GBOT activities during the Gaia End-of-Observations testing (public version)

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Abstract

In the first quarter of 2025, Gaia will enter the last phase of its operational phase, the End-of-Observations testing phase. One of the tests, foreseen to be conducted during this time, will be a test concerning the Basic Angle Variations, which involves changing the Solar Aspect Angle of Gaia from the nominal $45°$ to $0°$ and several intermediate values. GBOT will exploit this to measure the brightness of Gaia in various passbands to shed light into the issue, why the pre-launch assumptions of the satellite's brightness have been off by such a large margin. Also, with multi-colour photometry, one could derive information on the reflective properties of the aged payload, in comparison with GROND multi-passband data from the commissioning phase of the mission in 2014. Additionally, a public outreach campaign for amateur astronomers is being prepared. This document is an abridged version of **?**, aiming at the public outreach activities

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1 Introduction

The **G**round **B**ased **O**ptical **T**racking programme was set up to ensure that the orbit of Gaia can be reconstructed to the required positional and velocity accuracies of 150 m and 2.5 mm s^{-1}, respectively. Accurate knowledge of the position of Gaia ensures that orbits for solar system bodies can be accurately determined, while accurate knowledge of the velocity ensures that the astrometric performance at the bright end of the survey is not limited by error in the aberration corrections (for more details see **?**).

The above requirements on the orbit reconstruction of Gaia are beyond the scope of the conventional means of satellite tracking by ranging and doppler measurements of position and velocity relative to the active ground-station. Hence DPAC and ESA collaborated in setting up the GBOT programme which consists of a small network of 2m class telescopes spread around the Earth, a data processing centre at Paris Observatory, and the necessary interfaces to the Flight Dynamics team at ESOC. The VST with its OMEGACAM instrument and the Liverpool Telescope are the main telescopes contributing observations to GBOT.

The brightness of Gaia in the sky was rather uncertain before launch and was estimated at 18 ± 3 magnitudes in the optical. We now know that apparent brightness of Gaia is 21.0 ± 0.7, see also Sect. 3 for the long-term evolution. This discrepancy between the expectation and reality resulted in a need to completely reevaluate the GBOT programme and alter it in a way, so that it would still have been viable. This meant the limitation to telescopes of the 2+ m class. As these are far less abundant than smaller telescopes, let alone the combined planned fleet of 1 and 2+ m facilities, the cadence of GBOT observations was larger than anticipated. While the GBOT group still tried to secure one set of observations every 24 hours, the gaps due to weather, technical issues, and competition with other observing programmes, meant that this often did not work, thus additional measures using the data tranfer antennae (ΔDOR, see `https://en.wikipedia.org/wiki/Delta-DOR`) had to be carried out during the mission, the two methods complementing each other.

More details on the GBOT programme and its operations can be provided on request.

With the operational phase of the Gaia mission now coming to a close, the pre-decommissioning End-of-Observations (EoO) testing phase, gives us the unique opportunity to shed light into the matter of the missing brightness. One of the experiments, which will be conducted, aiming at understanding the not anticipated 6-hour oscillation in the Gaia Basic Angle (see , involves the re-positioning of the Gaia space-craft from the nominal Gaia Solar Aspect Angle of $45°$ to $0°$, and then several intermediate values, before returning back to $45°$.

Given the still little understood Gaia brightness issue, i.e. why Gaia has turned out to be approx. 3 mags fainter than the pre-launch estimate, this is an excellent opportunity to shed light into this problem. Additionally, as Gaia's surfaces have aged during the 11 years in space, comparison of the planned observations with existing data from the early phase of the operational mission, taken with the GROND simultaneous camera (see Sect. 3, can yield information about the aging process of spacecraft surfaces and their reflectivity properties. This document deals with the planning of these observations during the EoO testing phase of Gaia in January and February 2025.

1.1 Important Note concerning this document

) The matter discussed in this document is now finalised Therefore this is the final update to this technical note, which will be distributed to all consumers. Please note that there is a project webpage hosted at ESA, with the URL `https://www.cosmos.esa.int/web/gaia/end-of-observations`, which is updated much more frequently that this document and should serve as the first reference. Note that even after Dec. 2024 last minute changes can occur. During the critical phase, i.e. in January and February 2025, i.e. just before and during the test, information will be mainly distributed via the project webpage, `https://www.cosmos.esa.int/web/gaia/end-of-observations`.

2 Synopsis and timeline of the Gaia EOO BAV test

2.1 The BAV-3 – Sun Aspect Angle Variation test

The Basic Angle Sun Aspect Angle Variation test aims at verifying theories on the origin of the 6-hour heliotropic[1] oscillation of the Basic Angle, see **?**. As differential solar radiation is the source of this oscillation, this will vary with the Solar Aspect Angle (SAA), which is the angle between the rotation axis of Gaia and the direction of the Sun, as seen from Gaia. A SAA of $0°$ means that the rotational axis fully aligns with the vector Sun-Gaia and $45°$ (the nominal case) means that the two form an angle of $45°$ between them. This test itself will put Gaia into the two extreme and four intermediate values for the SAA, see Table 1. Gaia will be by far brightest at an SAA of $0°$, when the observed beam will be almost entirely due to specular reflection, while the faintest setting at SAA=$45°$ will be akin to the nominal case.

The test will commence by a slow slew from SAA=$45°$ to $0°$, with a slew speed of $1°$/hour, i.e. lasting about 45 hours. The slews between the different SAA of the test itself will presumably be much faster, i.e. up to $0.11°$/sec which is the maximal allowed slew rate, and will thus be negligible for these observations.

[1]Because of the heliotropic motion of the Earth Gaia system around the Sun, the true period of the 6-hour oscillation of the Basic Angle is not exactly 6 hours, but slightly more, following the heliotropic angle Ω

2.2 The test timeline

2.2.1 The timeline during the planning phase

The official end of Gaia measurements has been set to be at UTC=2025-01-15T06:15:00 (OBMT=16385.61 rev). The EoO tests, including the one of interest in our context, have been finalised in Deccember 2024. Note that this still means that small last minute times changes related to the can happen. This also applies to all Gaia-related times given in Sect. 2.2 and Table 1. Therefore, we recommend to refer to the EoO webpage, `https://www.cosmos.esa.int/web/gaia/end-of-observations`, which is updated far more often than this document. The detailed slew timeline will be distributed to all relevant parties, once available.

2.2.2 The timeline of the actual test

The tentative timeline of the BAV-SAA test are given in Table 1, with the start and end times of every phase indicated by their UTC and also the Gaia OBMT. Note that the slew times between the different SAA steps are not listed, as these are too short. With a possible maximal slew speed of $0.11°$/sec (see Sect. 2.1 for more details) :these will be between 45 and 136 secs. After the actual test, the spacecraft will be slewed to $28.5°$ and then back to $45°$, in preparation for the disposal of Gaia. Currently this is beyond the scope of these add-on observations, but may be added at a later stage.

3 Existing Measurements

Apart from the r' band magnitudes, obtained with the astrometric measurements on a regular basis, i.e those shown in Fig. 2, we were able to secure 7 multi-passband observations with the GROND instrument during the commissioning phase in early 2014, shown in Fig. 3.

4 Observing strategy

4.1 Solar, Earth and Reflection Aspect Angle

Before starting off describing the particulars of the observing strategy during the BAV-3 EOO (SAA slewing) test, we need to address an important issue, namely that concerning the two different aspect angles involved. The Solar Aspect Angle (SAA), i.e. the angle between the rotational axis of Gaia and the line Sun - Gaia has been mentioned a couple of times throughout this document.

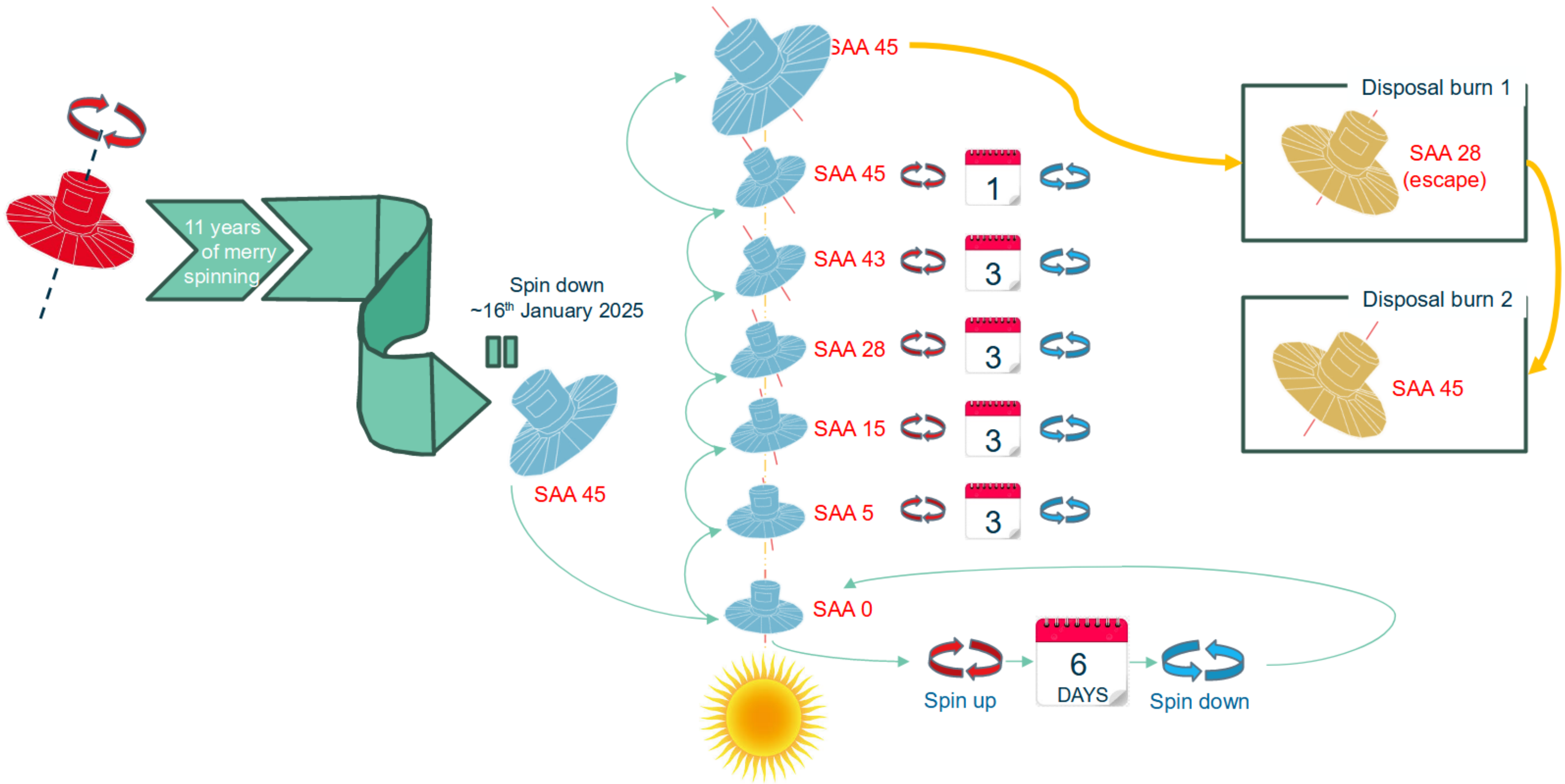

Figure 1: The timeline of the End of Observations phase of Gaia, indicating the time used for each step. *Credits: ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgements: Gaia Flight Operations Team.*

Table 1: The tentative times of the different steps of the BAV-SAA variation test. The most relevant items are highlighted in boldface. The slews between the different SAA steps of up to $0.11°$/sec (see Sect. 2.1 for clarification) are not shown, as their duration is short, and thus irrelevant for the GBOT observations. More items may be added. Note that these times may change, even shortly before the experiment. We recommend to use the online table, which can be found under `https://www.cosmos.esa.int/web/gaia/observe-gaia`, since this resource is updated much more often, and the values shown here have been taken from the online table, so that should entries differ, refer to that version. The times shown here are from February 06, 2025

UTC_{start}	UTC_{end}	OBMT$_{\mathrm{start}}$ [rev]	OBMT$_{\mathrm{end}}$ [rev]	R-mag	Action
2025-01-13T22:26		**16380.37**			**Full Moon**
	2025-01-15T06:15		16385.61	~ 21	SAA=$45°$, NSL, nominal operations
2025-01-16T00:00:00				~ 21	Station keeping manouevre #62
2025-01-20T12:36	**2025-01-22T11:23**	**16406.73**	**16414.53**	getting brighter	**Slew SAA=**$45° \rightarrow 0°$
2025-01-22T11:23	**2025-02-16T09:12**	**16414.53**	**16490.09**	$\sim 14 - 15$	**SAA=**$0°$ sun steering
2025-02-10T09:16	**2025-02-16T09:12**	**16490.17**	**16514.16**	$\sim 14 - 15$	**SAA=**$0°$
2025-02-12T08:02		**16497.97**			**Full Moon**
2025-02-16T15:07	**2025-02-19T15:05**	**16515.15**	**16527.14**	~ 15	**SAA=**$5°$
2025-02-19T21:10	**2025-02-22T21:08**	**16528.19**	**16540.15**	? (between 15 and 21)	**SAA=**$15°$
2025-02-23T03:13	**2025-02-26T03:11**	**16541.17**	**16553.16**	? (between 15 and 21)	**SAA=**$28°$
2025-02-26T09:16	**2025-03-01T09:14**	**16554.17**	**16566.17**	? (between 15 and 21)	**SAA=**$43°$
2025-03-01T15:19	2025-03-02T15:15	16567.18	16571.17	~ 21	SAA=$45°$
2025-03-02T16:30	**2025-03-04T15:27**	**16571.38**	**16579.20**	getting brighter	**Slew SAA=**$45° \rightarrow 0°$
2025-03-04T15:27	**2025-03-04T16:30**	**16579.20**	**16579.38**	~ 15	**SAA=**$0°$
2025-03-04T16:30	2025-03-04T16:38	16579.38	16579.40	$\sim 15 \rightarrow\sim 21$	quick slew SAA=$0° \rightarrow 45°$
2025-03-14T06:54		**16617.78**			**Full Moon, total lunar eclipse**

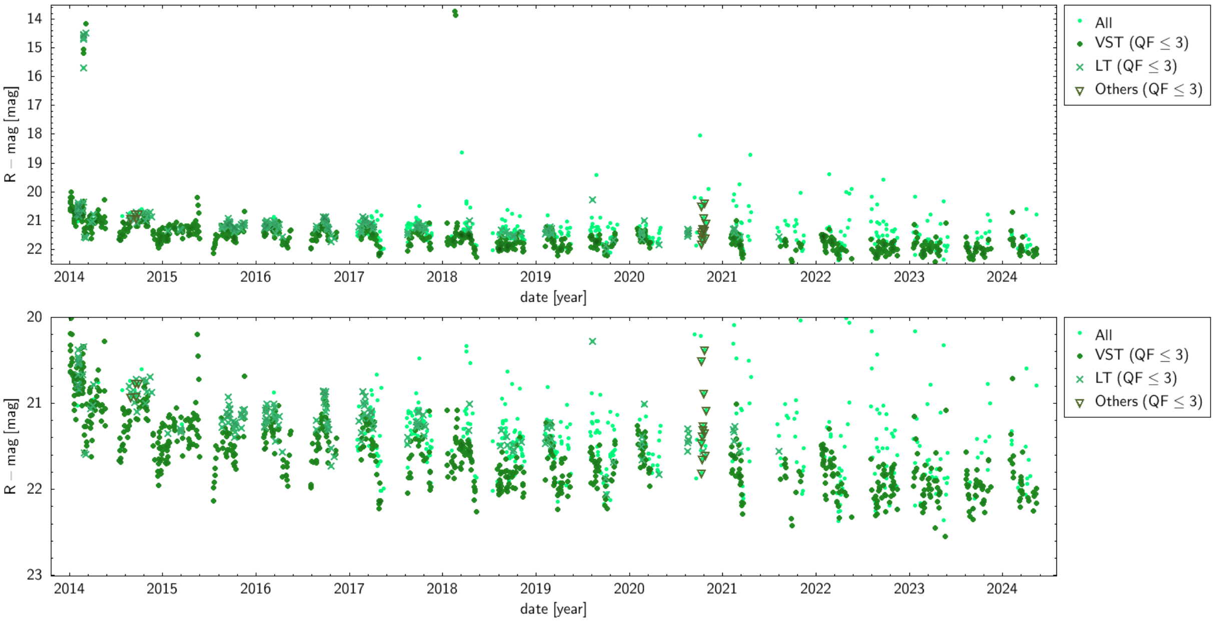

Figure 2: The evolution of Gaia's magnitude during the whole operational phase of the Gaia mission. The upper panel shows all observations, including the bright values in the commissioning phase and a safe mode in 2018, the lower panel focusses on the normal magnitude range

Another, equally important angle is the Earth Aspect Angle (EAA), which is the angle between Gaia's rotational axis and the vector Earth - Gaia. Would Gaia permanently stay at the L2 position, these two angles would be ideally exactly the same, as the object tripel Sun - Earth - Gaia would be on the same line. However, Gaia is on a Lissajous type orbit oscillating around the L2, bringing it up to $15°$ from the L2 position in the sky. As the exact location of the L2 is in the permanent Earth shadow, Gaia is never found there, but always some angle above or below the L2 or preceding or following the L2 (taking the ecliptic as the plane of reference). For an EAA of $0°$ the reflective surface of the Gaia Deployed Shield Assembly (DSA) would exactly face Earth. This might have as a consequence that Gaia is not at its brightest at SAA=$0°$, but some other value, such as SAA=$5°$, or in extreme cases, even $15°$.

A third angle, which we call the Reflection Aspect Angle (RAA), is related to the previous two, and is defined as the angle between the line Earth – Gaia and the specular reflection vector of the Sunlight falling on the Gaia surface, i.e. the normal to the visible side of Gaia's DSA. From a strictly geometric point of view, if this vector points directly towards Earth, Gaia will be at its brightest. However, given the degradation of the surfaces of the satellite by 11 years worth of wear and tear due to the harsh environment, it is unclear, how reflective the once pristine Kapton layered surface is.

We have calculated the RAA for the times of the SAA variation test. The results are shown in the Fig. 4 Unfortunately the geometric situation is less than optimal, so minimum value of the

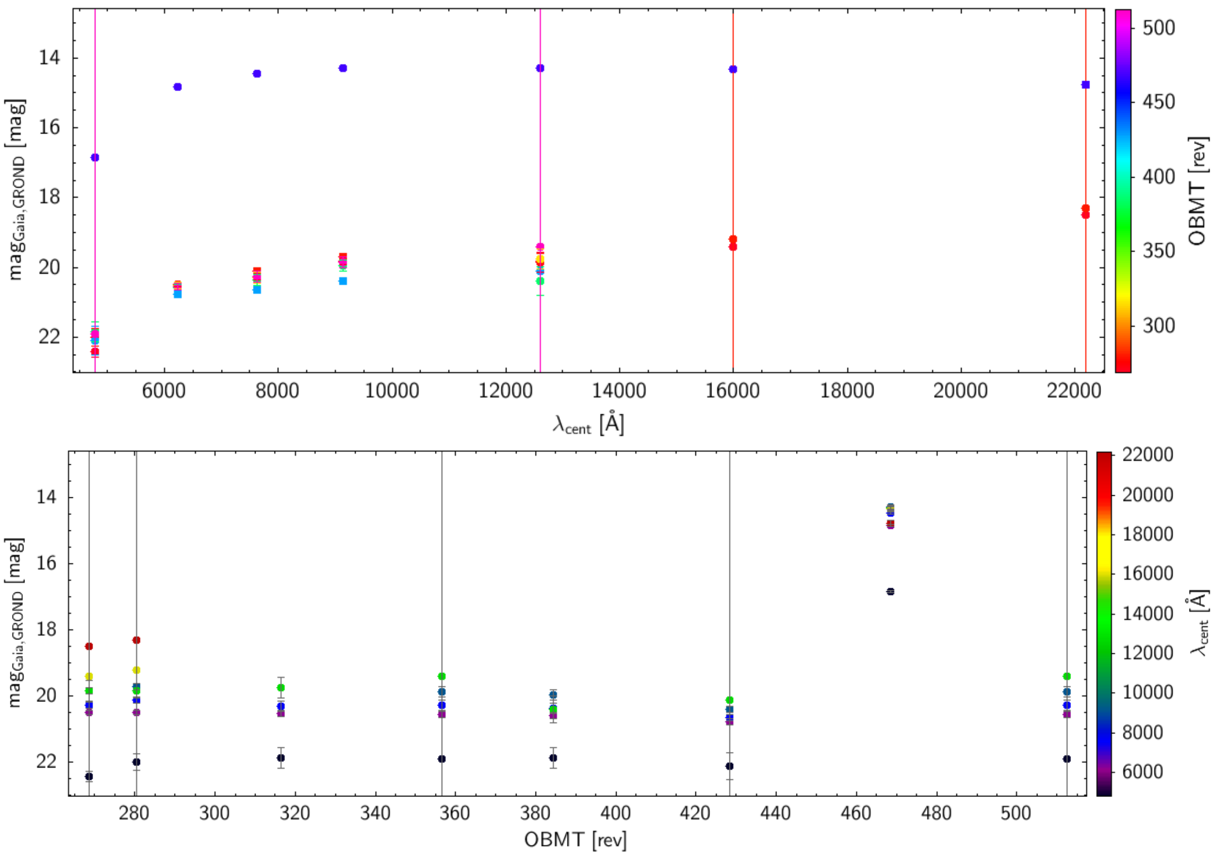

Figure 3: The GROND photometry taken during the Gaia commissioning phase in 2014. The upper panel shows the magnitudes vs. the central wavelengths of the passband with the date in OBMT[rev] colour coded, while the lower panel shows magnitudes vs. time (in OBMT[rev]) with the central wavelengths of the passbands colour coded

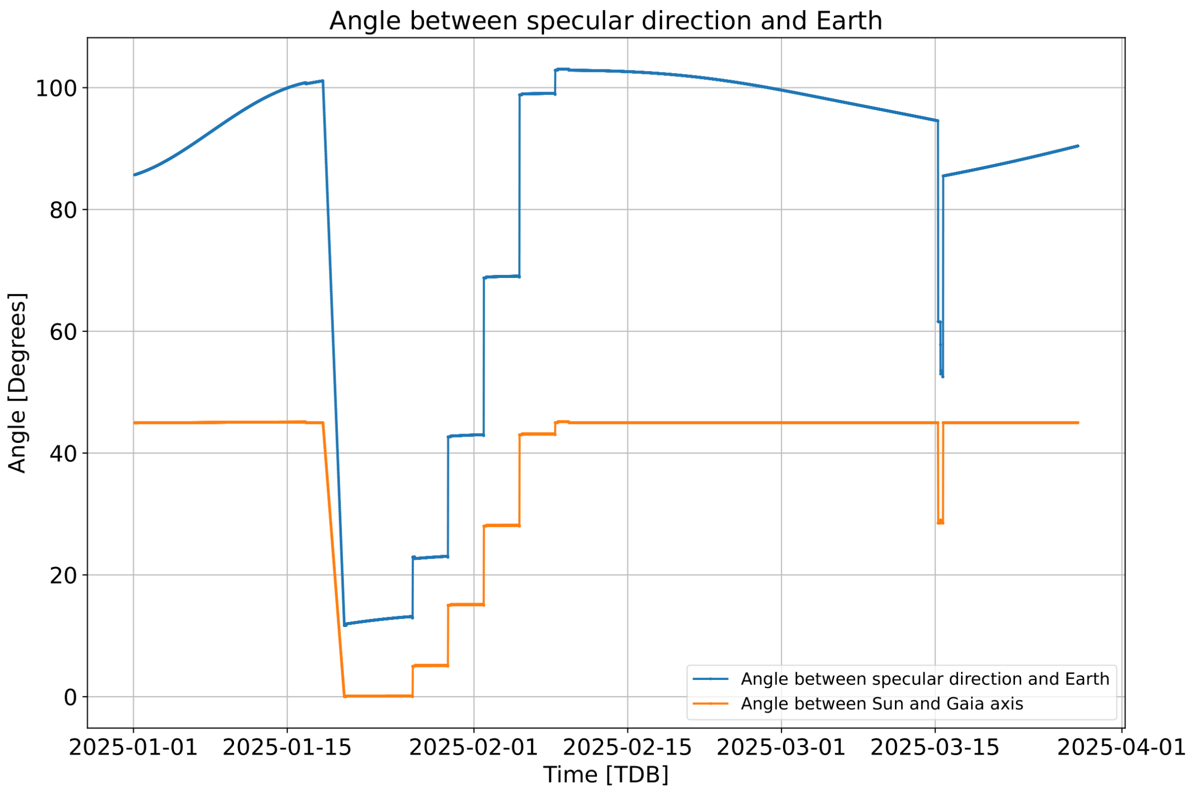

Figure 4: The Solar Aspect Angles (SAA, blue) and Reflective Aspect Angles (EAA, orange) during the EOO test phase in January and February 2025 (courtesy, T. Nogueira and A. Sagrista-Selles)

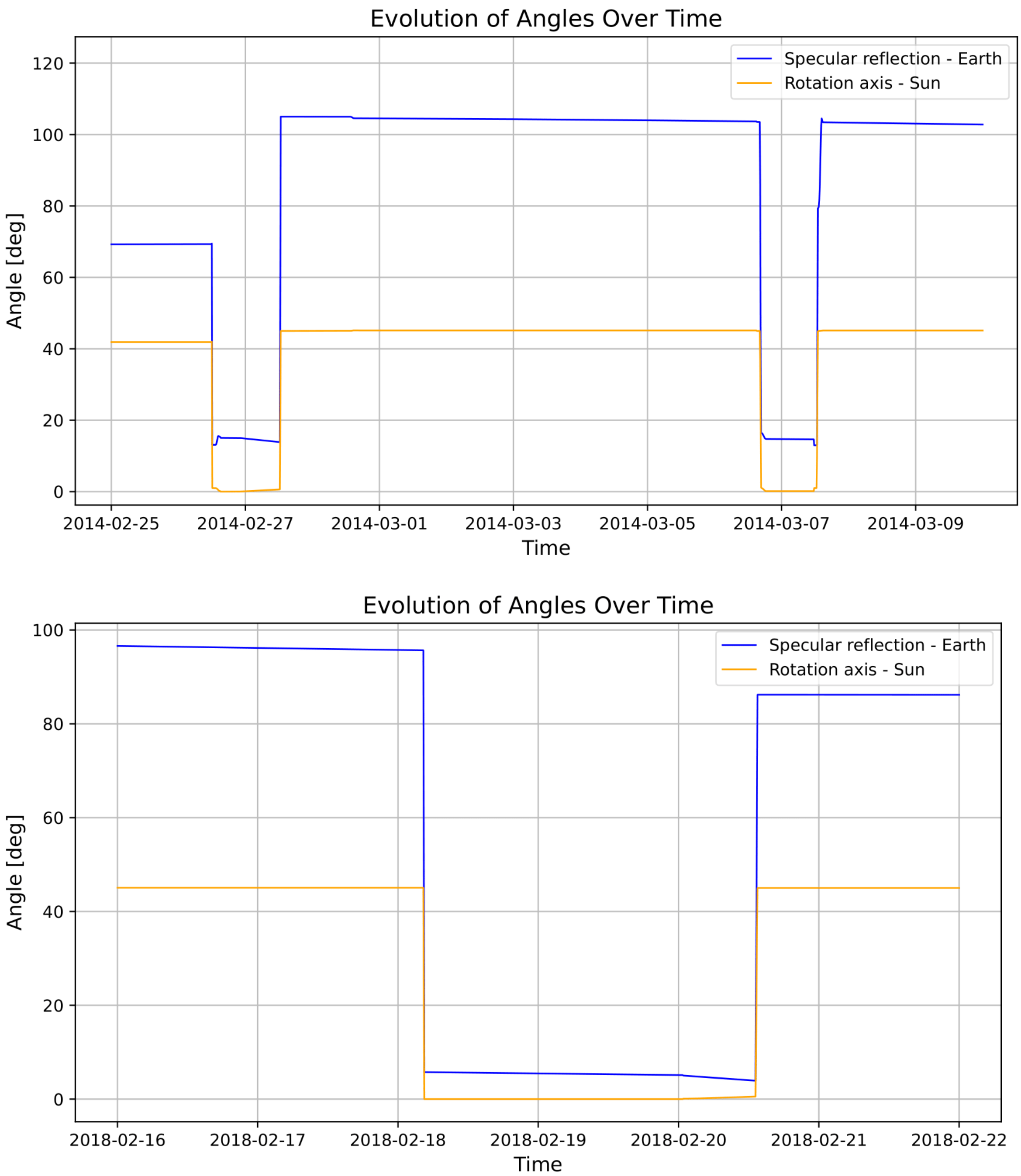

Figure 5: The Solar Aspect Angles (SAA, blue) and Reflective Aspect Angles (EAA, orange) during the historic SAA=00° phases in February and March 2014, and the safe mode event in February 2018 (courtesy, T. Nogueira and A. Sagrista-Selles)

RAA will be about 13 degrees at the beginning of the time, Gaia is at SAA=0 degrees, and at about 22 degrees at the SAA=5 degrees phase. Therefore, the maximum brightness of Gaia may be fainter than the expected 14-15 mag. In order to assess the possible range of the expected brightness, we have also calculated the RAA for the previous SAA=0 degrees observations in 2014 and 2018, see Fig. 5. While the 2018 data was taken under a much smaller RAA (i.e. the specular reflection beam being much closer to Earth than foreseen for the EOO phase in early 2025), both 2014 instances were at similar, if not slightly worse (larger) RAA. This could give some estimation of what to expect. It is to be noted that this does not allow us to make predictions in absolute terms, i.e. what magnitude Gaia will be. The main reason for this is the aforementioned condition of the reflective surface — after all the last SAA=0 degrees data we have, date from 2018! Details of the strategy of the observations officially planned by GBOT, and the instruments involved, are described in detail in the full version of this document, i.e. **?**, which is not public, and are omitted here, as they are not of relevance for the targeted audience, and may contain information, which is not aimed at the general public.

5 Outreach opportunities

Over the last 11 years, Gaia has been one of the most iconic and successful astronomic space missions, mankind has ever attempted. In fact, in terms of the number of publications, it is *the* most successful mission. Gaia is also well regarded both in the community of professional astronomers, as well as the amateur astronomers world-wide. Unfortunately, given the faintness during nominal operations, it was/is beyond the reach of the larger crowd of satellite observers and even more the public as a whole. However, as this will temporarily change during the end of observations tests, described in the document, the idea is to draw the attention of the general public, especially amateur astronomers to this fact. Therefore it was decided to promote a public observing campaign for amateur astonomers (mainly, but also the general public) to observe Gaia with their instruments, this way giving enthusiasts an opprtunity to say ”good-bye” to Gaia, the space-craft, which is the instrument behind this amazing and revolutionary database. Given our experience from the launch time, when a similar campaign was implemented, there is likely to be a significant response to such a call.

With this past experience in mind, it is best to plan this in a bit more detailed way. At current, we are collecting resources, contacting associations and popular science magazines. The ”Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e.V. (BAV)” (`https://www.bav-astro.eu/` has already been contacted, and a first more detailed call for observations, have been sent in on August 2, 2024. The ”American Association of Variable Star Observers (AAVSO)” (`https://www.aavso.org/`[2] have been contacted. Note that these two organisations have the resources, and expertise to actually contribute to the actual GBOT EOO observations during the brighter phases in a scientific way, this way enhancing the observations officially planned by the GBOT group.

[2]Response pending

With the redaction of the German amateur astronomy magazine "Sterne und Weltraum (SUW)" (https://www.spektrum.de/lp/suw_magazin) being based in Heidelberg, contacts there have already been made, and calls for observations has been published in the January 2025 edition of this magazine. We have also contacted "Sky&Telescope", the main US-based popular astronomy magazine, i.e. the one with the largest reach, and a similar article has been placed in the January 2025 issue[3].

With some prime intended consumers of this document (**?** for the partner observatories and **?** for the public) being based in Italy, the UK, France, and Chile, these are encouraged to contact their pendants to either the magazines or related associations and organisations. Some examples would be "Astronomy Now" (https://astronomynow.com/), "Ciel et Espace" (https://www.cieletespace.fr/), and the Italian and Chilean analogues. Such calls for amateur observations can be made with the use of material from this document. Two cautionary notes should be included in any such effort:

1. All timeplans are, as documented in the previous sections in this document, are very dynamic and can be subject to change, even after things having been officially finalised, towards the end of 2024. This needs to be made clear, and also links to current information resources need to be provided, for easy access to updates in the time tables and everything else.
2. As we do not have the man-power to reduce raw data from multiple sources, all data sent in needs to be fully reduced. As most observers outside of BAV and AAVSO will be "pretty pictures" rather than scientific data, a generally pleasing image format might be sufficient.

5.1 Repositories

All data obtained by amateurs or non-partner institutions (the data from the partner observatories, i.e. the Liverpool Telescope and the VST, will be treated the usual way, i.e. GBOT automatically downloads those) can be deposited in three repositories, depending on the type of the data:

1. All image (and short video clip) files, i.e. jpeg, png, tiff, mpeg, gif, ..., can be sent directly to gaia-helpdesk@esa.int. A selection of these files will be shown on Gaia Cosmos. When sharing your files, please mention a credit line to go with the image, and if possible, the date, time and location of observation. Please do read point 3 in case you wish to send very large files.

[3] Note that the S&T editions are released about two months prior to the cover date, i.e. the January 2025 issue has been released in November 2024.

2. All FITS data can be put on this VO-type repository, which can be reached under https://dc.g-vo.org/citigbot/q/upload/form. Note that this portal ONLY accepts FITS files. Please adhere to the instructions given on the entry page. Please be reminded to only submit fully reduced data.

3. All other files, i.e. ASCII, CSV, VO-table, etc. can be put on a cloud, based at the University of Heidelberg, Germany. This service is not open access, but will be granted upon request, to prevent misuse. For upload access, please contact maltmann@ari.uni-heidelberg.de, and insert GBOT-EOO HEIBOX access into the mail header. Image/video files, which are too large to be accepted by the gaia-helpdesk email account can also be put there, with the same mode of access applying.

5.2 Instructions for Observers

5.2.1 When to observe?

The different SAA-values are listed in the table. Depending on your equipment, the lower SAA levels are going to be the brighter ones. As the step-phase of the test starts at SAA=0° and works its way up to 45°, you will get an estimate from your data, whether it is still feasible to continue observing at the next SAA level.

Note that prior to the step phase, there is a 48 hour constant slew phase, during which Gaia is slewed from the nominal SAA=45° to the SAA of 0°. Especially for those with large aperture equipment, it may well be worthwhile to observe this phase too (you might not have any luck at the beginning of this slew phase, but at some time, detections should kick in), as this will give us access to intermediate values (the SAA changes during the step phase slews, are to short to be of any use). Actually, this phase could potentially provide the most information, since this is a slow but continuous slew, covering all SAA between 45 and 0°, while the later step phase only allows observations at those fixed values as specified. Therefore, we strongly encourage observers to observe during this timespan of 48 hours too.

5.2.2 Filters, passbands, etc.

The operational GBOT observations were carried out in a red passband, as this was the best compromise between S/N (object brightness and sky background), differential colour refraction. During the commissioning phase in 2014, i/I passbands were also tested, but the achievable S/N was inferior, so that red light was chosen.

That said, for this EOO compaign, observations in all passbands are welcome. In fact, during the early phase of Gaia, we performed some observations with the GROND camera, which is a simultaneous Optical/NIR photometer, mounted onto the 2.2 m MPIA telescope at La Silla observatory, see Fig. 3. These data have the SDSS g'r'i'z'+ NIR JHK passbands (see image). While it would be very useful to have observations in bluer passbands, maybe even bluer than g' (which is similar to the Johnson B in central wavelength), the magnitude drop-off from r' to g' is approximately 2 mag, at least in the pristine Gaia of 2014 (see Fig. 3) — this may of course have changed since then. Therefore, we expect the majority of observations to be in the spectral region encompassing the R/r', i' and possibly z' bands. White-light (i.e. without any filter inserted) observations are also welcome. Please specify what filter has been used, when you upload data.

5.2.3 Observing times

This is quite difficult for us to assess, as we do not know, what equipment you have. For guidance, consult the magnitude estimates given in Tab. 1, or its counterpart on the ESA webpages. . Normally, Gaia has a magnitude of $\sim 21-21.5$ mag in a red (Cousins-R, or SDSS r') passband, and is generally much fainter in bluer parts of the spectrum.

Concerning the amount of images taken, this is completely up to you, for us it is of course, the more the better.

5.2.4 Some notes about the ephemerides

1. The predicted magnitudes given in the ephemeris files are those of the nominal settings, i.e. with SAA=45 degrees. Therefore they will be around 21 mag, even when SAA=0 degrees. It is not possible or even worthwhile to adapt the magnitudes to reflect the SAA changes during the test. First, it would mean a lot of effort, and second the timetable of the different phases may change on short notice. Therefore the magnitudes given in the ephemerides should best be ignored.
2. Shortly after the final science data have been obtained, a large station keeping manoeuvre (SKM) is scheduled. This means the trajectory of the space-craft is altered, and with a total change of the velocity of 2.7 m/s, this translates to about 32"/day (assuming all of the change is in transversal direction). However, the most recent set of ephemerides have already taken this into account, so the ephemeris taken from the public server should be reasonably accurate.

5.3 Resources

This section contains a list of resources connected to this outreach activity. As more and more sites will be set up, this section is likely to expand.

1. The GBOT public ephemeris server. This server can give out the ephemerides of Gaia for every city worldwide, with a population larger than 100,000 people. For

most parts on Earth, this will be sufficient to locate Gaia in the sky. This service can be found under `http://gaiainthesky.obspm.fr/index_gaia.php?page=FOV&sous_menu=public`.

2. the main campaign webpages are hosted by ESA, and can be accessed following the link `https://www.cosmos.esa.int/web/gaia/observe-gaia` for the public EOO phase observations. For the Gaia EOO phase as a whole, see `https://www.cosmos.esa.int/web/gaia/end-of-observations`
3. The Gaia-EOO ZAH/ARI webpages, URL: `https://zah.uni-heidelberg.de/institutes/ari/gaia-end-of-life`, are now obsolete. You will be redirected to the correspnding ESA pages, see previous item
4. As time passes, more resources may be implemented, also from third parties, such as the aforementioned organisations and magazines.

References

Acronyms

The following table has been generated from the on-line Gaia acronym list:

Acronym	Description
AAVSO	American Association of Variable Star Observers (AAVSO)
BAV	Basic-Angle Variation
BAV	Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne
DPAC	Data Processing and Analysis Consortium
DSA	Deployable Sunshield Assembly
EAA	Earth Aspect Angle
EOL	End of Life (also denoted EoL)
ESA	European Space Agency
ESO	European Southern Observatory
ESOC	European Space Operations Centre (ESA)
EoL	End of Life (also denoted EOL)
GBOT	Ground-Based Optical Tracking
GROND	Gamma-Ray-burst Optical/Near-infrared Detector (ESO)
INAF	Instituto Nazionale di Astrofisica (Italy)
LT	Liverpool Telescope
MPIA	Max Planck Institute für Astronomy (Heidelberg)
NIR	Near InfraRed
NSL	Nominal Scanning Law
OBMT	On-Board Mission Timeline
SAA	Sun Aspect Angle
SDSS	Sloan Digital Sky Survey
SKM	Station Keeping Manoeuvre
SuW	Sterne und Weltraum (astronomy magazine)
S&T	Sky & Telescope (astronomy magazine)
TBW	To Be Written
UTC	Coordinated Universal Time
VLT	Very Large Telescope (ESO)
VST	VLT Survey Telescope (ESO)