**: The GNSS-RO instrument is expected to be capable to track Galileo occultations after an instrument s/w update. It is currently investigated whether such an upgrade can be performed within 2023.