Gaia Mission Planning Evolution - Improved efficiency for "the new normal"

Julia Fortuño Benavent[a]*, Peter Collins[b], Jonas Marie[c]

[a] *Gaia Spacecraft Operations Engineer, Telespazio Germany GmbH c/o ESA-ESOC, Europaplatz 5, 64293 Darmstadt, Germany, julia.fortuno.benavent@ext.esa.int*
[b] *Head of Gaia & OPSSAT Mission Operations Unit, European Space Operations Centre, Robert Bosch Str 5, 64293 Darmstadt, Germany, peter.collins@esa.int*
[c] *Ariel Spacecraft Operations Manager, European Space Operations Centre, Robert Bosch Str 5, 64293 Darmstadt, Germany, jonas.marie@esa.int*

* Corresponding Author

Abstract

Gaia, which was successfully launched on 19 December 2013 and transferred to a Lissajous orbit around the second Sun-Earth system Lagrange point, is an ESA astronomy mission to investigate the structure and evolution of the galaxy by measuring the positions of one billion stars to unprecedented accuracy.

The instrument data production rate varies significantly depending on the number of stars in the part of sky being scanned, and with the prescribed spin and precession rates a scan of the densely populated galactic plane occurs for approximately every 20 in 100 days. The estimated average data volume downlinked by Gaia is 200 Gbits of compressed data per day (ca. 8 downlink hours/day), increasing up to 700 Gbits/day for high density areas (ca. 24 downlink hours/day).

The ground station time required for the downlink of this data has been heavily optimised through long-term mission planning, involving modelling of the onboard data acquisition rates (via stellar density and telescope pointing) and link budget. However, in case ground station scheduling changes due to higher priority requests by other missions (e.g. launches or critical activities replanning) result in a decrease of available downlink time for Gaia, this may impact the timeliness of science data delivery or in the worst-case lead to deletions of science data if the on-board mass memory storage saturates. In recent years Gaia has had to face several of these ground station rescheduling activities due to an ever-increasing demand for ESA's ground station network from its own missions and external institutional and commercial operators. Using classical approaches to manage such cases requires considerable team effort on a case-by-case basis to assess the impact on science data downlink and to mitigate it by securing alternative ground station tracking time.

This paper describes a new approach and associated application that was developed by the Gaia Flight Control Team to support such rescheduling activities by leveraging automation and thereby improving efficiency of the overall process. The tool is first used to analyse the adequacy of the ground station scheduling with respect to Gaia science downlink requirements. It then enables a quick and automatic assessment of the impact in case of missing downlink time and a search for free visibility slots in the ESA's deep-space network schedule to mitigate it through additional bookings. The tool also allows for the generation of output request files that can be immediately ingested and processed by ESA's global ground station scheduling system.

The new application has not only demonstrated a significant reduction of team effort and time spent in case of re-scheduling needs but has also further improved the estimate for on-board mass memory fill level over time. This helped closing the loop with the long-term planning process and optimising the time requested by the mission for ground station usage, which will continue to be a driver for future mission planning efforts in order to most efficiently share ESA's ground station network between all stakeholders.

Keywords: mission planning, scheduling, ground station, optimisation, automation

Acronyms/Abbreviations

API	=	Application Programming Interface
BOT	=	Booking Optimisation Tool
CLI	=	Command Line Interface
DPAC	=	Data Processing and Analysis Consortium
DSN	=	Deep Space Network
ECSS	=	European Cooperation for Space Standardization
EIRP	=	Equivalent Isotropically Radiated Power
EMS	=	ESTRACK Management System
EPS	=	ESTRACK Planning System
Es/No	=	Energy Per Symbol To Noise Power Spectral Density
ESA	=	European Space Agency
ESOC	=	European Space Operations Center
ESTEC	=	European Space Research and Technology Centre
ESTRACK	=	European Space tracking network
FCT	=	Flight Control Team
FDEF	=	Flight Dynamics Event File
FDR	=	Flight Dynamics Operations Request
GNU	=	GNU's not Unix
GPS	=	Galactic Plan Scan
GS	=	Ground Station
G/T	=	Gain to Noise Temperature
GUI	=	Grafical User Interface
L2	=	Second Earth Lagrangian Point
LTP	=	Long Term Planning
MPS	=	Mission Planning System
MTL	=	Mission Timeline
MTP	=	Medium Term Planning
OSSUPD	=	Operational Service Session Update
OWLT	=	One Way Light Time
PAA	=	Phased Array Antenna
PDHU	=	Payload Data Handling Unit
PNG	=	Portable Network Graphics
POR	=	Payload Operations Request
PUS	=	Packet Utilisation Standard
REST	=	Representational State Transfer
SOC	=	Science Operations Center
SSCH	=	Science Schedule
STP	=	Short Term Planning
TOR	=	Template Operations Request
XML	=	Extensible Markup Language

1. Introduction

The Gaia mission was launched on the 19 of December 2013 on a Soyuz-Fregat ST-B from Kourou in French Guiana and was operated by the European Space Operations Centre (ESOC), in Darmstadt, Germany. Gaia is an ESA cornerstone mission, which relies on the proven principles of ESA's Hipparcos mission to solve one of the most difficult, yet deeply fundamental challenges in modern astronomy: to create an extraordinarily precise three-dimensional map of about one billion stars aiming at star magnitudes up to 20 throughout our Galaxy and beyond. After 11 years in orbit, Gaia spacecraft operations came to an end on the 27th of March 2025 after depletion of the cold gas needed to maintain Gaia’s high precision pointing and spinning. The Gaia mission, however, will continue and culminate in two major data releases that are in preparation and currently scheduled for 2026 and 2030.

The spacecraft was designed with a high level of onboard autonomy, but the nature of the mission dictated that a relatively large amount of ground station contact was necessary to be able to downlink the data that Gaia generated. From its Lissajous orbit around the second Lagrange point (L2), the spacecraft was continuously observing during the 11 years of science mission, using Solid State Mass Memory to store data onboard whilst out of contact with the ground.

The instrument data production rate varied significantly depending on the number of stars in the part of sky being scanned. This was particularly relevant during periods when the spacecraft was scanning along the galactic plane where stellar densities are very high. In these periods maximum ground station coverage was required.

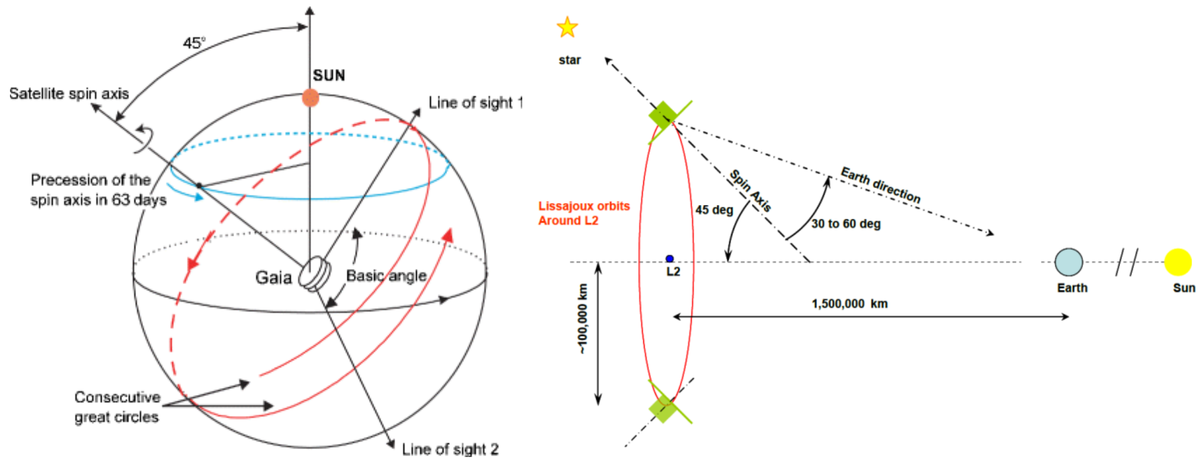

Figure 1: Gaia attitude and orbit profiles

Gaia was in daily contact with ESOC via ESA's 35 metre Deep Space ground station network in Cebreros (Spain), New Norcia (Australia) and Malargüe (Argentina). Normally only one ground station was required per day for command and control of the spacecraft and data downlink. With the prescribed spin and precession rates a scan of the densely populated galactic plane occurred for approximately every 20 in 100 days. During this time increased ground station coverage using a combination of the ESA's Deep Space Antennas was required to return the majority of the scientific data. Even with 3 stations some data loss still occurred during peak data production periods. This was taken into account in the mission design. The estimated average data volume downlinked by Gaia was 200 Gbits of compressed data per day (ca. 8 downlink hours/day), increasing up to 700 Gbits/day for high density areas (ca. 24 downlink hours/day).

2. Gaia Mission Planning

This section gives a description on how the mission planning process was implemented for Gaia [1].

2.1. Background

The design and operations concept for the Gaia mission has as primary aims stability of the spacecraft in all aspects, dimensional, vibrational and thermal (and therefore power consumption). This is a necessity for the measurement stability of the optics and focal plane. Nominal operation of the mission entails a continuous execution of a smooth scan law steered by cold gas thrusters with absolute minimal switching of onboard loads and a constant solar aspect angle.

Data acquisition rate is highly variable driven by the portions of the sky that were traversed at any time by the telescope fields of view and is as such predictable based on the pre-knowledge of the scan law, which was defined and fixed (for most of the mission duration) soon after launch. It should also be noted that during galactic plane scans the data acquisition rate is so high that data could be deleted on board even with continuous tracking (i.e. even with the maximum possible 24hrs/day of station time on the ESA 35m deep space network data would still be lost). This coverage profile represents 33% of the capacity of the network and planning this together with other missions which share the same visibility could often be problematic.

The spacecraft has a classical onboard time release Mission Timeline (serviced by ECSS PUS service 11 commands) of length 2400 commands and the mission operational guidelines requires that its operational maintenance allows planned operations to continue in the case of at least one missed uplink pass.

These led to two of the design drivers for the mission planning system:

1) That there is no need for a complex simulation of the spacecraft systems; during nominal operation there are no changing conditions in the spacecraft's environment, attitude or resource usage that need to be modeled and constraint checked. Regardless of this the system should still be capable of ensuring that commanding constraints are enforced.

2) That accurate and efficient booking of the station tracking periods is performed. This has to be performed long enough in advance such that it can be planned alongside the other European Space tracking network (ESTRACK) users, efficiently to allow those other users as much of available time as possible and accurately to ensure that Gaia had sufficient time to download its onboard stores each day.

2.2. Implementation

The Gaia MPS system has as its primary aim the transformation of planning inputs from the Gaia planning partners into booking, scheduling and commanding products for the ESOC systems used in the management of the Gaia Mission.

The end results of the mission planning processes are the booking of ESTRACK ground stations in accordance with the expected science downlink needs of the mission and the generation of commanding products for the automation systems and the spacecraft itself. This was performed in 2 stages, long term planning and short term planning, which are described below.

2.2.1. Long Term Planning

Long term planning is the process of generating the request to the ESOC EPS (ESTRACK Planning System) for tracking time on the 35m stations. This is performed biyearly roughly six months ahead of the first tracking period under considerations and consists of daily requests for a calculated number of tracking hours. This request is then processed by the EPS using a predefined mission agreement (minimum pass length, minimum elevation, maximum period between passes) and exclusion criteria (e.g. no tracking during a lunar occultation of the spacecraft) and alongside requests for other ESTRACK users using a priority scheme.

The LTP process uses the following inputs:

- FDEF (Flight Dynamics Event File): An XML formatted parameterized list of significant orbital and visibility events. Of interest to the LTP process are the visibility masks for the horizon, 5˚ and 10˚ elevations. These contain as parameters the calculated onboard elevation of the Earth as seen by the spacecraft antenna (PAA), the spacecraft range and the spacecraft's geocentric Right Ascension and Declination.
- Science Schedule: This is a list generated by the Gaia Science Operations Center (SOC) that gives predicted data rates (with 12-hour resolution) for onboard acquisition and storage based on the known predicted fields of view of the telescopes and a sky model. The estimation algorithm was refined in the early mission phase using the measured in-flight data volumes as a calibration reference.
- Link budget parameters: These include the Gain to Noise Temperatures (G/Ts) of the individual stations, a predicted Equivalent Isotropically Radiated Power (EIRP) for the onboard PAA against elevation angle and the calculated limiting Energy Per Symbol To Noise Power Spectral Density (Es/No) levels[1] for each of the available telemetry encoding schemes.

The tools for generating the long term planning requests were written using GNU Octave[2] and comprise a set of command line interface (CLI) commands for importing and maintaining the relevant inputs and performing the planning itself.

The output of this process is a data structure that in addition to including the required booking request for each day includes model visualization data (total acquisition, downlink, storage volume, bitrate in use etc.) allowing report generation. Further CLI commands are used to generate the XML formatted booking requests from the output data structure.

A modified version of the booking calculation script is used once the booking process has completed and Gaia has received its initial allocation. The same calculation is performed but this time constraining the available hours of downlink to those booked. For this run it is the visualization data generated that is of the most interest allowing the comparison of the ideal booking against that allocated and is used for evaluating where to managerially deal with any shortfalls. The diagnostic information plotted being, in turn, daily tracking hours, Payload Data Handling Unit (PDHU) usage (storage of data on board, capped to 103GBytes), and daily onboard deletion[3] [Figure 2]. These plots aid the managerial team in determining where effort (primarily in negotiation) is best spent in resolving booking issues.

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[1] For the Gaia mission the limiting Es/No is set to 3dB above that at which a frame loss rate of 1 in 10^5 would be experienced.

[2] An open source MatLab clone available from https://www.gnu.org/software/octave/.

[3] Note that deletion can occur in even the ideal (requested) case during the Galactic Plan Scan periods.

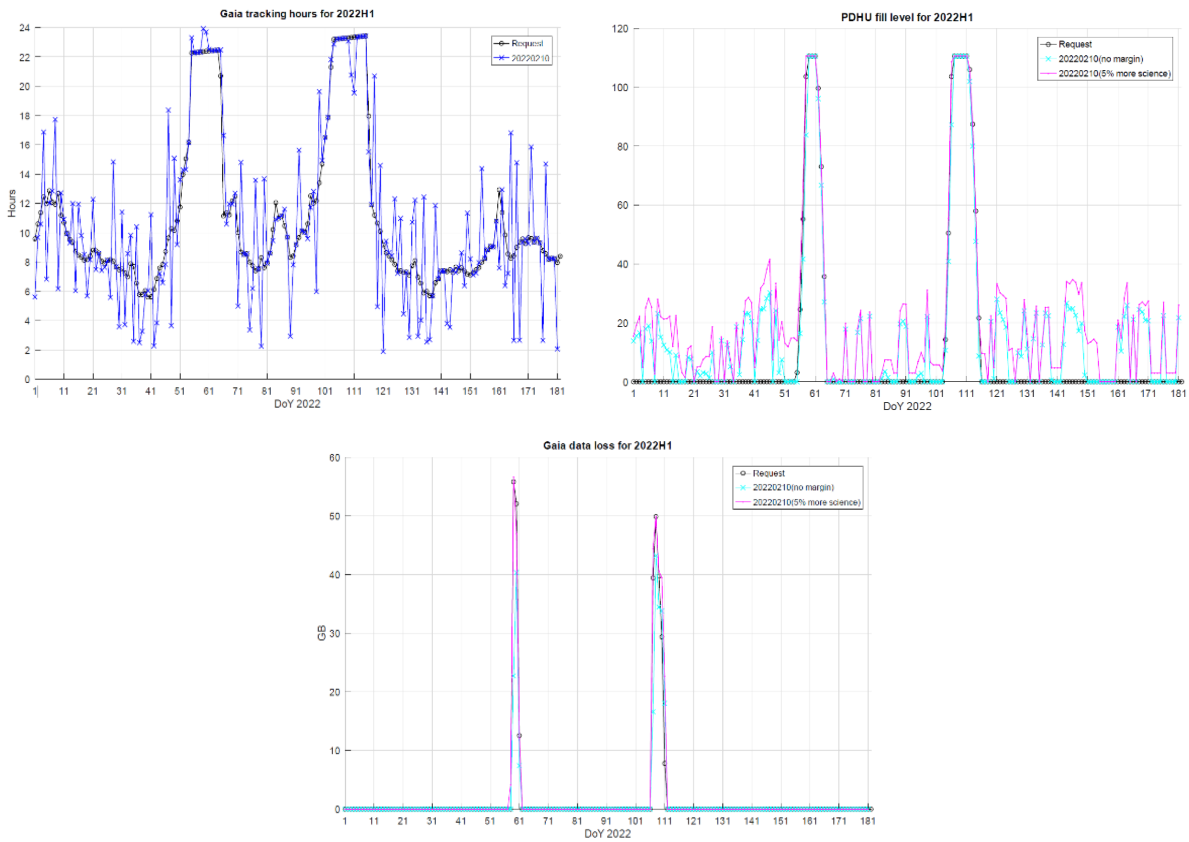

Figure 2: Long term planning plots

2.2.2. Short Term Planning

The Gaia short term planning process is a classical weekly generation of commanding output from an internally generated skeleton and externally supplied high level commanding products. The variable inputs consist of:

FDEF	: Flight Dynamics Event File.
PlanView	: EPS generated station booking list
OWLT	: Flight Dynamics generated One Way Light Time interpolation inputs.
POR	: Payload Operations Requests (supplied by the Gaia SOC).
FDR	: Flight Dynamics (commanding) Requests.

In addition, the generation of the event and commanding skeleton is driven by the mission planning system (MPS) Synthetic Events definitions (events that are generated at runtime based on dedicated planning rules), and final checks by State Model definitions (safety checks that ensure through the definition of allowed system states that the S/C is operated without violating operational constraints). A further commanding definition is supplied by the Template Operations Requests (TOR) files which schedule additional routine operational activity commanding based on the event skeleton.

The Gaia MPS used for short term planning is a standalone offline system that is run on its own dedicated server hardware. The system is implemented as a server/client architecture whereby the user interface is an Eclipse based graphical client that communicates using CORBA with the actual planning engine running as a background daemon.

The short term planning (STP) process for Gaia is performed on a persistent plan with committal points separating the inviolable (exported and sent to commanding sink) and modifiable (open to planning changes) being generated on each command generation run. In short, the planning process has the following workflow:

1) If there are significant changes for the period to be planned,
    a. Import new Planview, FDEF or OWLT files
    b. Rerun the synthetic events (which will update the events beyond the latest command committal horizon).
    c. Reimport the TOR files (which will re-schedule the background commanding based in the updated events)
2) Import external commanding inputs (POR and FDR files)
3) Run State Model checks on commanding and environment consistency
4) Generate the commanding products (updating the committal points).

3. New scenario and mission planning evolution

In recent years, there has been an ever-increasing demand for ESA's ground station network from its own missions but also from external institutional and commercial operators. This, combined with the fact that Gaia was in extended mission since 2019 and had lower priority than other newer missions, made it increasingly challenging to secure all the requested station time, particularly during the Galactic Plan Scan (GPS) periods requiring 24 hours downlink per day.

3.1 Usage of ESA-external station networks

In 2018, the Gaia mission entered into an agreement with NASA Deep Space Network (DSN) to use their 35m antennas to fill the gaps in coverage and availability of the ESA's deep space stations during the GPS periods. After completion of the LTP process for the ESTRACK stations scheduling, a request was submitted to NASA DSN to fulfil the missing hours in a second stage.

In addition, Gaia also reached an agreement to use Goonhilly private deep space antenna after a validation campaign carried out during 2021/2022, with the first supported pass in April 2022. This was also proven to be very helpful in some periods where there were still gaps not covered by either ESTRACK or NASA DSN.

Due to the increasing difficulty in obtaining all the requested hours from ESTRACK, the number of booked hours with NASA DSN and Goonhilly increased significantly in recent years as shown in Figure 3. For example, the use of external stations was crucial in August 2024 where a Gaia GPS period coincided with high priority JUICE LEGA[4] operations and there was significant overlap in visibilities between both missions.

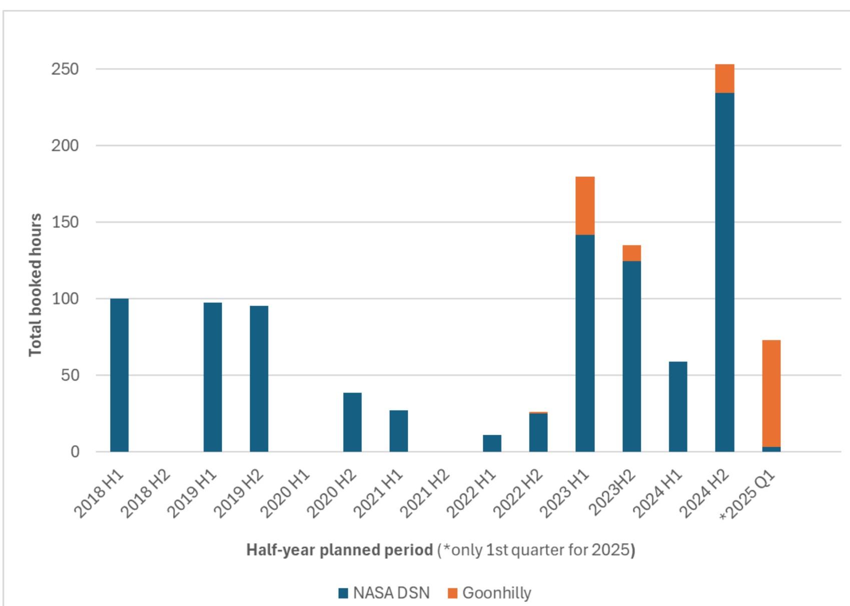

Figure 3: Booked hours with NASA DSN and Goonhilly stations

[4] https://www.esa.int/Science_Exploration/Space_Science/Juice/Juice_s_lunar-Earth_flyby_all_you_need_to_know

3.2 Ground station rescheduling due to launches or critical activities replanning

Due to several new missions being launched in the last years and critical activities for already flying missions, ESA's deep space network had to face several launches delays and replanning of critical activities, requiring a rescheduling of the stations and impacting all other missions using the deep space antennas.

The ground station time required for Gaia for the downlink of the science data was heavily optimised through the long-term mission planning process. In case ground station scheduling changes resulted in a decrease of available downlink time for Gaia, this could impact the timeliness of science data delivery or in the worst case led to deletions of science data if the on-board mass memory saturated.

In the 4th quarter 2022, Gaia had to face several of these ground station rescheduling activities due to several consecutive launch delays of the Japanese Hakuto-R M1 mission that was being supported by ESTRACK[5]. Using classical approaches to manage such cases required considerable team effort on a case-by-case basis to assess the impact on science data downlink and to mitigate it by securing alternative ground station tracking time.

In view of the new launches in 2023 of Juice[6] and Euclid[7] missions and the possibility of facing new launch delays and ground station rescheduling, Gaia FCT developed a new tool to help in assessing the impact of any lost tracking time and look for free slots with alternative stations with reduced time and effort. This tool, called Booking Optimisation Tool (BOT), is presented in detail in the following section.

4. Booking Optimisation Tool (BOT)

The aim of the Gaia long term planning process is trying to optimise the ground station bookings for Gaia according to the following criteria:

- Outside GPS periods: avoid exceeding 3 days without emptying the PDHU or having an excess of downlink hours
- During GPS periods: minimize the data losses and ensure the PDHU is empty as close in time as possible to the start of the GPS and as soon as possible after the end of the GPS.

The Booking Optimisation Tool is conceived to assist the Gaia planner in this activity.

4.1. *Requirements*

1) The tool shall offer the following functions:

   a. Generate plots to help in assessing the suitability of a PlanView file (containing the ground station booking list) in terms of science data downlink and PDHU emptying requirements. Three plots will be displayed with the following information:
      - Booked passes and PDHU fill level in GB at the start and end of each pass
      - At the end of each pass: PDHU fill level, data lost and surplus of downlink time, expressed in both GB and downlink hours
      - Number of days since last time the PDHU was empty

   b. Generate a list of all Gaia booked passes and all free slots between passes with all stations on visibility with Gaia (also including NASA DSN and Goonhilly). This will help to look easily for free GS slots in case of lost or missing downlink hours. The tool shall allow to add new passes or extend already booked passes but also to delete or shorten booked passes in case of an excess of booked hours. It shall also allow to plot the result of applying the selecting changes and compare with the original result.

   c. With the selected changes, generate booking request files (OSSUPD) to add, delete or modify GS passes. The OSSUPD files are XML files with a specific format that can be automatically imported into the EMS (ESTRACK Management System).

2) The tool shall be able to retrieve PlanView and visibility files from the EMS portal via a REST API.

3) The tool shall be run from any Gaia operator computer.

[5] https://esoc.esa.int/content/esa-ground-stations-support-first-commercial-moon-landing
[6] https://www.esa.int/ESA_Multimedia/Videos/2023/07/Euclid_liftoff
[7] https://www.esa.int/ESA_Multimedia/Images/2023/04/Juice_launch11

4.2. *Implementation*

The tool is developed in Python 3.10 (particularly Micromamba[8] python distribution for maximal platform support), following a rapid prototyping design and a modular approach to facilitate the evolution to future missions. The third-party modules listed in Table 1 are used.

Table 1. Python modules for BOT development

Module	Reference	Usage
Requests	https://requests.readthedocs.io/	For access to the REST API
Matplotlib	https://matplotlib.org/	Plotting support, especially the TK embedded canvas
Numpy Scipy Pandas	https://numpy.org/ https://scipy.org/ https://pandas.pydata.org	For the vectorized computations and time series analysis
Tkcalendar	https://tkcalendar.readthedocs.io/	For date picker
Lxml	https://lxml.de/	For XML parsing and writing
Openpyxl	https://openpyxl.readthedocs.io/	For Excel manipulation

The GUI was developed in TK using the internal python module tkinter to maximize the compatibility with legacy systems under strict configuration management. Testing and development was done in Windows 10 architecture, although the multiplatform capability of all the modules allows the program to run also in Linux devices.

The BOT GUI contains two areas, the first one for the inputs and functional buttons and the second one to display the output plots, as shown in Figure 4.

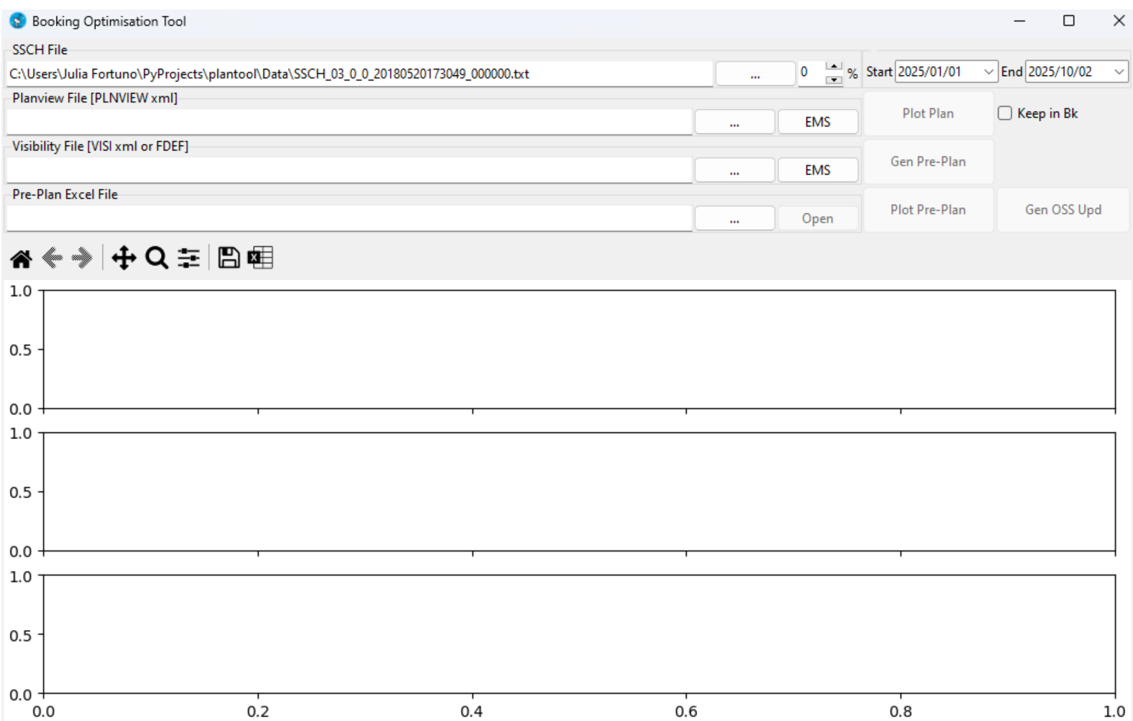

Figure 4: Booking Optimisation Tool GUI

[8] https://mamba.readthedocs.io/

The period under analysis is selected via the calendar inputs at the top right.

The required inputs files are:

- SSCH: Science schedule provided by Gaia SOC that gives predicted acquisition data rates with 12-hour resolution. The file can be browsed from a local folder.
- Planview: XML file containing the station booking list, delivered once per week by the ESTACK scheduling team. It can be browsed from a local folder where it is saved, but it can also be retrieved from EMS via REST API to get a more updated list for the selected period in case changes are suspected.
- Visibility file: It contains the periods of visibilities of all the ground stations with Gaia. The tool accepts two types of files, a Flight Dynamics Event File (FDEF) from a folder or a visibility file that can be retrieved from EMS via REST API.

When a SSCH and Planview files are selected, the output plots can be generated as shown in Figure 5. The tool gives the possibility to save the plot in PNG and save the data used in an Excel file.

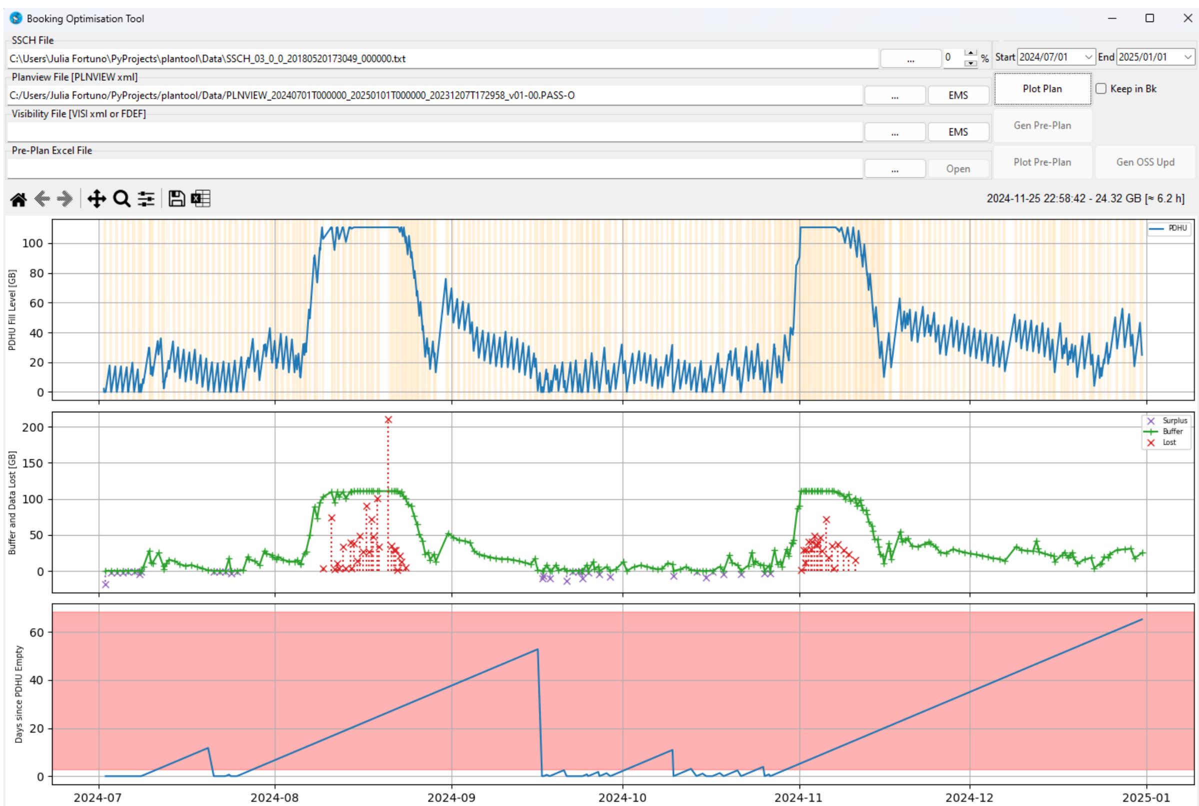

Figure 5: Output plots from the input SSCH and Planview files

When a visibility file is also selected, the tool allows to generate the so-called Pre-plan. This is an Excel file that contains all the booked passes for Gaia and between them, all the free slots on visibility with Gaia for all stations (see Figure 6). When the Pre-Plan file is generated, it becomes an input file appearing in the GUI input area.

	A	B	C	D	E	F	G	H	I	J	K
1	OSSREF	BoT	EoT	Duratic	Statio	DDOF	Statu	Actioi	Referer	Hours	Offse
2	EVENT-2022.343.12.32.14.510525-10094591	2024-01-01 00:50:55	2024-01-01 08:25:13	7.571667	MLG	FALSE	Booked		INI		
3		2024-01-01 08:25:13	2024-01-01 08:35:47	0.176111	MLG	FALSE	Ex_EoT		INI		
4		2024-01-01 08:25:13	2024-01-01 13:35:14	5.166944	GDS	FALSE	New		INI		
5		2024-01-01 09:40:46	2024-01-01 18:04:39	8.398056	CAN	FALSE	New		INI		
6		2024-01-01 11:40:25	2024-01-01 20:27:43	8.788333	NNO	FALSE	New		INI		
7		2024-01-01 17:16:24	2024-01-02 01:34:43	8.305278	GHY6	FALSE	New		INI		
8		2024-01-01 18:00:06	2024-01-02 01:34:43	7.576944	MAD	FALSE	New		INI		
9		2024-01-02 00:16:20	2024-01-02 01:34:43	1.306389	MLG	FALSE	Ex_BoT		FIN		
10	EVENT-2023.164.16.20.28.374233-2162908	2024-01-02 01:34:43	2024-01-02 08:39:02	7.071944	MLG	FALSE	Booked		INI		
11		2024-01-02 08:39:02	2024-01-02 13:37:01	4.966389	GDS	FALSE	New		INI		
12		2024-01-02 09:42:20	2024-01-02 18:07:53	8.425833	CAN	FALSE	New		INI		
13		2024-01-02 11:45:00	2024-01-02 20:30:50	8.763889	NNO	FALSE	New		INI		
14		2024-01-02 17:19:57	2024-01-03 01:33:31	8.226111	GHY6	FALSE	New		INI		
15		2024-01-02 18:03:16	2024-01-03 01:33:31	7.504167	MAD	FALSE	New		INI		
16		2024-01-02 18:03:41	2024-01-02 20:15:47	2.201667	CEB	FALSE	New		INI		
17	EVENT-2023.164.16.20.28.637849-2162910	2024-01-03 01:33:31	2024-01-03 08:42:18	7.146389	MLG	FALSE	Booked		INI		
18		2024-01-03 08:42:18	2024-01-03 13:38:45	4.940833	GDS	FALSE	New		INI		
19		2024-01-03 09:43:52	2024-01-03 18:11:08	8.454444	CAN	FALSE	New		INI		
20		2024-01-03 11:43:47	2024-01-03 20:10:17	8.441667	NNO	FALSE	New		INI		
21		2024-01-03 17:23:30	2024-01-04 00:40:50	7.288889	GHY6	FALSE	New		INI		
22		2024-01-03 18:06:26	2024-01-04 00:40:50	6.573333	MAD	FALSE	New		INI		
23		2024-01-03 18:06:51	2024-01-03 20:15:47	2.148889	CEB	FALSE	New		INI		
24	EVENT-2023.164.16.20.29.570513-2162916	2024-01-04 00:40:50	2024-01-04 07:53:23	7.209167	MLG	FALSE	Booked		INI		
25		2024-01-04 07:53:23	2024-01-04 13:40:26	5.784167	GDS	FALSE	New		INI		
26		2024-01-04 09:45:20	2024-01-04 18:14:22	8.483889	CAN	FALSE	New		INI		
27		2024-01-04 11:45:23	2024-01-04 20:37:01	8.860556	NNO	FALSE	New		INI		
28		2024-01-04 17:27:04	2024-01-05 01:27:23	8.005278	GHY6	FALSE	New		INI		
29		2024-01-04 18:09:35	2024-01-05 01:27:23	7.296667	MAD	FALSE	New		INI		
30		2024-01-05 00:30:54	2024-01-05 01:27:23	0.941389	MLG	FALSE	Ex_BoT		FIN		
31	EVENT-2023.164.16.20.29.168763-2162914	2024-01-05 01:27:23	2024-01-05 08:48:48	7.356944	MLG	FALSE	Booked		INI		
32		2024-01-05 08:48:48	2024-01-05 13:42:05	4.888056	GDS	FALSE	New		INI		

Figure 6: Output/Input Pre-Plan Excel file

The Pre-Plan file allows the user to add new passes and extend, shorten or delete booked passes. It also allows to select the whole slot or specify a number of hours and offset from the beginning or end of the pass.

Changes in the Pre-plan file can also be plotted and compared against the original result from the Planview, as shown in Figure 7.

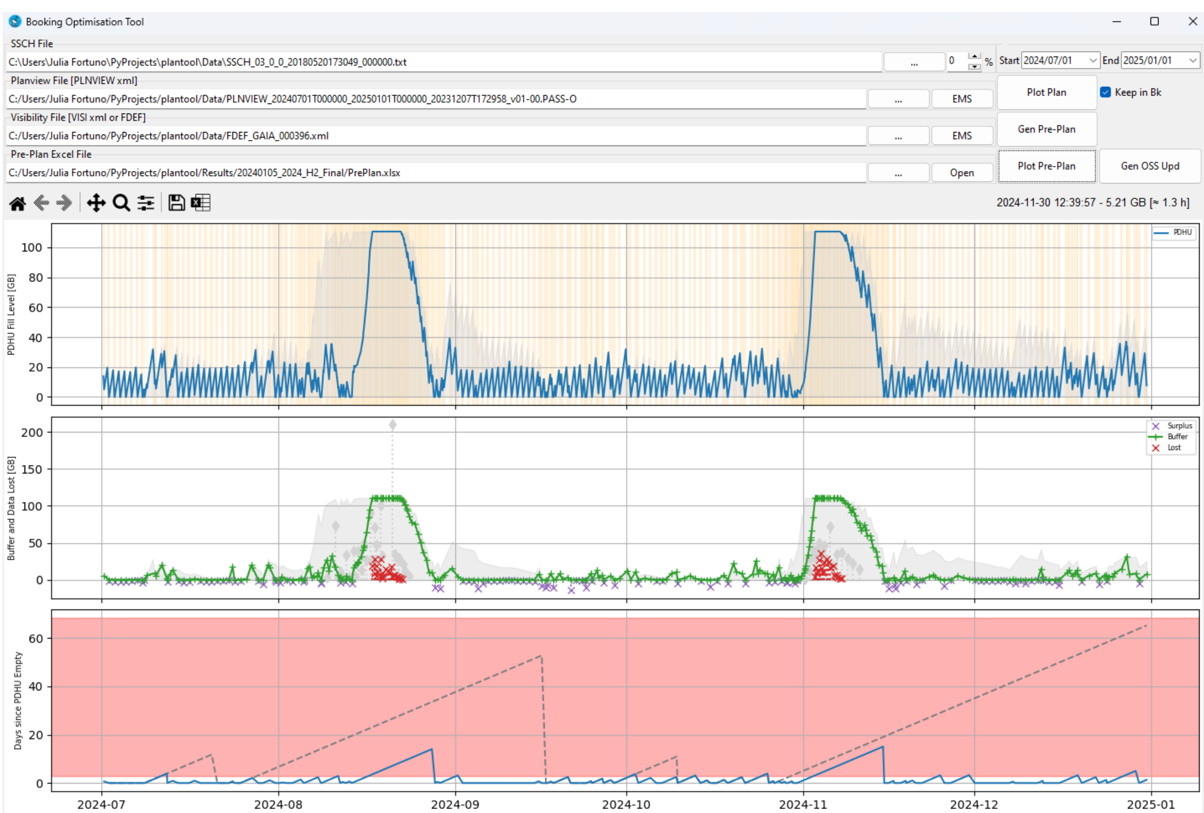

Figure 7: Output plots from Pre-plan vs. result from original Planview on grey background

Finally, the tool offers the possibility to generate OSSUPD request files for the addition/modification/deletion of the passes selected in the Pre-plan Excel file. This saves time for both the Gaia FCT and the ESTRACK scheduling team who only need to verify the successful automatic import of the requests.

4.3. Results

The use of the BOT has demonstrated several advantages compared to previous planning approaches.

4.3.1. Significant reduction of team time/effort for rescheduling activities

Before the development of the BOT, rescheduling activities were very tedious and time consuming, requiring the use of several tools and many manual actions. The typical workflow was as follows: 1) use the Octave scripts for long term planning to analyse the impact of the lost downlink time; 2) search for other alternative GS free slots with visibility on Gaia day by day using the EMS Portal; 3) check again with the Octave scripts the result of adding some new slots, that involving some manual adjustments; 4) if not good enough, repeat again the points 2 & 3 until obtaining an acceptable solution; 5) finally, book the new slots one by one in the EMS Portal (done either by the Gaia FCT themselves or by the ESTRACK scheduling team).

The new BOT integrates these steps into a single tool, streamlining and speeding up the process to less than one hour per rescheduling activity compared to several hours with the traditional tools.

4.3.2. Optimisation of the estimated PDHU fill level

The BOT has also been found to provide a much better estimation of the PDHU fill level than the Octave scripts used for long term planning. It has therefore become an essential tool for the Gaia long term planning process, helping in the refinement and optimisation of the bookings initially provided by the EPS.

The Octave scripts provide a coarse estimation of the PDHU occupancy. The fill level is calculated at the end of each day without considering the start/end times of the passes. However, the BOT calculates the PDHU fill level at the start and the end of each pass, giving a much more accurate and fine-grained estimation. In fact, when comparing the estimation in GB from the BOT with the real PDHU occupancy in sectors[9] from the telemetry for periods in the past, the plots match very closely as shown in Figure 8.

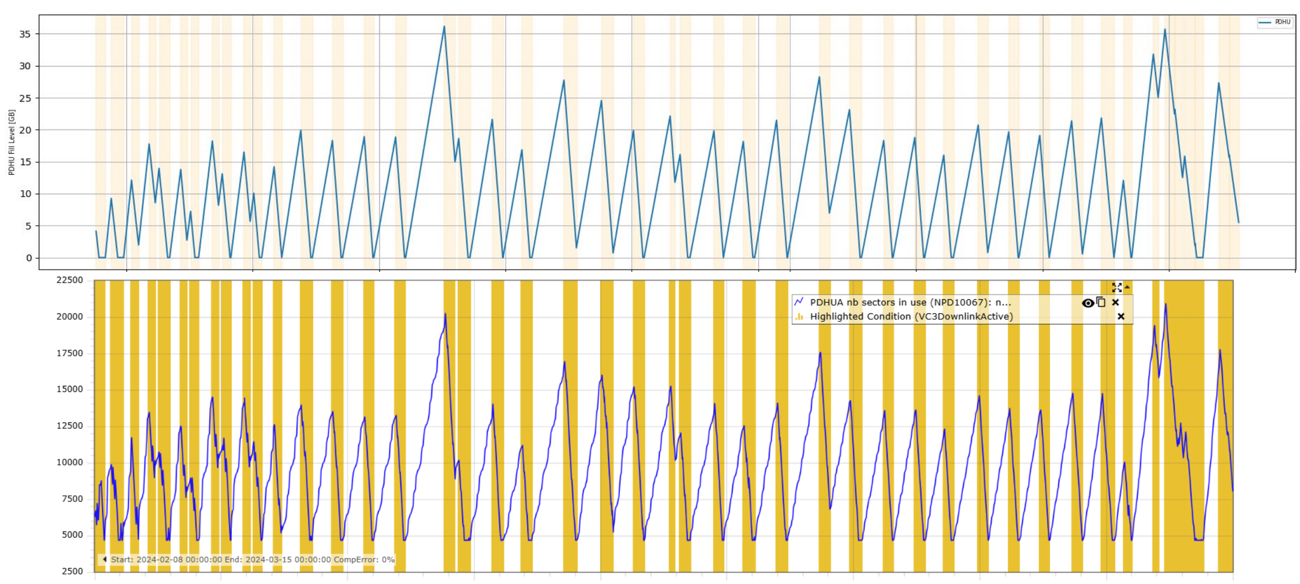

Figure 8: PDHU fill level in GB from BOT vs. PDHU used sectors from telemetry

[9] When the PDHU is empty the number of sectors in use is around 4700 as these are "pre-allocated" sectors to cyclic files. One sector is approximately equivalent to 0,00176 GB.

4.4. Future work

Since Gaia mission operations came to an end on 27 March 2025, no further work is planned on the current version of the Booking Optimisation Tool. However, this tool could be adapted and improved for other missions. Some ideas are presented below.

4.4.1. Adaptability to other missions

The tool comprises two main functions. The first function is to generate plots to assess the suitability of the ground station bookings to the data downlink requirements. Since these requirements can vary significantly between missions, this part of the tool could be adapted to each new mission depending on how data is acquired and downlinked and what needs to be displayed in the plots. This may however require significant changes in the code.

The second function is searching for ground station available slots, adding/deleting/modifying passes and generating OSSUPD requests to be imported directly in the EMS. This part of the tool could be easily adapted for any other mission with few changes in the code.

4.4.2. Possible improvements of the tool

The tool had to be developed in a short period of time because it needed to be operational as soon as possible. Therefore, a relatively simple approach was chosen when deciding which coding language to use and how to implement the user interface. This makes it still open to many possibilities for improvement such as those suggested here.

1. The user interface was implemented as a GUI using the Python tkinter module. With more development time, a more complex implementation via a web-based interface could be envisaged.
2. An Excel file is used as output file to list the booked passes and free GS slots, and the same file is used as input to select passes to be added/modified/deleted. It requires user familiarity on how to fill in the different input cells. Other ways of implementing this feature could be considered.
3. The tool could be further automated to propose to the user a list of passes to be added/modified/deleted in order to meet the data downlink requirements.

5. Conclusions

During the eleven years of Gaia science operations, it was one of the missions with higher demand of ESA´s deep space stations, especially during the Galactic Plan Scan periods where 24 hours/day of tracking time were required. In recent years, Gaia had to face several ground station rescheduling activities due to the replanning of launches and critical activities from other missions with higher priority for booking requests. This, together with an increase in the number of missions supported by ESA's deep space network, made it increasingly challenging for the Gaia FCT to secure all the required station tracking time. With the initial aim of helping in these rescheduling activities the Gaia FCT developed the Booking Optimisation Tool (BOT).

The new application has demonstrated a significant reduction of team effort and time spent in case of rescheduling needs, but additionally, it has been found to be a very beneficial tool during Gaia long term planning process to better optimise the ground station requested time thanks to the improved estimation of the payload memory fill level. Optimisation of ground station usage will remain a key factor for future missions planning efforts to most efficiently share ESA's ground station network between all stakeholders.

Acknowledgements

Spacecraft operations are a team effort requiring the support of multi-discipline expertise across ESA, industry and the Gaia scientific consortia (DPAC). The authors gratefully acknowledge the excellent contributions of the wider Gaia mission operations team, the Gaia ESA Project team, Project Scientists and Mission Manager in ESTEC, the SOC and DPAC, Airbus Defense & Space, and associated subcontractor experts to the Gaia endeavor and to the work behind this paper. A big thanks also to the ESTRACK, NASA DSN and Goonhilly teams for their essential support in scheduling and downloading the huge amount of data generated by the Gaia mission.

This paper is also dedicated to the memory of our beloved colleague and friend Gary Whitehead who was fundamental in many aspects of Gaia mission operations, including the initial design and implementation of the mission planning processes.

References

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