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Pushing the limits of Gaia ground segment automation: lessons learnt from a lights-out scenario

Marco Casanova-Álvarez*[a], Peter Collins[b], Jonas Marie[c], Julia Fortuño Benavent[d], Philippe Tatry[e], Eric Ecale[f]

[a] *Gaia Spacecraft Operations Analyst, Serco Services GmbH c/o ESA-ESOC, Lise Meitner Str 10, 64293 Darmstadt, Germany, marco.casanova.alvarez@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] *Gaia Mission Operations Unit, European Space Operations Centre, Robert Bosch Str 5, 64293 Darmstadt, Germany, jonas.marie@esa.int*
[d] *Gaia Spacecraft Operations Engineer, Telespazio Germany GmbH c/o ESA-ESOC, Lise Meitner Str 10, 64293 Darmstadt, Germany, julia.fortuno.benavent@ext.esa.int*
[e] *In Orbit Performance and Support for Astrometry, Airbus Defence and Space, 31 rue des Cosmonautes, 31402 Toulouse cedex 4, France, philippe.tatry@airbus.com*
[f] *In Orbit Performance and Support for Astrometry, Airbus Defence and Space, 31 rue des Cosmonautes, 31402 Toulouse cedex 4, France, eric.ecale@airbus.com*

* Corresponding Author

Abstract

With the increasing number of missions to be operated by ESOC in the coming years and the necessity of remote operations exacerbated due to the Covid19 pandemic, there is a deep interest in exploring and pushing the limits of ground and space-based automation in ESA missions. With all flying ESA astronomical missions controlled from ESOC already operated in parallel by a single on-shift operator, and with new missions joining soon, the Gaia flight control team's (FCT) response to this increasing challenge is to minimise spacecraft supervisor interactions through means of on-ground and on-board automation. In this context an operations scenario where no spacecraft controller is required at all during routine operations is presented. The addition of on-call engineer workload, delayed reaction times, potentially elongated service outages and their impacts, plus other metrics, will be used to assess feasibility of operations based around maximising use of automation and minimising human interaction and supervision. This concept goes somewhat beyond the more simple approach of automating sets of linear tasks, and in addition to the technical software solutions requires motivated on-call support personnel organized across several domains, including industrial support partners for specific off-nominal situations, which is only possible thanks to the collaboration of the companies involved in this project.

In recent years the Gaia mission accomplished notable milestones automating spacecraft operations thanks to in-house developed tools, including automatic alerts to the on-call engineers using the Remote Alert System (REALS), and use of the Mission Automation System (MATIS) software to execute all nominal pass activities, post-process downlinked data and react to common spacecraft and ground segment anomalies. An extended usage of these tools, plus additional solutions, will be presented in order to understand the challenges encountered to move to a scheme whereby all routine (and common non-routine) operations are performed without the necessity of an on-console operator. Potential extensions are also explored in the context of other already flying and under preparation ESA missions.

Keywords: operations, automation, autonomy, ground segment, improvements

Acronyms/Abbreviations

AOCS	= Attitude and Orbit Control Subsystem
AOS	= Acquisition of Signal
API	= Application Programming Interface
ARB	= Anomaly Review Board

ASD = Auxiliary Science Data
BOD = Beginning of Day
ConOps = Concept of Operations
DPAC = Data Processing and Analysis Consortium
DSN = Deep-Space Network
ECSS = European Cooperation for Space Standardization
Es/No = Symbol energy to noise ratio
ESA = European Space Agency
ESAC = European Space Astronomy Centre
ESOC = European Space Operations Centre
ESTRACK = European Space Tracking Network
ESTEC = European Space Research & Technology Centre
FCT = Flight Control Team
FOP = Flight Operational Procedures
FOS = Flight Operation Segment
GPS = Galactic Plane Scan
HK = House keeping
I/F = Interface
LMS = Lightweight Monitoring System
MATIS = Mission Automation System
MCS = Mission Control System
MOC = Mission Operations Centre
MTL = Mission Timeline
PDHU = Payload Data Handling Unit
PUS = ECSS Packet Utilization Standard
PLUTO = Procedures Language for Users in Test and Operations
REALS = Remote Alert System
SDS = Science Data System
SKEL = Spacecraft Key Event Log
SMF = Service Management Framework
SOC = Science Operations Centre
SWS = Software Support
TC ACK = Telecommand acknowledgment
TCH = Telecommand History
TM = Telemetry

1. Introduction

The Gaia mission was launched on the 19th of December 2013 on a Soyuz-Fregat launch vehicle from French Guiana in Kourou, and is operated by ESOC in Darmstadt, Germany. Gaia is an ESA cornerstone mission that 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.

The Gaia spacecraft contains a relatively large fraction of bespoke units, due largely to the incredible precision requirements. Gaia’s digital camera is the largest ever flown in space, containing 106 CCDs, which are around 90% light efficient (c.f. 20% typical terrestrial camera efficiency). The telescope is linked to the on-board AOCS subsystem, providing precise rate measurements used to control the rotation of the spacecraft once every six hours, and allow an overall control rate error equivalent to one rotation every 410 years. Moving parts on board are strictly minimised, e.g. no reaction wheels and no mechanically steerable antenna. The data is downlinked through a novel electromagnetically steerable phased array antenna and attitude control is provided by a micro propulsion system that has its first operational flight use with Gaia. An atomic clock is used for very precise timestamping of all data produced on-board.

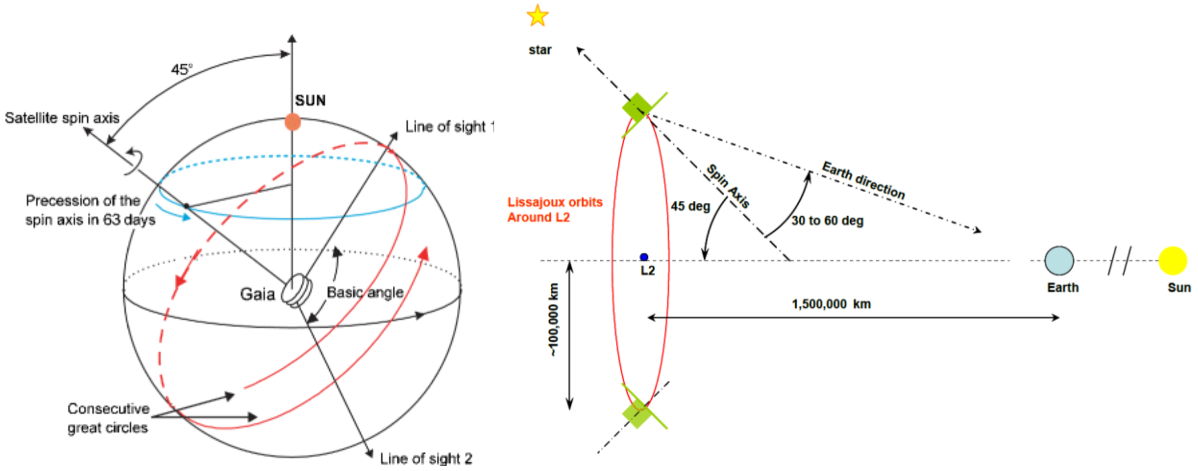

Figure 1 Gaia attitude and orbit profiles.

The spacecraft is designed with a high level of on-board autonomy, but the nature of the mission dictates that a relatively large amount of ground station contact is necessary to be able to downlink the data that Gaia generates. From its Lissajous orbit around L2 the spacecraft is continuously observing during the nominal 5-year science mission (although with cold gas resources still remaining for attitude control Gaia is now in its ninth year of science mission operations), using Solid State Mass Memory to store data on-board whilst out of contact with the ground. Gaia is in daily contact with ESOC via ESA’s 35-metre Deep Space ground station network in Cebreros (Spain), New Norcia (Australia) and Malargüe (Argentina). Since the amount of science data generated on-board varies according to the area of the sky being scanned, the amount of time needed to downlink it varies as well. This is particularly relevant during periods when the spacecraft is scanning along the galactic plane where stellar densities are very high. In these periods up to 24 hours per day of ground station coverage is requested. Initially it was planned to have one ground station pass per day outside of galactic plane scans for command and control of the spacecraft and data downlink, though this was later increased with in-flight experience demonstrating that more time would be needed if all acquired data was to be downlinked to ground.

2. Gaia Operations Overview

While XMM-Newton (launched 1999) and Integral (launched 2002), the other two ESA Astronomical missions controlled from ESOC, are constrained by the reduced storage on-board meaning maintaining constant ground contact with continuous commanding capability, Gaia’s on-board storage and autonomy allows the pre-load of commands to be executed at their due time using an on-board time release based MTL (serviced by PUS service 11). In the case of Gaia, the length of the passes is primarily constrained by the amount of science data generated on-board that must be downlinked, varying from ~ 8 hours up to 24 hours in case of a GPS. Besides the continuous science downlink performed during the passes, the routine pass activities include the dump of the HK stores, uplink of the MTL and general monitoring of anomalous events in real time or from the on-board storage.

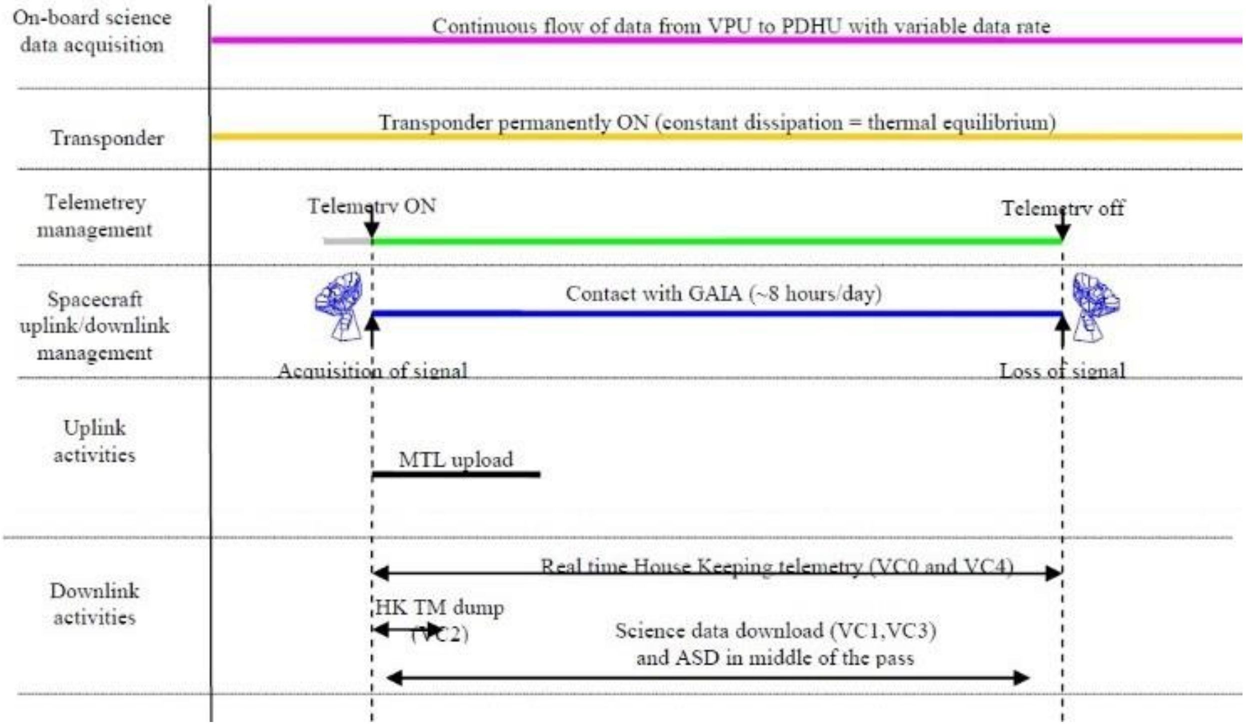

Figure 2 Gaia Pass activities.

As unpredictable asynchronous events can occur on-board at any time, Gaia uses a mission specific PUS service (Service 155) to store any events with severity higher than 2[*] (as defined in [1]). This store, the Spacecraft Key Event Log (SKEL), allows easy access in case on on-board anomalies which require ground intervention. In case there is an event in the SKEL, its content is dumped (if there is a pass on-going, during that one, if outside of passes, in the next one) and the store is cleared, and the appropriate contingency operations are executed (if needed).

2.1 Merge of the operations across Astronomy Missions

The similarities between XMM-Newton and Integral missions, in addition to cost saving reasons, lead in 2008 to the merge of their FCTs and the reduction of spacecraft operators to only one person for both missions. However the major operational differences with Gaia, especially due to their contrast in on-board storage and autonomy, played an important role in the operator team merge in April 2018. As a result of this process, the Gaia operator team was merged with the six XMM-Newton/INTEGRAL operators into one single team operating all the three spacecraft in parallel. A joint effort from the three missions identified the workload and the knowledge required for the operators to guarantee a minimum effect on science production without compromising spacecraft safety [2]. At the beginning it was established that for Gaia a 2-hour commanding window would be granted at the beginning of each pass to perform all the routine pass activities, but with increased automation implementation the time in which the Spacon has to actively perform operations in Gaia has been decreased dramatically up to the point where almost only monitoring tasks are required.

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[*] According to the PUS standard, the Service 5 corresponds to on-board events with severity levels ranging from 1 to 4: Informational event (5,1), Warning Event (5,2), Alarm Event (5,3) and Fatal Event (5,4).

3. Evolution of Gaia automation

3.1 Open loop automation

After Gaia ‘s instrument commissioning, it was observed that fainter stars could be detected by the spacecraft than initially expected [3], which considerably increased the data volume to be downlinked (by ~45%). To retrieve all the data with extra ground station time without increasing the team size (leading to a mission cost increase), an approach to take passes without human operators present via pre-planned science downlink operations was implemented.

One 8h pass per day was maintained with a human operator in control, with an additional pass dedicated purely to science downlink executed without an operator present. In this scenario science data transmission was started automatically via the on-board MTL that was populated in advance by ground, and the data downlinked to the ground station and forwarded to ESOC automatically. This approach had the drawback of an increased risk of science data loss on the space link in comparison to a concept fully reliant on human operators with the possibility to intervene in case of problems. To mitigate this risk, an On-Board Control Procedure (OBCP) was developed and operationally activated in November 2014 to protect the Science downlink by only allowing it to continue in the presence of a good uplink carrier signal detected at spacecraft level from the ground station (i.e. the uplink level at the spacecraft is used as a “proxy” for the downlink level at the ground station) [4].

To help mitigating the risk of not increasing the time with human operators present, the in-house developed REmote Alert System (REALS) was adopted to forward SMS notifications of selected messages generated by the Mission Control Software (MCS). REALS is used to alert the on-call Spacecraft Operations Engineer (SOE) and Spacecraft Operations Manager (SOM) about any unusual events ongoing and it also includes a confirm/retry mechanism to mitigate problems such as SMS delivery failure or SOE unavailability, i.e. unless REALS receives positive confirmation of SMS reception by the user, it will try again by moving to the next person in the notification list [5]. With the operational use of REALS in place, the dedicated ground communication links for housekeeping data were also connected for passes without an operator present, in addition to the links for science data, as part of the pre-programmed commanding. In this context, the main benefit of REALS is a potential earlier notification of critical on-board anomalies, not related only to science downlink but also the health of the spacecraft. However this system is also limited because, even if via REALS the on-call SOE is made aware of a problem, it still requires manual intervention to fully resolve it and sometimes this can only be accomplished with delay after human access to the system and diagnosis of the details has been performed. Going further, this system in isolation does not allow automation of routine tasks that may have dependency upon other tasks, i.e. it cannot pre-check nor shift activities according to real-time events, rather it runs a fixed pre-defined plan and reports the status.

The component to integrate REALS into the MCS is the so called AlertPush software, that is used to transform messages in the MCS log into XML files and send them to the REALS Server system.

The following diagram depicts the REALS system and its high-level interface context:

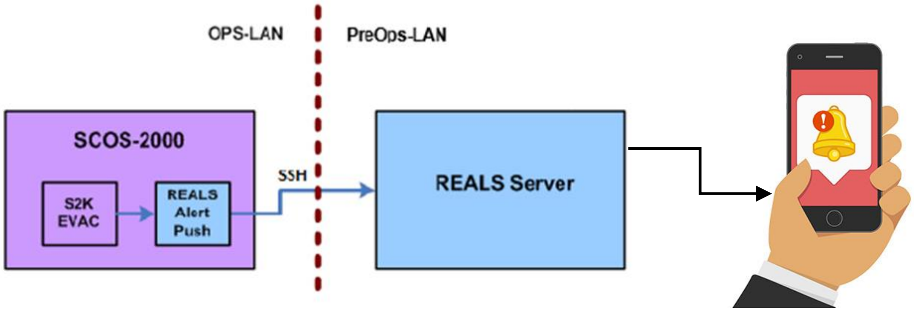

Figure 3 REALS Architecture.

The SCOS Action Manager (EVAC) is responsible for detecting and triggering execution of a set of predefined actions. An Action Configuration File contains the mission-specific definition of which events trigger which actions. When the EVAC receives an Event ID, then the Action Configuration Table is searched. If the Event ID is found in the table, then the corresponding action is triggered. The action defined for REALS purpose is the execution of a script that will generate as output a text file with the description of the event.

The generated event files will be captured by the REALS AlertPush application running on the MCS host and transmit via SSH a small XML event file to the REALS server, from where it will be sent as an SMS to the relevant user via the connected modem.

Initially in Gaia, REALS was used to send SMS only for spacecraft related events (e.g. on-board events with a certain criticality as explained before, parameters with values out of predefined limits, telecommand failures. In the framework of the Gaia Lights-out project, REALS has been extended to also send SMS for critical problems coming from the MCS and MATIS systems. It implied the addition of new entries in the EVAC configuration file and the creation of new scripts and files to deal with these new events.

3.2 Closed loop automation and current state

Over time the Gaia FCT was able to evolve and improve the mission automation concept to introduce closed-loop automation, which has the capability to react to on-board and ground station telemetry and events in real time, in addition to performing pre-planned operations based on a running ground-based schedule. In the absence of an on-shift Spacecraft Controller this system can therefore compensate by performing some tasks automatically. In Gaia the system builds on previous infrastructure developments and is a combination of the current MCS (SCOS-2000 software as the baseline), the Mission Automation System named MATIS (which acts as the automated operator), and a Service Management Framework (SMF) that consists of sets of drivers that connect between the various ground segment elements such as the MCS and MATIS. MATIS was developed by the ESOC ground infrastructure division, and Gaia has been the first ESOC mission to use it operationally [6][7][8].

Using the Mission Planning System files as an input, MATIS schedules and executes tasks that manage the MCS, ground stations and spacecraft. It is composed of a system designer and an operations manager, the former being a tool set for developing operational procedures (written in a domain-specific language based around PLUTO) and the latter a scheduler that activates these procedures according to timed-based events. The procedures can be configured to release commands to ground or spaced based elements, receive, and process telemetry, and invoke alerts for the operator. These procedures can invoke actions or wait until specific events are received, and then make decisions according to the statuses of the ground stations and spacecraft.

In Gaia the first use of the closed loop automation was to manage and monitor the communication links between the operations centre at ESOC and the 35m ground stations that form part of ESA’s deep-space network. In case of a station anomaly, communication interruption or low transfer rate, offline retrievals for the missing data stored locally at the ground station can be performed. Ground station related anomalies can be detected through ground station telemetry (via the in-house developed software system LMS), which is being processed by MATIS in addition to the spacecraft data. Space link interferences (e.g. bad weather, station configuration or equipment problems) can also be monitored using this telemetry, which can be used by MATIS procedures to decide whether and when to interrupt science data transmission on-board. Because of the ability to interpret and react to telemetry, MATIS can detect anomalous behaviours that cannot be covered by the open-loop automation approach and react to them by means of telecommands.

To reach the point of reacting to events commanding the spacecraft, a lot of effort was spent ensuring that MATIS is able to command with zero impact or risk. To accomplish this a series of pre-conditions were determined to be checked prior to any commanding operation, such as examining the value of a flag announcing who will do the activity (the Spacon or MATIS) and high-level flags indicating the health of the TC/TM links. This method was designed and initially used to ping the spacecraft (test the connection), but it was then modified for each new controlling activity done by MATIS, such as the HKTM packet store downlink, the MTL uplink, or the SKEL dump. Furthermore MATIS is using an API to upload data into the operational activities logging solution called Uberlog, providing a severity indication that allows to filter and automate messages in order to produce periodic reports.

Across nominal and contingency operations, MATIS has notably reduced the workload and hours that the spacecraft controller of the astronomical division has to spend. The current daily time required in Gaia is up to 30 minutes, and most of this is only for monitoring the system rather than carrying out specific button-clicking tasks. The progression of automation and the envision of more optimized human resources for spacecraft supervision (sharing the first line of support along missions) lead to an almost fully unsupervised scenario which will be presented in the following sections. Fig [4] shows the decrease of Spacon time performing Gaia operations due to automation improvements, based on information extracted from the electronic logging system of when human operators were interfacing with the Gaia system.

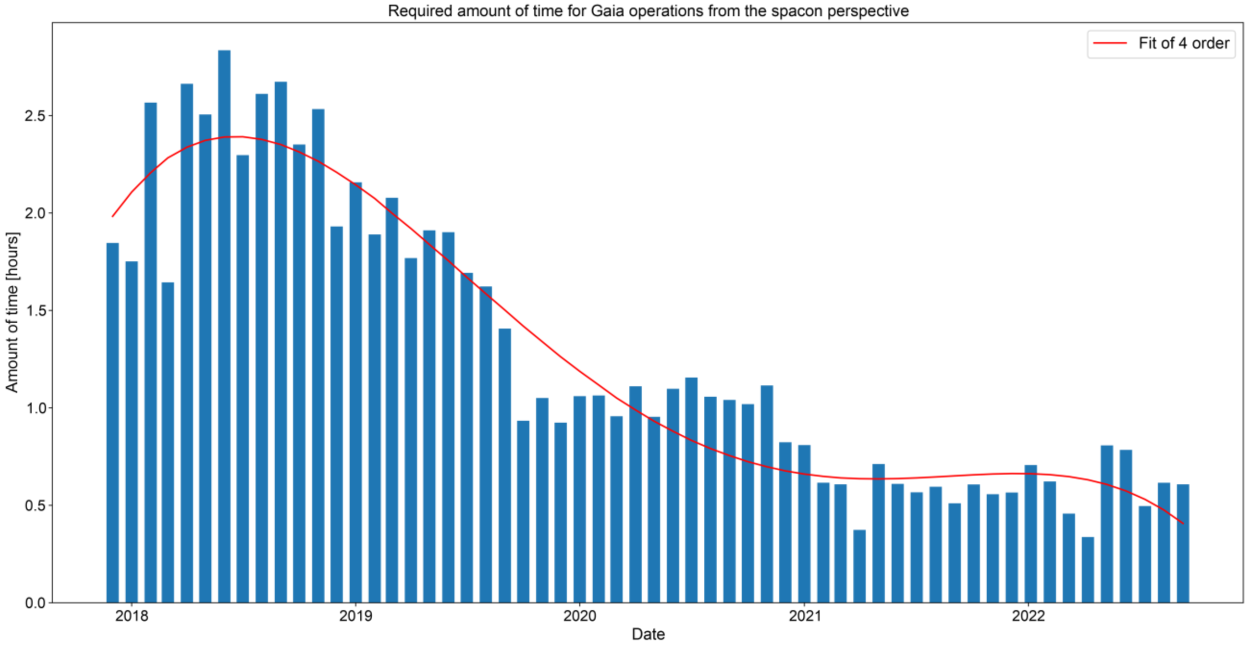

Figure 4 Decrease on Spacon time performing Gaia pass activities.

4. Lights-out test

4.1 Aim

During the pandemic situation lived across the world, remote operations became a necessity. Moreover, future concepts of operation centres where mission supervisors monitor tens of missions at the same time (as currently done by private constellation companies for many identical/similar spacecraft comprising a specific mission concept) point to the necessity of highly automated missions, in order to minimise manual ground interactions with a single S/C as the supervisor won't be able to retain deep knowledge of each specific mission. Due to the high degree of autonomy of the Gaia spacecraft and ground segment, the mission is a well-suited candidate to examine the limits of this approach within the ESOC domain. A "lights-out" scenario in this context refers to an operations scheme where no spacecraft supervisor interactions are required during routine (and some contingency) operations. This is achieved by automating all routine operations and autonomously monitoring not only the S/C health but also the different ground systems such as the Ground station (e.g. antenna tracking via EsNo), the MCS or even the MATIS automation system itself. This configuration was applied by the Gaia FCT to the operational ground segment in September 2022 for a period of one week to demonstrate the approach's feasibility and collect lessons about areas of improvement. During this period, the on-call SOE was in charge of performing the increased monitoring tasks which involve reacting any alert autonomously forwarded via REALS or performing a set of daily tasks detailed in the next section. In the future, this actions can be carried out by a supervisor handling high-level alarms from high automated missions such as Gaia during the lights-out scenario.

4.1 Implementation

In the current nominal configuration, real-time segments of the Gaia FOS can be abstracted into infrastructure (non-MCS machines/processes), MCS (including hosting machine resources/additional processes, the MCS software itself and in-coming information from the spacecraft), MATIS and the Ground Stations. Fig. [Figure 5] shows the current information flow in case of an anomaly of any kind, and who are the relevant actors.

The scheme adopted was to use a web-based dashboard (that was already in-use since several years by the team and so required only some small extra configuration changes) to summarise any infrastructure or process/data flow problem of the MCS (normally non-urgent issues). This dashboard refreshes its content information every 15 minutes, and it is used by the FCT and software support teams on working days to spot any relevant issues. Any spacecraft issue (e.g. on-board parameters showing an out-of-limit value, abnormal on-board events, telecommand verification failures) is caught via two different systems, depending on the criticality of the problem: non-urgent issues are detected by the Spacon via live TM coming from the spacecraft or performing a daily printing of the problems that happened outside of visibility thanks to the playback data. The more critical and urgent issues are also forwarded to the on-call SOE by REALS via SMS.

For MATIS problems (e.g. conditions for an action not met, crash of processes), the messages are injected to Uberlog (a textual logging tool) to be read by the SOE on-call or the Spacon. Diagnostic information is also displayed in the MATIS real-time log available in MATIS Operations front-end. Real-time ground station or communication line issues (managed by ESTRACK) are reported by ESTRACK via voice-loop to the Spacon, who depending on the urgency of the matter would notify the on-call SOE. The Spacon provides the ultimate ‘safety net’ in the real-time monitoring chain, and depending on the complexity, urgency and criticality of the issue will escalate the issue to the on-call SOE via email (if non-urgent) or call the 24h on-call SOE service provider. the SOE assesses the scenario and potential recovery actions required and, if necessary, initiates a meeting with all relevant parties to further study the issue.

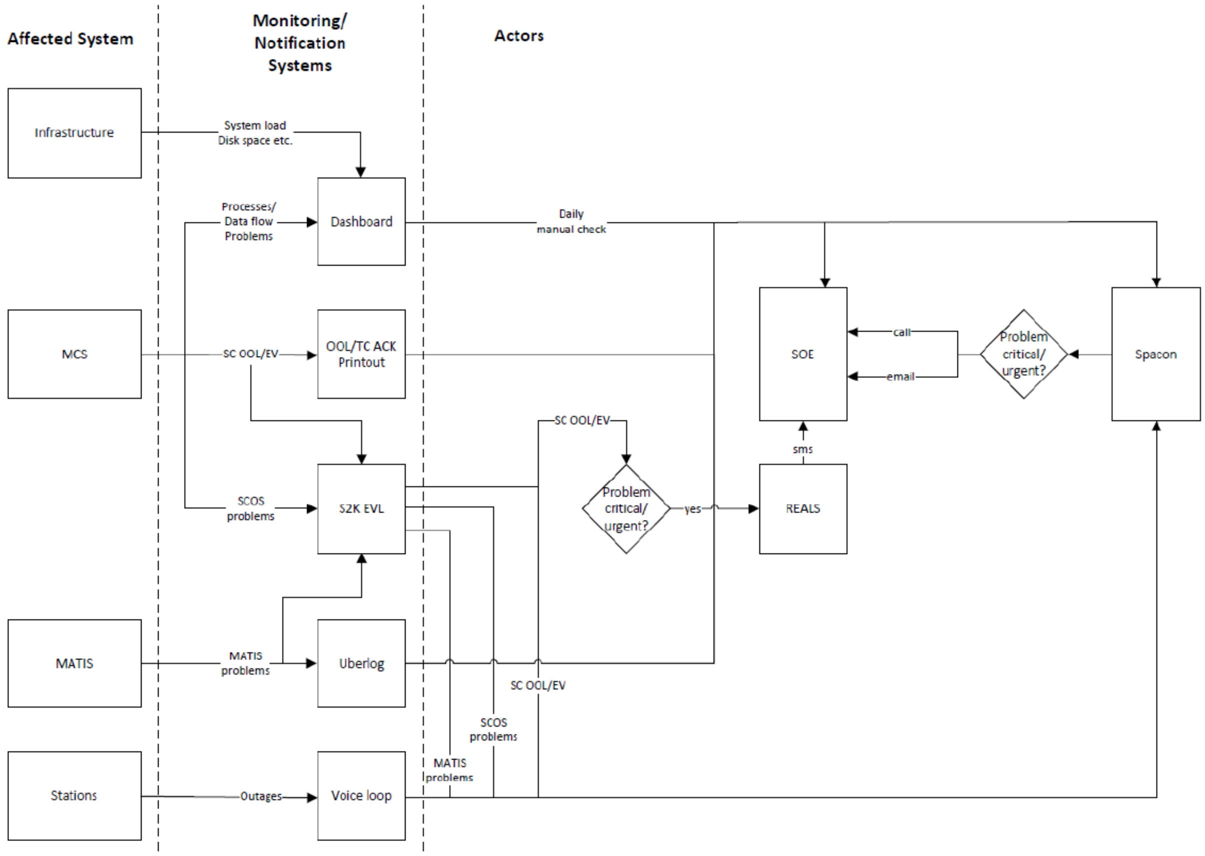

Figure 5 Pre-lights-out notification flowchart.

Since the goal of the lights-out scenario is to minimise Spacon interactions with the Gaia ground segment, Fig [5] can be used to identify the areas that require modifications. Table 1 enumerates the tasks that no longer will be performed by the Spacon and will be addressed by the on-call SOE instead. Notification timeliness is estimated based on the applied monitoring mechanism.

Problem	Notification System (Spacon)	Notification Timeliness (Spacon)	Notification system (SOE)	Notification Timeliness (SOE)
Machine problem	Dashboard	Immediate	Dashboard	Daily
S/C playback problems	MCS printout	Daily	MCS printout	Daily
MATIS process	MATIS	Immediate	REALS*/Uberlog	Immediate/Daily (Urgency dependant)
MCS problem	MCS	Immediate	REALS*/Dashboard	Immediate/Daily (Urgency dependant)
Ground Station issues	Voice Loop	Immediate	Spacon	Immediate/Daily (urgency dependant)
Spacecraft alerts	SCOS	Immediate	REALS*	Immediate

*Needs implementation before test

Table 1 Notification workflow by type of problem for pre-lights-out and lights-out scenarios.

As seen in the table, manual checks can be covered by the on-call SOE on a daily basis while alarms (depending on urgency) will be caught by the REALS system. While in a future setup the notification of Ground Station related issues could be handled in a different and potentially more automated way, for the scope of this first test it was agreed by the FCT that voice loop interactions with ESTRACK would still be handled by the Spacon and eventually, in future tests, the ground station operator could for example call the on-call SOE directly instead of using the voice. Once the changes in the notification chain presented in Table 1 are performed, the ground segment monitoring and notification roadmap is as following:

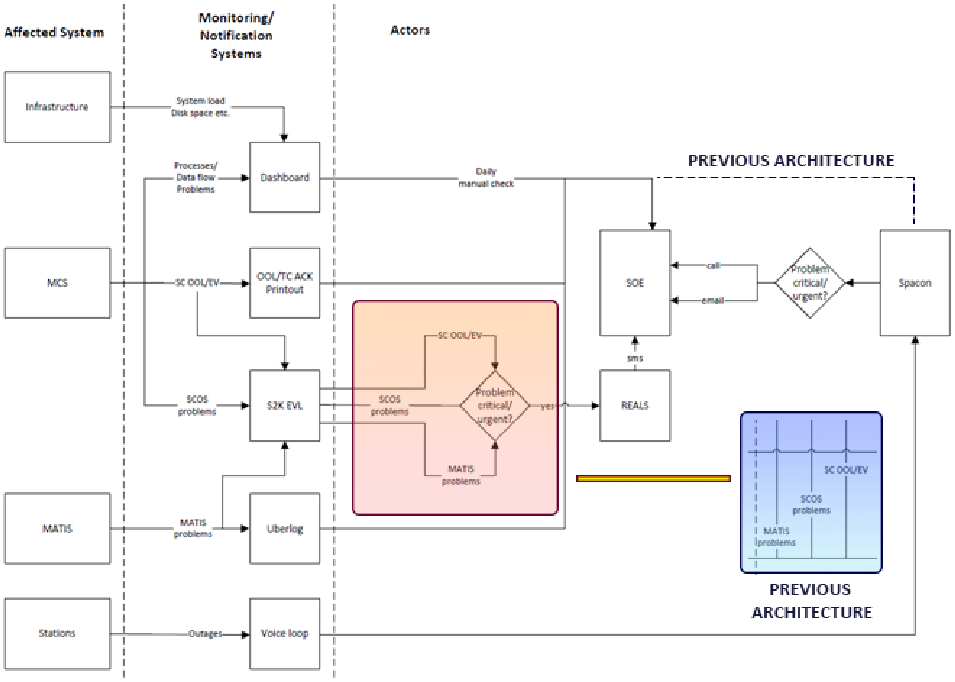

Figure 6 Lights-out notification flowchart.

4.2 MATIS REALS Interface

One of the principal modifications performed in the Ground segment to allow the lights-out test was to create a link between MATIS notifications (formerly being injected into Uberlog, MCS and MATIS logs) to a real-time system which allows SMS real-time notification to the on-call SOE. To do so several options were analysed, and considering that the mission was already using REALS it was decided to also inject these notifications into the MCS system, thereby creating a link between the two:

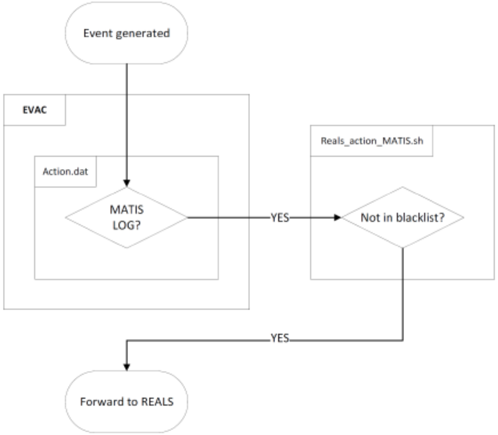

Figure 7 MATIS REALS I/F

After reviewing all the activities performed by MATIS (commanding and non-commanding), an analysis on the time-constrained and critical operations was performed to select the MATIS messages which should be routed to REALS. A total of 98 messages were selected for REALS notification (of which only 12 were not yet included in the SCOS event log) mostly from commanding procedures failing the execution of commands, checks of the MTL uplink (verifying that the file to be uplinked in the desired one) and crashes of MATIS procedures themselves (continuously monitored with watchdogs). Based on this selection, a blacklist was created to filter out MATIS logs via regular expressions that are not intended for REALS forwarding. This approach has been chosen to ensure that any new MATIS log entry that might be created in the future shall be passed to REALS by default (and then can subsequently be added to the blacklist if necessary).

The configuration file (required to match event types with scripts to execute) used for REALS event forwarding also needed to be adapted to evaluate any message coming from MATIS (thanks to its MCS identifier), check if the message is not contained in the blacklist, and if so, create a file for REALS to collect and forward to the REALS server which then notifies the users via SMS.

4.2 MCS REALS interface

In the case of Gaia, two different servers are used to receive real-time data from the spacecraft, the MCS where the commanding and HKTM archiving is performed, and the SDS archiving the scientific data. Without a Spacon in the loop it is necessary to monitor both systems, and also ensure there is a monitoring mechanism in place to report critical problems and to assess whether REALS itself is functioning correctly or not across the full system (as certain MCS processes that are required for REALS may crash, which may become critical considering the increased use of the system to relay alerts). To do so, the Gaia REALS implementation includes a heartbeat mechanism which informs the user of outages of the notification chain, and even of outages in the heartbeat mechanism process itself, for both the MCS and the SDS.

After evaluating the relevant SCOS logging messages, 18 failure cases were flagged as urgent requiring an immediate recovery to mitigate significant operational impact (e.g. delayed science delivery, outage of a notification system). 17 of them entailed the crash of an MCS process.

There was a single remaining failure case involving the complete loss of the prime MCS/SDS server that cannot be caught by this mechanism. Such a scenario was considered very unlikely to occur without any pre-cursor problem that would itself lead to an on-call notification being generated, and indeed in almost nine years of continuous Gaia operations this case has never been encountered. In the unlikely case of a sudden outage, the ESTRACK team would anyway inform the Spacon who would then inform the SOE. Further still any machine unavailability is also indicated on the monitoring dashboard so would be detected latest as part of the daily checks. The EVAC/REALS interface for MCS anomalies is configured similarly to MATIS events, but this time using a whitelist (rather than blacklist) as the failure cases comprise a static list. As the SDS machine has no dedicated direct REALS interface, a rule was added to transfer selected events for REALS to the out-tray directory in the MCS machine.

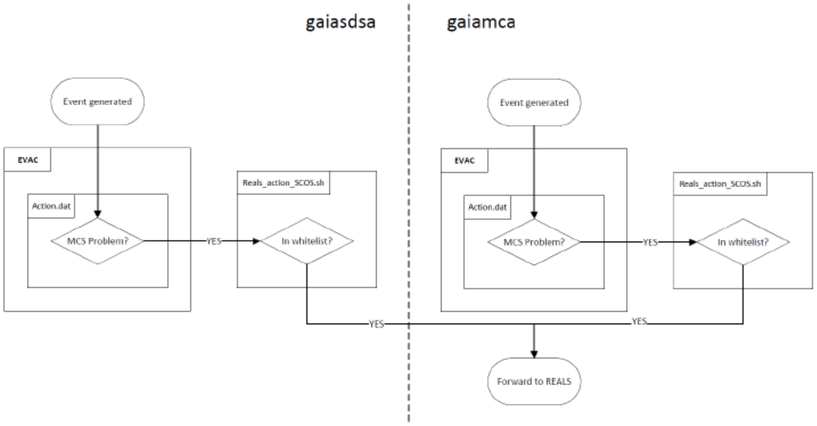

Figure 8 MCS REALS I/F.

5. Results

During the execution of the lights-out scenario the SOE on-call collected information to assess the increase of their workload with a lights-out configuration in place. Additionally, the anomalies that occurred during the testing period were good test-cases to verify that the notification mechanisms used were the appropriate ones and the contingency operations could be performed in the same manner.

In terms of time spent by the on-call SOE in activities related to real-time operations, the daily checks performed had a minimum-maximum duration of 15-90 minutes. It was also shown that with time the on-call SOE became used to the checks and there was a decrease in the time required for the daily checks at the end of the tested week. In addition to the daily checks, weekly processes such as mission planning, minute of meetings preparation etc. add ~3 hours of support required by the on-call. During the testing period, the on-call SOE received a total of 20 notification incidences (by REALS, Uberlog or directly in the MCS as part of the checks) from which the majority were not requiring follow-up action or minor incidences (mainly of the ground systems).

Thanks to the experience acquired by the team throughout the entire mission, REALS only forwards a subset of alarms that the SOE on-call needs to receive at any time, thanks to blacklists or whitelists (depending on the system). This filtering protects the SOE on-call against e.g. false positive alarms flooding during the night. In Fig. [9] a statistical analysis is presented of the different alarm messages generated in the MCS that were analysed by REALS throughout the entire mission. Thanks to a blacklist of frequent OOL and events where no on-call interaction is needed (e.g. MATIS performing autonomous contingency operations), a first set of alarms is discarded. Moreover, consistency checks or soft limit OOLs are discarded as well in a second filter. Only 11% of the total alarms were forwarded to the on-call SOE via REALS, of which 68% were test alarms (such as the daily heartbeat), which provides an indication of how frequent an alarm is for the Gaia REALS configuration.

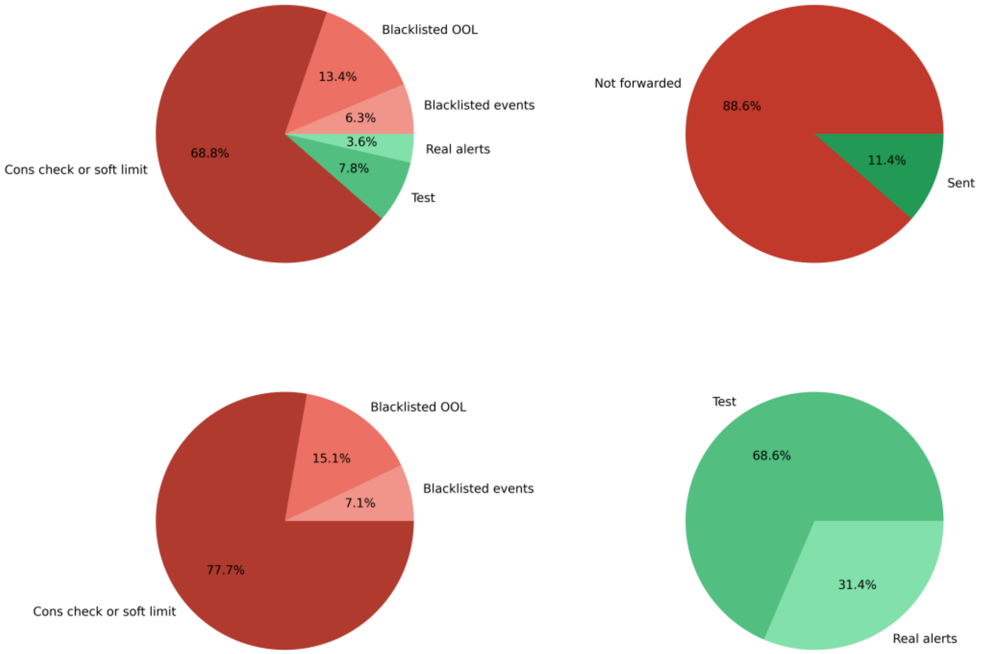

Figure 9 REALS alarms statistics

After the test ended, it was decided to keep the REALS heartbeat notification for the science data server in place because it has a negligible impact on SOE notification frequency but at the same time informs of potential ground segment issues, e.g. server or file transfer system outages. A procedure summarising all (extended) on-call SOE tasks during the test period also proved useful as a training document and dynamic resource of information. Throughout the process of preparing the test, many lesson learned were collected about how the autonomy of the Gaia ground segment could be further improved, and in more general terms how a future ground segment could be designed to facilitate a more straight forward integration of automated monitoring and notification systems. Some of these lessons learned are presented in the next section.

6. Future work

In this section, potential improvements proposed in case of a second a more extended lights-out test will be explained. The intention of the already performed test was mainly to highlight any inconsistency or corner case where the spacecraft supervisor was not informed of an anomaly by any means. With the lessons learnt from the preliminary tests, the following changes would help enable an extended lights-out scenario to be executed with even more confidence.

6.1 ESTRACK

While in the already performed test the scope was limited only to the FCT, in the future it is foreseen to also consider alarms from the ESTRACK Network, thereby informing the S/C supervisor about ground station anomalies that could potentially have an impact during a Gaia support. In addition, all real-time operations communications between the FCT (the Spacon) and ESTRACK are currently performed via a voice-loop which no longer may be possible if the Spacon position is replaced by a supervisor monitoring many more systems. Due to Gaia's specific limitations to re-downlink scientific data it is of specific importance to stop the downlink before any data loss, and currently this is performed via the OBCP and MATIS procedures as explained above. In the future, another layer of protection could be added instructing the ESTRACK operator to drop the uplink carrier down under any condition where the data downlink could be compromised triggering the OBCP to stop science downlink. This is a mission specific case but general operations experience shows that given the breadth of different missions being operated by ESOC there are many such 'mission specific' cases, and so a robust automated system to allow transfer of ground station logs to/from MCS systems could be beneficial.

6.2 MATIS

Due to limitations of the MATIS version used during the lights-out test, some activities were not yet performed by MATIS which could be handled by the automation system in the future. For example, to increase the robustness against overflow of the on-board HKTM stores (sized for ~ 50h), an additional automated HKTM dump half an hour before the end of the pass could be automated to increase robustness and reduce even more the manual tasks to be performed.

Another limitation of the MATIS system prevented the usage of autonomous recoveries more broadly for some of the more usual anomalies encountered. One such useful (and operationally ready) recovery that MATIS already performs via manual operator trigger occurs 6 times per month on average, and so full automation of this (without manual trigger) would bring an additional benefit.

Additionally, increased logging could be implemented to give the supervisor more information about critical situations such as MATIS failures. Even if currently the commanding procedures already have watchdogs implemented monitoring MATIS processes and alerting about any crash at MATIS level, in a wider study an increment of the existing watchdogs could be very useful even for the lower criticality procedures.

6.3 Anomaly Database

The anomaly database represents the entry point for any anomaly recovery as it links any spacecraft or ground issue with the required recovery action (normally pointing to a specific procedure of the FOP). Traditionally the Spacon would use this tool to see how to proceed with any recovery (if to be handled by them) or they would confirm the necessity of escalation of the alarm to the on-call engineer (who also would read the relevant Anomaly DB entry to proceed with the recovery). During the lights-out scenario, as the role of the Spacon is replaced by more automation and notification systems, new MCS and MATIS recoveries would need to be performed by the S/C supervisor. To help finding the recovery needed in the future, a unique ID could be contained in the logs produced via MATIS and REALS to point to a unique entry of the Anomaly DB with specific actions to perform in case of those alerts being raised. Even though the utility of this change is considerable for a test-only scenario, the amount of work required to perform such changes for a longer-term lights-out period is considered a worthwhile investment.

6.4 REALS

As already explained, REALS allows to filter the alerts (using a blacklist to discard specific alerts or a whitelist to specify which alerts to forward). The fact that not all the alerts are forwarded raised the question about why those alerts have the assigned severity in the first place if no immediate action is required. For those alerts (a small subset of the total) a review is planned to assess the validity of the defined severity levels.

A current limitation of REALS in terms of operational reliability is that a heartbeat message to confirm service availability is generated only every 24 hours. This implies that in case of a failure of any of the REALS components, the on-call SOE is not alerted until the next heartbeat is generated, i.e. worst-case 24 hours later. Therefore, a future work item could be to investigate reliable and more immediate service outage notifications without spamming the recipient with more frequent heartbeat messages.

In a longer term, future notification systems for spacecraft operations replacing REALS will allow to not only receive anomaly messages but also access from the same application the commanding history, plots of relevant parameters over desired time periods, and display the necessary recovery procedures. All these features would be of high interest and utility for a spacecraft supervisor as the preliminary assessment of an anomaly could be made from a mobile application where access to some operational documents (e.g. procedures) and operational data (e.g. parameters value over a time range) is accessible with the required security constraints.

6.5 Dashboard

As an improvement in the Dashboard covering non-urgent ground anomalies, a periodic notification summary could be implemented (push) rather than requiring the user to retrieve the information themselves (pull).

7. **People as a prerequisite (and complement) to automation**

Among the prerequisites for automation (including technical and organisational) one is the experience acquired by the teams on the Spacecraft detailed design, the daily in-orbit operations/behaviour, and the effort required to create an "integrated team". In other words, an enhanced automation cannot usually be implemented "from scratch".

"People" are the prime-factor to ensure the success of the day-to-day in-orbit lifetime, and this is particularly key-driver for very complex missions (i.e. on cutting-edge spacecraft and operations) that are not – by consequence – flawless despite any upstream efforts that may lead to a very efficient development phase.

In the case of Gaia mission, the mind-set, approach, and practical implementation are based on some underlying principles:

- An end-to-end and multidisciplinary way of working which breaks the walls and promotes the synergies between the spacecraft designers (system, attitude & orbit control, data handling, communications, thermal behaviour, materials), the spacecraft operators (TM/TC exchanges, routine & emergency procedures, 24/7/365 on-call duty), the ground segment specialists (antennas & data flow) and the Science teams (acting as "end users" of the mission). This allows to create complementary viewpoints from within this "integrated team".
- A continuous enhancement of the know-how throughout the mission duration: daily passes and support during in-orbit operations strengthen the very detailed knowledge of the spacecraft functioning and behaviour (e.g. Gaia has ~35,000 TM parameters acquired by the spacecraft, which clearly requires time and experience to understand).
- The in-house capability to trade-off criteria as incidents occur in order to target a "users oriented" approach, i.e. oriented to answer to the question "what is best for this particular mission's end goals?"
- The technical and operational creativity (i.e. avoidance of the "Not Invented Here" syndrome) to anticipate and to cope with glitches, unexpected trends, off-nominal situations, failures etc., on both hardware and/or software, by generating innovative ideas, new potential solutions, preventive actions and recovery actions.

Such principles are derived on the Gaia mission by the team organisational structure (between ESA, Science users and Airbus Defence and Space as industry) and by the daily way of working. The following is a non-exhaustive list of actions successfully put in place since the beginning of the mission (over for 9 years ago):

- The First Look Report analyses by the Science team contribute to quickly crosslink the spacecraft behaviour with Science performance impact, such that an efficient reactivity between the various domain is achieved.
- The TM daily processing (including some derived parameters to assess the short, medium and long term behaviour), and the Gaia monthly reports produced by the FCT, are very useful to anticipate the behaviour of all the on-board systems (including trends, glitches etc.).
- The Gaia weekly teleconferences with participation from ESOC (Flight Control Team), ESTEC (Project Scientist), ESAC (Science Operations Team), DPAC (scientific users), Airbus Defence and Space (Spacecraft manufacturers) contribute to share inside the Gaia wide community, and distribute current information efficient in order to be able to react quickly if needed.
- The SOC participation to spacecraft ARBs provides in real-time the perspective of the Science impact and thus contributes to well focus the effort where it is relevant for the mission benefit.
- The on-call duty (MOC, Airbus Defence and Space) contributes also to increase the reactivity in case of in-orbit anomaly.

In summary it could be said that beyond the automation capabilities, the team work by "knowledge-workers" (as coined by Peter Drucker in the 1960's) is not just a "nice to have", it is a "must to have".

8. Conclusions

This paper shows a summary of the ground segment automation of Gaia, from an open loop approach to closed loop non-real time supervision where no spacecraft controller is required. Throughout the years of operation, the Gaia mission merged its controllers team with XMM-Newton and Integral missions, having to reduce the manual workload of this role as one single on-shift operator started controlling the three missions in parallel. From this moment onwards, several mechanisms have been placed in both space segment (e.g. OBCPs) and ground segment (e.g. MATIS) to automate the nominal and well-known repetitive contingency operations of the mission. In September 2022, the Gaia FCT carried out a lights-out test where the spacecraft controller role is replaced by automation and alert filtering and forwarding systems: MATIS and REALS respectively.

A lights-out scenario has shown the potential of automated spacecraft operations where only supervision is required. The test conducted during a one-week period validated the notification mechanisms put in place ensuring the correct forwarding of alerts depending on the urgency of the anomaly. Different metrics such as notification triggers or time per action of the on-call SOE have been collected in order to provide an understanding of the reduction in effort achieved following a lights-out approach in contrast to the traditional manual real-time monitoring operations concept followed by most space organizations.

When analysing the logging messages of the automation system, the lack of convention used (e.g. declaring whether an issue is critical or urgent) has been spotted. A better analysis (e.g. grouping messages by severity or urgency or procedure name) can be performed if the system is designed from the beginning following a set of rules (e.g. all error messages are routed to the same notification systems)

Some systems of the Gaia ground segment lacked a direct on-call reporting mechanism since they relied on 24-hour Spacon availability to recover or communicate faults based on criticality/urgency. To move towards a multi-mission team and remote monitoring in the future, it would be advantageous to give monitoring and external notification (e.g. using REALS or any other advanced systems) capabilities as native features to all ground segment systems.

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