

Multi-Mission Spacecraft Operations by a single operator with minimal impact on science return

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Abstract

XMM-Newton and INTEGRAL are ESAs high-energy astronomy missions, both in operation for two decades. Since launch, both spacecraft have gathered a remarkable amount of astronomy data fulfilling the needs of scientific community all over the world. These two space observatories have gained overwhelming interest among X-Ray and Gamma Ray Astronomers, XMM-Newton for example frequently enjoys an over-subscription factor of six. GAIA, a “billion-star mapper” in operation since 2013 accumulates data to prepare a precise 3D space catalogue of our galaxy, mapping stars and other astronomical objects down to the magnitude of 20 M. Because of the enormous interest from the scientific community, it is common sense that ESA would like to keep all three missions in operation for as long as possible. However, it is a difficult task for ESA management to keep all these missions running in parallel owing to budgetary constraints. Therefore, a merged operational concept came into effect for the first time in the 2008, resulting in the merged operations of the XMM-Newton and INTEGRAL Flight Control Teams (FCT). After 10 successful years of joint operations, a decision was taken to merge the spacecraft controller teams of both XMM/INTEGRAL and Gaia. The operational concept of all three missions varies greatly; XMM-Newton and INTEGRAL were built based on three decades old technology. Both space observatories comprise minimum on-board autonomy and have minimal on-board storage capability, resulting in highly labour-intensive operations. It is important to note that there are many constellation missions where a SPACON is controlling numerous satellites at a given time. The main difference from the case under consideration is that these satellite missions are not designed to be operated in parallel. Altering operations concepts of satellite missions in their extended routine operations phase is not an easy task. The objective of this paper is to present the "merged operations concept" relating to the simultaneous operations of these three space observatories by a single Spacecraft controller with a minimum impact on science output.

This paper examines how all levels from mission planning to anomaly handling is achieved without overloading the Spacecraft controller who is on console round the clock. Special emphasis will be given to the methods (such as automation) that have been developed and the Flight Operational Procedures that have been put in place to reduce the workload of the Spacecraft Controller. A merged operations concept enables missions to operate successfully on a reduced budget while accomplishing the mission objectives.

Keywords: (automation, concept, controller, merge, multi-mission, workload)

Acronyms/Abbreviations

ACC	Attitude Control Computer
AOCS	Attitude and Orbit Control System
ED	Event Designator
EPIC	European Photon Imaging Camera
ESAC	European Space Astronomy Centre
ESTRACK	European Space TRACKing
FCT	Flight Control Team
FDIR	Failure Detection Isolation and Recovery
FOP	Flight Operations Procedure
FTS	File Transfer Stack
GAIA	Global Astrometric Interferometer for Astrophysics
GMMS	Global Monitoring and Management System
IBIS	Image on Board the INTEGRAL Satellite
INTEGRAL	INTERNational Gamma Ray Astrophysics Laboratory
IXG	INTEGRAL, XMM, GAIA
JEMX	Joint European X-ray Monitor
LCL	Latching Current Limiter
LELA	Live Ed Look Analysis
LMS	Lightweight Monitoring System
MCS	Mission Control System
MOIS	Manufacturing and Operations Information System
MATIS	Mission Automation System
OBCP	On-board Control Procedure
OBDH	On-Board Data Handling
OEM	On-board Event Monitoring
OM	Optical Monitor
PLM	PayLoad Module
SDLP	Science DownLink Protection
SOC	Science Operations Centre
SPACON	SPAcecraft CONtroller
SVM	SerVice Module
ToO	Target of Opportunity
XMM	X-ray Multi-Mirror

1. Introduction

ESAs XMM–Newton and INTEGRAL missions first commenced their merged operations in 2008. After a decade of success, it was decided to merge further the Spacecraft controller team with that of GAIA. Unlike the previous occasion, it was a challenging task to further merge with a mission with an entirely different operational concept. All three spacecraft were never designed to be operated in parallel, presenting many challenges for the flight control teams. This paper examines how these challenges were overcome in April 2018 without overloading the SPACON with minimum impact for science data production.

1.1 XMM–Newton

XMM–Newton, ESAs X–ray observatory was launched in December 1999 under its Horizon 2000 program^[1], being the largest science satellite ever built in Europe at the time. The objective of the mission is to solve the unknown mysteries of some of the most violent space phenomena with high accuracy spectroscopy measurements and image detection capability. The mission was originally planned for 2 years with an extension of further 8 years; nevertheless, it steps into its third decade of operations without major impact neither to its payload nor to the service module. A seven-meter-long telescope tube housing consists of three telescopes containing 170 Wafer thin cylindrical mirrors. The focal plane assembly is located at the other extremity of the telescope tube housing three EPIC cameras and two Reflecting Grating Spectrometers (RGS), with Optical Monitor (OM) attached to the service module. A highly elliptical 48-hour orbit enables the spacecraft for long uninterrupted observations beyond the Van Allen radiation belt. Due to minimal availability of on-board storage on XMM–Newton, it is necessary to downlink data in real time.

Therefore, it is needed to establish continuous and reliable ground coverage throughout the orbit. The XMM–Newton MOC, where the spacecraft is controlled, is located at ESA/ESOC Darmstadt, Germany with the SOC (Science Operations Centre), located at ESA/ESAC Villafranca, Spain. Ground station coverage is provided by ESA/ESTRACK ground station at Kourou, French Guiana, SSC ground stations at Yatharagga, Australia and at Santiago, Chile.

1.2 INTEGRAL

INTEGRAL is an Astrophysics laboratory that was launched in October 2002. Although it can be described as a gamma ray telescope, INTEGRAL's suite of instruments are capable of detecting and observing a broad range of the electromagnetic spectrum, from optical to soft gamma-rays. Science data obtained from INTEGRAL helps understand the most violent and exotic objects in the universe and its chemical composition. Initially planned for 2 years with an extension up to 5 years; however, it is now entering its 21st year in orbit, owing to its excellence in scientific return. INTEGRAL is expected to re-enter the earth's atmosphere in 2029^[2]. as a result of orbit altering manoeuvres performed in 2015 in order to comply with ESA space debris policy. The Spacecraft operates on high elliptical orbit with the northern inclination of 79 degrees with an orbit of ca. 63 hours (2.5 days). Similar to XMM, the scientific observations are carried out beyond the radiation belt region where the spacecraft spends most of its orbit. Its service module is for the most part, a copy of XMMs, but with small improvements in the AOCS and OBDH subsystems. INTEGRAL's payload consists of an imager (IBIS), Spectrometer (SPI), two X-ray instruments (JEMX), an optical monitor (OMC) and a radiation monitor (IREM) which observe simultaneously during the observation window. ESA/ESTRACK ground station at Kiruna, Sweden tracks INTEGRAL except for a short period of its orbit during the perigee passage as prime ground station. However, external ground stations at Villafranca, Maspalomas in Spain and Weilheim in Germany are used occasionally in the event of unavailability of the prime ground station at Kiruna.

1.3 GAIA

GAIA is ESA's astrometric observatory. Launched in 2013 and originally planned to operate for 5 years it is currently extended until 2023. The successor to HIPPARCOS (operated from 1989 to 1993), GAIA operates in Quasi-periodic Lissajous orbit at Lagrange point (L2) with an orbital period of 180 days – chosen due to its gravitationally and thermally stable environment. The primary objective of the GAIA mission is to create a high precision 3-dimensional map of our Milky Way Galaxy to enhance our knowledge on our Galaxy's composition, structure and evolution. In order to achieve the mission objective GAIA intends to cover the celestial sphere approximately 80 times. This will enable astrometric, photometric and spectrometric measurements over a billion stars down to magnitude of 20M. GAIA's payload module consists of an astrometric instrument (ASTRO), photometric instrument (PB/RP) and radial velocity spectrometer (RVS). GAIA is tracked by ESA/ESTRACK 35-meter-deep space ground station network at Cebreros (Spain), Malargue (Argentina) and New Norcia (Australia).



Figure #01 XMM–Newton, INTEGRAL & GAIA Space Observatories

2. Merged Operations Background

ESA hierarchy decided to reduce the operating costs of its missions due to the budgetary constraints. A feasibility study was conducted about reducing the costs and as a result, merged operational concept came into effect in the year

2008, resulting in the merger of the XMM–Newton and INTEGRAL Flight Control Teams. After a decade of successful operations, it was decided to merge the spacecraft controller service with GAIA. Owing to the major differences in operating concepts, it was evident from the feasibility study that the merged operations of three astrophysical missions XMM–Newton, INTEGRAL and GAIA would be more complex, unlike when it was first performed 10 years ago. XMM–Newton and INTEGRAL are legacy spacecraft containing very limited on-board storage. Therefore, it is essential to downlink the science data on real time basis. In contrast, GAIA, a more modern spacecraft has substantial on-board data storage capability and more sophisticated FDIR. In terms of workload the legacy spacecraft require 24/7 manual operations for planned and unplanned events. Therefore, the joint operations of three missions would prove to be highly labour intensive.

In order to operate XMM–Newton, INTEGRAL and GAIA in parallel, it is identified that not only the workload but also the knowledge and the SPACON training needed to be reduced. It is further identified that a failure case scenario that does not require immediate attention of the operator can be recovered by a dedicated member of the flight control team (On Call Engineer/Analyst), or by automation. Some of the routine tasks were either automated or de-scoped from the SPACON. The reduced instrument knowledge means a reduced training period for new operators. The training period is narrowed down to six months (reduced from ten) for all three spacecrafts, without compromising safety.

New and refined Flight Operations Procedures (FOP) have been created and the anomaly database amended to suit the merged operations. The relaxation of certain operations has been implemented to reduce the workload. The XMM–Newton and INTEGRAL FCTs further identified potential areas to implement via automation[†] and improve the existing automated tasks.^[3] GAIA has already implemented stepwise automation via MATIS and is expected to automate more tasks in future.^[4]

[†] INTEGRAL automation consists of only MOIS, whereas XMM automation uses two separate applications: Auto-commanding & MOIS. For simplicity, where XMM automation is mentioned, this includes both Auto-commanding & MOIS.

2.1 Mission planning process in merged operations

Individual mission planning for XMM–Newton, INTEGRAL and GAIA is co-ordinated at planning level such that no conflicts between missions are created. A conflict is known with the aid of a Windows based software tool called “De-Conflicting Tool” which interfaces with mission planning product data of all three missions. The “De-Conflicting Tool” flags up conflicts between missions based on set criteria. A conflict in merged operations is classified as when a critical activity of XMM–Newton and/or INTEGRAL falls into the GAIA commanding activity window. Under the normal circumstances, the conflict will be solved by shifting the GAIA commanding activity inside the pass window.

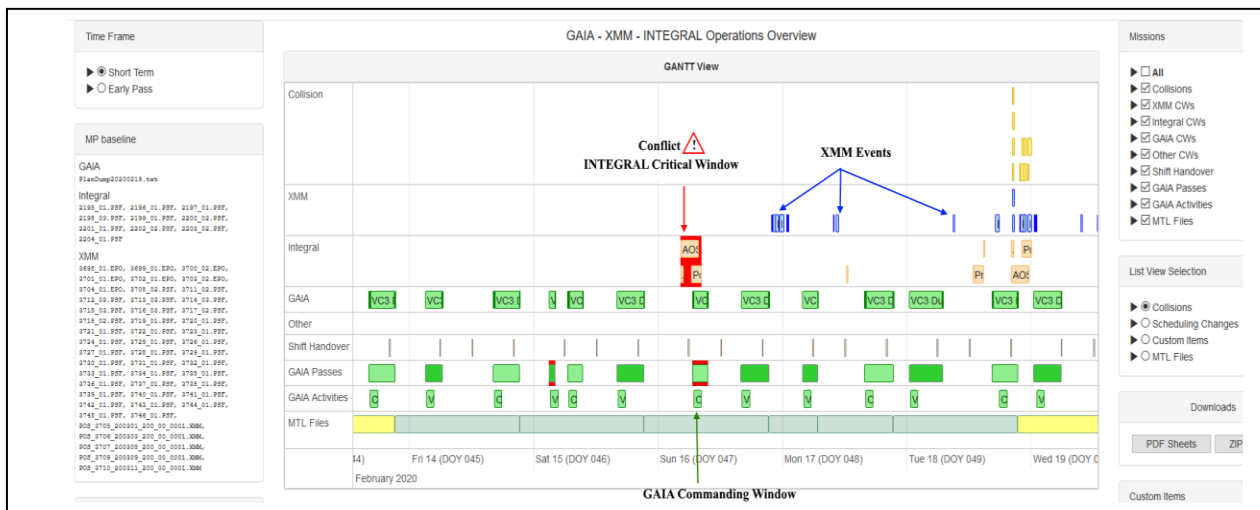


Figure #02 Short Term View of De-Conflicting Tool

3. IXG Automation

3.1 Current state of IXG Automation

A summary of the currently implemented automation procedures for each mission is given below. To present the importance of each procedure, they have been categorised into their approximate execution duration. Automated reactions to critical anomalies have also been included, however automated reactions in terms of on-board FDIR have been excluded.

	XMM	INTEGRAL	Gaia
Platform	AOCS unit switch-off recovery	Loss of attitude recovery	Uplink mission timeline *
	Sun sensor window reset	AOCS daily maintenance	Check and fill science gaps
	Send test command	Report/Reset onboard monitoring	Dump/re-enable Packet Store 1 *
	Open/Close groundstation links		Science downlink protection
	Timetagged command(s) check		Dump onboard house-keeping
Payload	OM to safe (unsafe conditions)	JEMX Front-End cycle *	
	OM switch-off (OM anomaly)	IBIS VETO switch-off *	
	EPIC instruments switch-off (electronics anomaly)	IBIS VETO cycle *	
	Instruments to Idle (High radiation)		
	Spectrometer to Safe (CCD anomaly)		
	Instrument timeline rejoin *		
	Instruments to safe *		
	OM software reload *		
	Eclipse monitoring		
	Radiation monitor reset		
	Post perigee radiation check		
	EPIC instruments Watchdog reset		
			Legend
		Semi-automated procedure *	
		Short duration	
		Moderate duration	
		Long duration	
		Safety critical anomaly	

Table #01 Currently implemented automation †

In the absence of sophisticated FDIR, the importance of automation for XMM and INTEGRAL (particularly XMM) cannot be understated. For both spacecraft, automation plays an integral part in keeping the spacecraft safe and is not merely a tool of convenience for the SPACON. This is apparent from the amount of recovery procedures concerning safety critical anomalies currently implemented. These critical recovery procedures are not a complete guarantee of spacecraft safety as these procedures are still ground based, a reliable space-link is required throughout the execution of the procedure, and any interruption to this could leave the spacecraft in an unknown and/or dangerous state.

Regarding GAIA, the amount of on-board FDIR and safety compared to XMM and INTEGRAL is substantial. Again, this is not a guarantee of complete anomaly mitigation, but most anomalies are handled by on-board software. Moreover, GAIA also has the capability to implement autonomous reactions on-board, further increasing the spacecraft safety and adaptability. It should be noted that INTEGRAL also has a basic on-board capability to react to anomalous situations, but this is considered rudimental by modern standards.

† Some previously used procedures have been discontinued due to a change in routine operations, these have not been included.

3.2 Impact of Automation

In recent years all three missions have undergone dramatic improvements to their respective ground-based automation systems, both in capability and in the number of procedures available. Automation is perhaps the most effective way of mitigating the risk of overloading the operator, while still maintaining spacecraft performance and safety. A small investigation into the impact of each respective automation system has been carried out. As all three

missions have several published papers regarding the implementation and/or operation of their automation systems, these details have not been included. [3]

Quantifying the impact of automation presents difficulties due to the very nature of the operator's role. Although a SPACON may have automated tools to conduct nominal activities and to recover from anomalies, he or she must be constantly aware of the status/activity of all spacecraft, mission control systems, and be vigilant to any anomalies. As such, it is inappropriate to define the workload of the SPACON purely based on the number of activities that carried out. Furthermore, with respect to procedures (automated or otherwise) there is a large variation in both complexity and execution duration, with some procedures requiring multiple days to execute.

Following the challenges described above, two approaches have been considered in order to give an overview how the automation for each spacecraft has had an impact in day-to-day operations. The first approach examining the quantity of telecommands sent by the operator/automation, and the second, examining procedures executed by the SPACON as recorded by the operation logs.

3.3 Telecommanding analysis

For the purpose of processing command statistics, a telecommand from an automated system has been defined as follows; XMM – any command released either from MOIS or “Autocommanding”, INTEGRAL – any command released from MOIS and GAIA – any command released by MATIS, including “throw events” used to open/close ground station links. As this papers focus is primarily on the operator's role, any commands produced as part of an on-board FDIR response have been removed, as have any command resulting from on-board processing of File Transfer Stacks (FTS). Furthermore, it is important to note that the routine commanding for both XMM and INTEGRAL is ground based, utilising an automatic mission timeline dispatcher – an “Autostack”. The use of such a system was always intended for routine operations since the mission inception. Therefore, commands dispatched by the Autostack are not included in the statistics for automated commanding but do contribute to the total commands issued.

As of the time of writing, few fully automated procedures exist. Instead, a method of “semi-automated” operation is adopted, whereby an automated procedure first seeks the approval of the operator, or whereby the operator launches a procedure as part of a recovery reaction. Again, as this paper is more concerned with the operator's role rather than the amount of telecommands executed, the telecommands issued by the SPACON or automated system have been represented as a percentage of total commands issued. A moving average over 50 days has been included to mitigate the effect of recoveries due to serious recoveries and special operations.

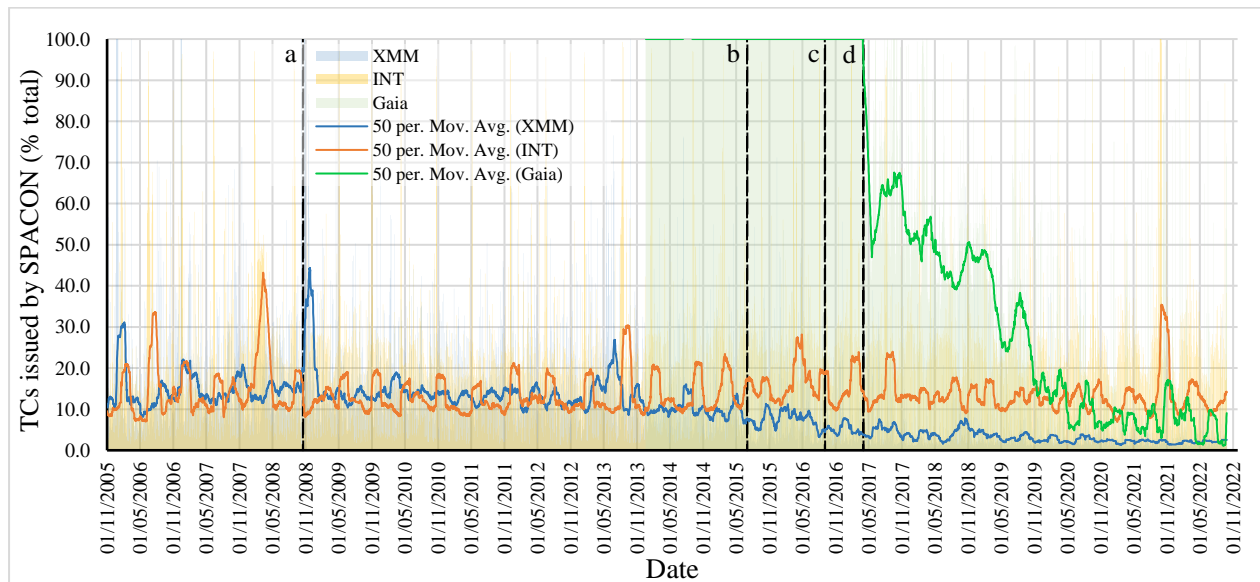


Figure #03 Percentage of manual commands issued

[a] 2008-10; Introduction of XMM Autocommanding, [b] 2015-07; Introduction of XMM MOIS, [c] 2016-09; Introduction of INTEGRAL MOIS, [d] 2017-04 Introduction of GAIA MATIS

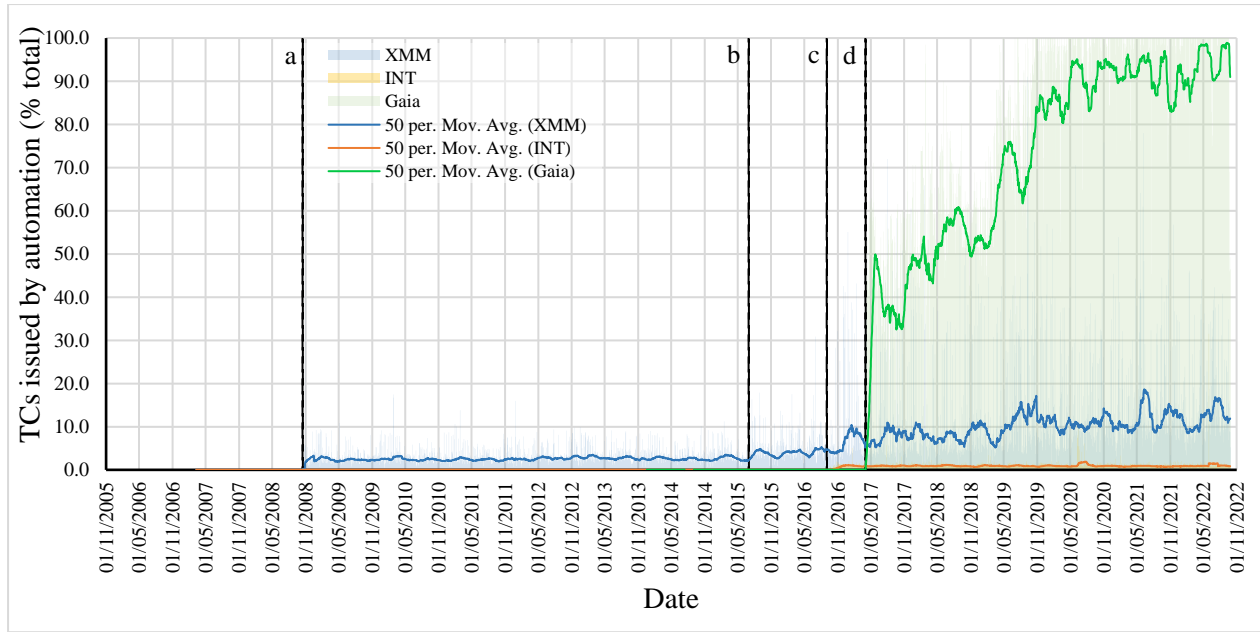


Figure #04 Percentage of automated commands issued

[a] 2008-10; Introduction of XMM Autocommanding, [b] 2015-07; Introduction of XMM MOIS, [c] 2016-09; Introduction of INTEGRAL MOIS, [d] 2017-04 Introduction of GAIA MATIS

3.4 Logged procedures

To complement the previous approach, the operator logs for each mission have been processed, filtering for all procedures carried out and logged by the SPACON. It is important to note that GAIA implements a top-level SPACON shift procedure containing many sub-steps, some of which refer to a separate procedure. To identify and separate each sub-step would be a difficult and cumbersome process as the consistency of the operator logs varies. As such, these steps and sub-steps have been included as separate entries. Similarly, to figures 03 & 04, a moving average over 50 days is included.

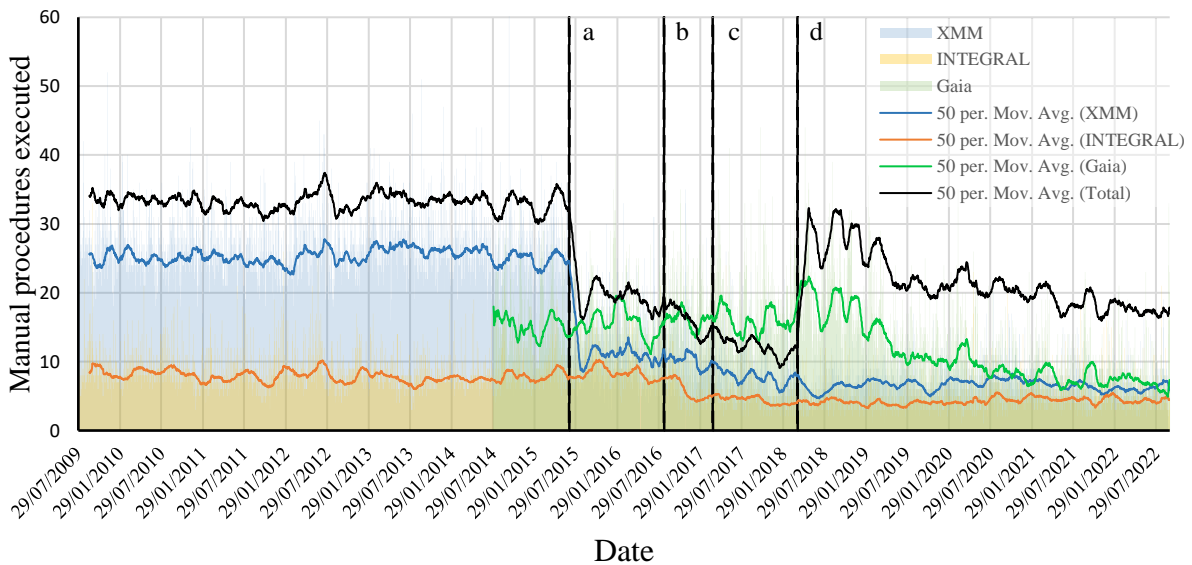


Figure #05 Total SPACON procedures executed

[a] 2015-07; Introduction of XMM MOIS, [b] 2016-09; Introduction of INTEGRAL MOIS, [c] 2017-04 Introduction of GAIA MATIS, [d] 2018-04 IXG Merge

All three missions show a decline in the manual procedures executed by the SPACON. The pronounced fall in the XMM procedures can be attributed to the automation of procedure typically executed hourly. The active role of the SPACON in routine operations for INTEGRAL was already much less than that of XMM; therefore, a less noticeable effect of automation is seen. The introduction of MATIS does not have an immediate effect on GAIA activities due to the gradual automation of procedures. Furthermore, the GAIA SPACON activities have a greater focus on ancillary activities such as MCS/automation management and data quality checking. As these activities are of low priority in terms of automation, the number of SPACON activities on paper remains moderate compared to XMM and INTEGRAL.

4. Review of Flight Operational Procedures

A major review of Flight Operations Procedures (FOP) took place to cater for the new operational concept. A Global Monitoring and Management System was utilised, several new MOIS automation procedures were developed and several new SPACON procedures were created for XMM–Newton instrument operations. In total 90 new and refined procedures were validated, and a total of 500 anomaly database entries were amended. A new XMM–Newton instrument only anomaly database was implemented, and several telemetry parameter limits were adjusted to avoid superfluous out of limit (OOL) generation. Similarly, the INTEGRAL anomaly database was re-structured, and colour coded. Procedural changes were adapted to ToO operations and Re-plan procedures which reduces significant number of manual operations on INTEGRAL. In comparison to the other two missions only minor changes were implemented on GAIA, including a revised pass procedure and a new anomaly database to reflect the reaction for “Super Alarms” and recovery procedures for automation failures.

4.1 Impact on Target of Opportunity handling

Targets of Opportunity (ToO) are unpredicted, unplanned astronomy events that require urgent observation. Such events are normally triggered externally owing to the detection of a new Supernova, Gamma Ray bursts, or other astronomical targets of interest. These events are needed to be observed as they are transient astronomical phenomena of great interest within the scientific community. The legacy spacecraft such as XMM–Newton and INTEGRAL are among the focal point of the astronomers to execute ToO observations. However, to execute such observation requires great effort from the Flight Control Team (FCT) and the Science Operations Centre (SOC) within a short period of time. It can be very challenging experience especially under merged operations where one SPACON controls multiple spacecraft.

INTEGRAL ToO handling efficiency has greatly improved as a result of the merged operations where the workload of SPACON has immensely reduced. The time-consuming strenuous AOCS activities and manoeuvres needed to reach the ToO attitude are no longer required to perform manually. Such activities have already been incorporated into the timeline at planning level. Due to the simplified approach, it is just a matter of loading the ToO timeline at suitable diverging point and execute the timeline operations. In case of a Fast ToO it may still require such manual activities as before the merger due to the time constrains.

The XMM–Newton ToO handling approach has also improved. The workload is slightly reduced compared to pre-merged operations. Similar to INTEGRAL, ToOs are implemented at planning level.

4.2 GMMS functionality in multi-mission operations

XMM–Newton, INTEGRAL and GAIA are operated round the clock by a single SPACON. Due to the intensity of the workload during the commanding activities on GAIA, a dedicated commanding window was implemented to allow the SPACON to concentrate on GAIA. A two hour commanding window was defined where the SPACON only be alerted by safety critical alarms relevant to XMM–Newton and INTEGRAL. These special types of alarms are named as a “Super Alarm” which are a subset of MCS alarms plus some additional critical alarms. This monitoring functionality is implemented in a Global Monitoring and Management System^[5](GMMS). Real-time data from all three missions is fed into GMMS. In order to filter out non-critical alarms from GMMS a blacklist has been defined. The blacklist contains all non-critical nature MCS alarms that do not require immediate attention of the operator. The blacklist will be ignored by GMMS during the commanding window. However, GAIA implements a whitelist that contains five “Super Alarms” that are active all the time. Before the commencement of GAIA commanding window, the MCS alarms of XMM–Newton and INTEGRAL missions will be disabled and GMMS monitoring will be

activated. Only the “Super Alarms” trigger has precedence over GAIA commanding activities during this period. After the elapse of the commanding window, the MCS alarms will be re-enabled and GMMS Monitoring will be deactivated for XMM–Newton and INTEGRAL missions.

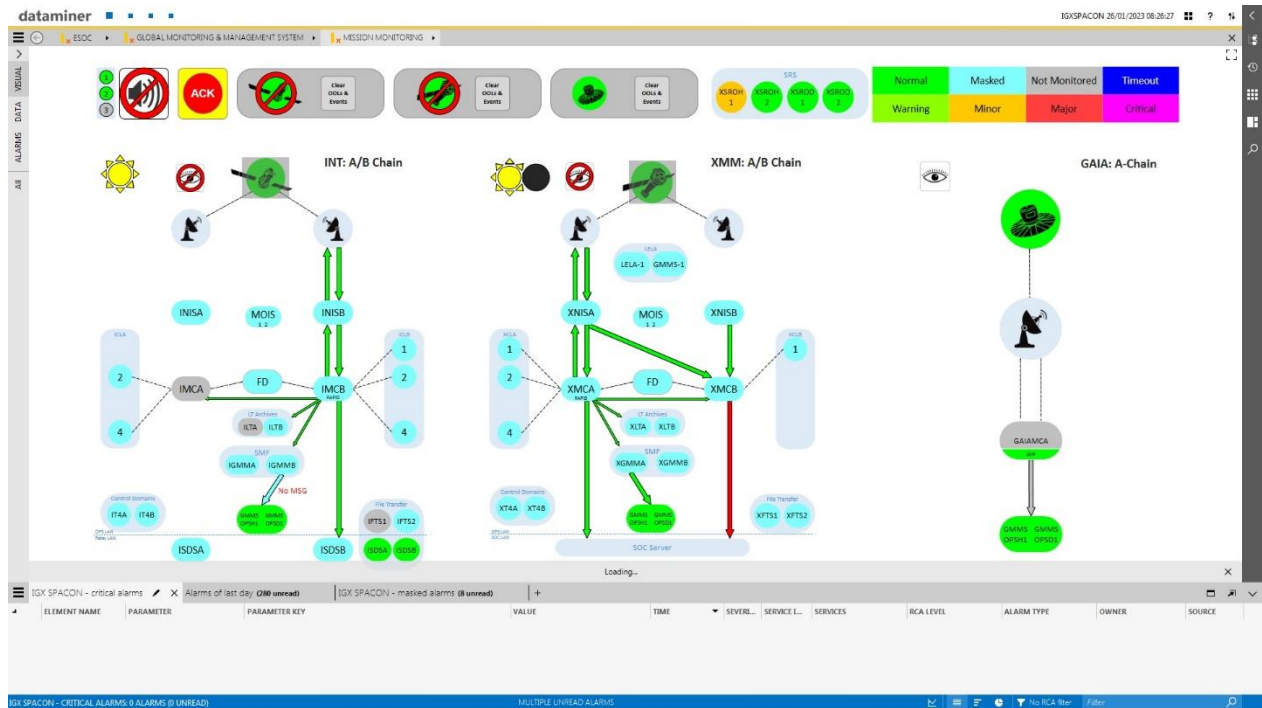


Figure #06 Global Monitoring and Management System (GMMS) Overview

4.3 Nominal operations strategy

Routine operations are de-conflicted at the mission planning level and no overlapping of critical operations is foreseen. Nevertheless, the effect of multitasking won't diminish due to the nature of operations. The Combined Event Analyser Tool is a versatile software tool, runs on a windows-based machine. This visualisation tool unfolds real time operations in a graphical representation consisting planned upcoming activities of all three missions. This tool works not only as an event visualizer but also has the capability to add special operational reminders, print events on shift basis, print shift handover sheets and can be used as a recovery aide.

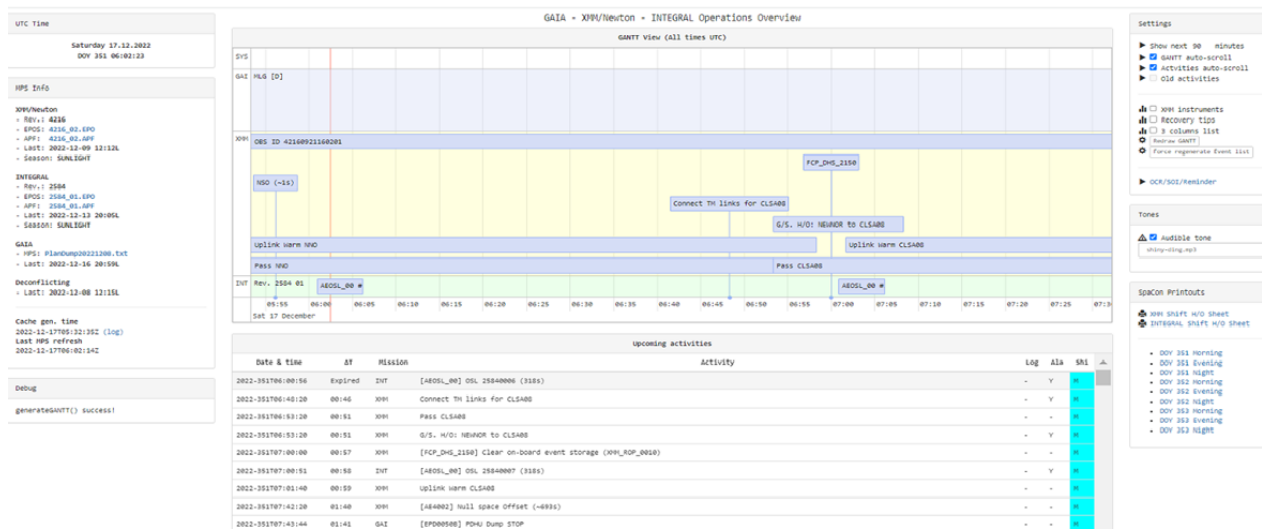


Figure #07 Event Display of Combined Event Analyser Tool

4.4 Contingency operations

Contingency scenarios are well defined in a dedicated procedure, considered as an entry point to a contingency situation in multi-mission spacecraft operations. This procedure guides the SPACON to identify which mission has priority considering various factors and prompt to the relevant mission Flight Operations Procedure (FOP). This method allows the SPACON to focus purely on one mission contingency at a time. XMM–Newton and INTEGRAL payload recoveries have been de-scoped from the operator to a greater extent. However, the anomalous instrument will be put into a safe state in the absence of an automated procedure. The affected instrument(s) will then be recovered by automation, or the on-call support Engineer owing to the severity of the anomaly. GAIA on the other hand handles most spacecraft anomalies autonomously via on-board software. However, an alarm will be raised to alert the operator, owing to the severity of the problem.

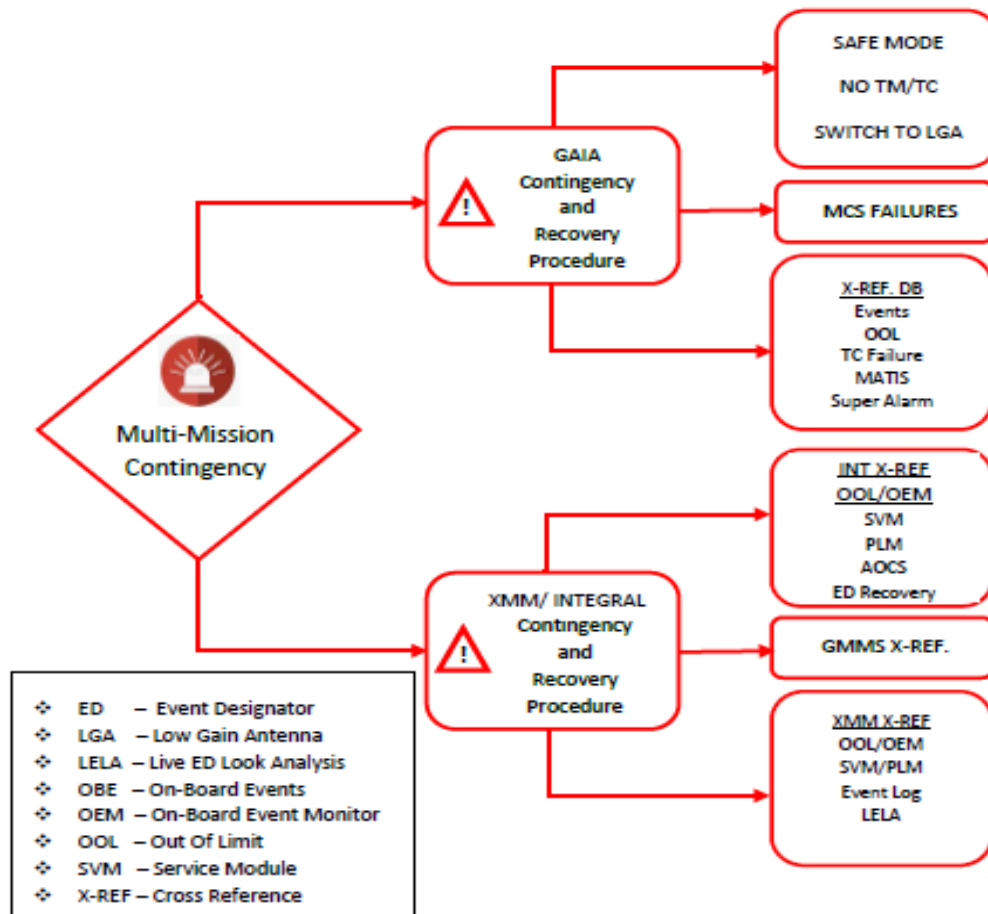


Figure #08 Contingency operations flow

5. Impact on Science Return

As a consequence of merged operations, some instrument recovery responsibility has been taken from the SPACON to reduce the workload. This enables the SPACON training period to reduce by at least 3 months. Most instrument anomalies are well documented and point to a subsequent action in line with the FOP. However, a certain level of competency is required to execute such contingency procedures due to the complexity of the instruments. The required competency won't be achieved with curtailed training. Therefore, the operator is only allowed to put anomalous instrument into a safe configuration until it is recovered and resumes timeline operations by the automation or the on-

call support engineer. This process incurs science data loss that can be significant impact depending on the affected instrument and the criticality of the observation.

Unlike GAIA both XMM and INTEGRAL instruments are vulnerable to high radiation environment as they cross the Van Allen radiation belts during the perigee passage. The radiation belt entry and exit times are difficult to predict precisely as the radiation models yields certain margin of error which affects observations^[6]. Safety mechanisms are in place to prevent the instruments being exposed to high radiation. Nevertheless, the re-join of the instruments into science observations following an interruption will be delayed as SPACONs are not trained to execute these procedures manually.

Other types of recurrent instrument anomalies are memory corruptions, TM (Telemetry) corruptions, auto-resets and LCL trips of electronic devices caused by solar events or Galactic Cosmic Rays. Ground segment failures such as ground stations failure, communication lines congestion and MCS related failures could lead to instrument misconfiguration.

5.1 XMM

Considering the main reasons for scientific interruptions on XMM, two of the main factors leading to a loss of science return have been attributed to high radiation and ground station outages. The former can trigger an automatic ground response to safe the instruments, and the later can cause interruptions into planned observations. An initial consequence of the XMM instruments being largely de-scoped from the SPACON, is that the instruments would only be recovered during working hours, or by the instrument on-call service. As a result, whole observations would be lost for one or more instruments. This loss on science was sometimes substantial during weekends and public holidays where recovery staff were unavailable. This loss has since been reduced due to new automated instrument re-join procedures and a part-time Instrument on-call service during an intermediate development phase.

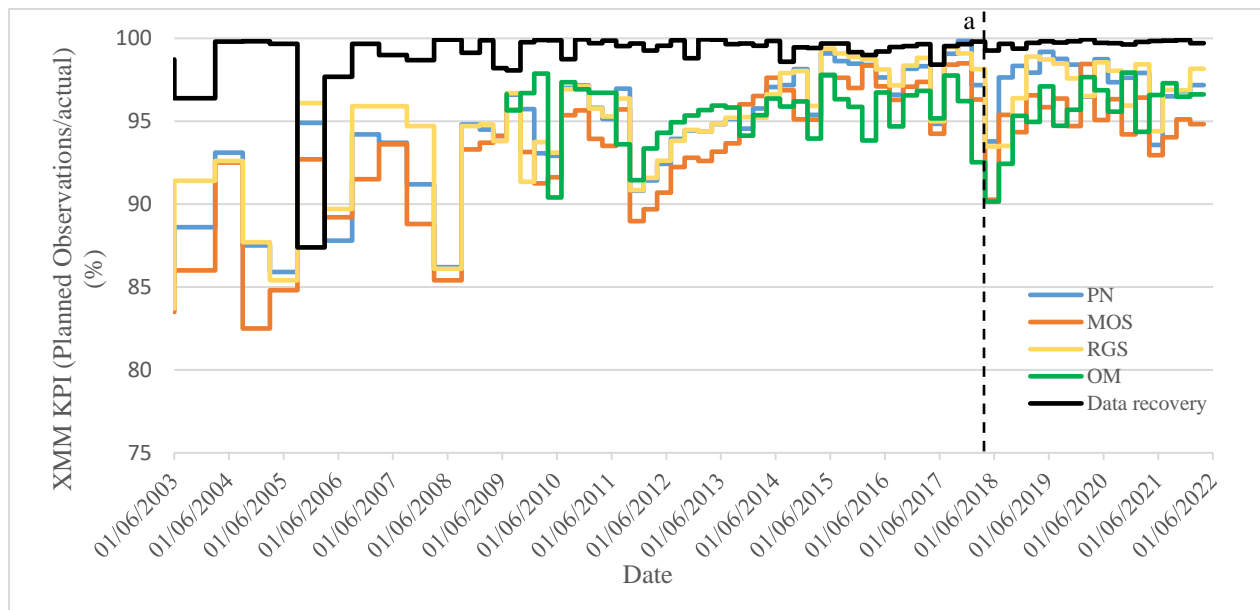


Figure #09 XMM Key Performance Indicators
[a] 2018-04 XM/INT GAIA merge

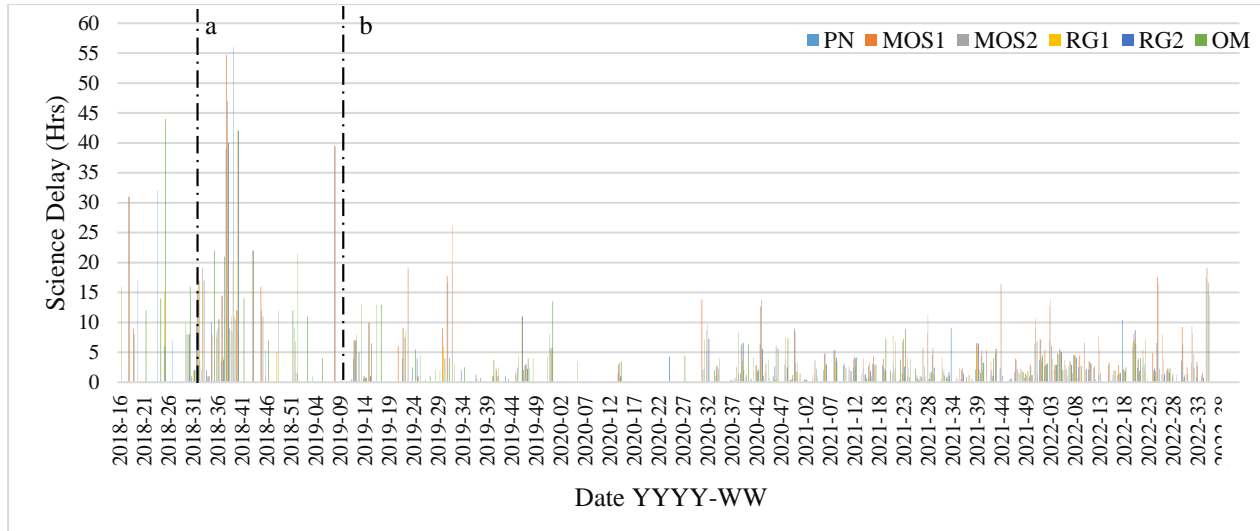


Figure #10 XMM Instrument delay
 [a] 2018-31 Introduction of instrument on-call, [b] 2019-09 Introduction of automated instrument recoveries

The impact of the merge on XMM is evident in Figures 09 & 10 but remains short lived. The KPI (ratio of planned to actual observation time) is briefly impacted but soon returns to pre-merged levels – remaining well above the required 75% threshold. The impact to the Data Recovery (Scheduled ground station coverage vs availability) is scarcely affected at all, remaining above the 95% performance requirement.

High radiation remains the biggest factor in terms of operational disruptions. As previously stated, the initial post-merge the strategy for dealing with this would be to set the instrument into an idle state, awaiting recovery during working hours. However, during the development phase of automated recovery procedures an interim on-call service was provided on a part-time basis to recover the instruments during the observations of high scientific value.

Though, the unpredictable nature of spacecraft operations cannot be avoided, the impact can be mitigated. Figure 10 shows that, despite the apparent increase in disruptions since the introduction of automated recovery procedures, the magnitude of such incidents is now mostly reduced, with many events now being below 10 hours and very few over 15. Most particularly disruptive events are a result of particularly high radiation events preventing the safe (including events on 2021-44 & 2022-23), and/or serious spacecraft anomalies (such as on 2022-33 caused by a Data Management Unit reset).

5.2 INTEGRAL

INTEGRAL seldom suffers from the issues that XMM faces in terms of scientific loss. The prime ground station used is more reliable and the observation windows for starts at much later in the revolution than XMM, far from the radiation belts. Furthermore, the scope for SPACONs in terms of INTEGRAL’s instruments is not as affected as that on XMM, with many instrument anomalies and re-join procedures remaining under the responsibility of the SPACON.

With the above in mind, and due to the fewer operational changes for INTEGRAL for the merge, the scientific impact for INTEGRAL as a result of the IXG merge can be considered negligible

5.3 GAIA

Although GAIA remains the highest priority, the situational awareness for the SPACON must still be divided between the three. As such, reaction times to anomalies on GAIA can be affected. Most interruptions and data losses are a result of ground station anomalies or bad weather, both of which can result in lost science packets. GAIA mitigates this to some extent by aborting the science downlink when no uplink is detected from ground via an On-Board Control Procedure (OBCP). This is useful in the cases where a ground station anomaly can cause a loss of spacecraft tracking. However, this OBCP has limitations, namely in the case of bad weather, where the downlink signal is far more

attenuated than the uplink. This results in a niche situation where the spacecraft still detects a healthy uplink signal and continues to downlink the science data, despite a degraded signal being received at the ground station.

Previously, the reaction from the SPACON would be to request the uplink to be aborted or halt the science downlink via telecommand. Due to the volume of science produced, any delay in this action would mean hundreds if not thousands of lost packets. Consequently, an automated Science-Downlink-Protection (SDLP) procedure was developed and implemented via MATIS.

The SDLP procedure monitors real time ground station data fed to the MCS via LMS (Lightweight Monitoring System), from this MATIS can monitor weather information and Es/No levels from the spacecraft and react accordingly to signal any degradation. MATIS is constantly monitoring the spacecraft signal level and will abort the science downlink via telecommand if the mean Es/No falls below a threshold. The advantages of this procedure are twofold; it overcomes the limitation of the OBCP and is faster than manual reactions. The procedure was implemented in May 2020 and the effect on the loss of data is shown in Figure 11.

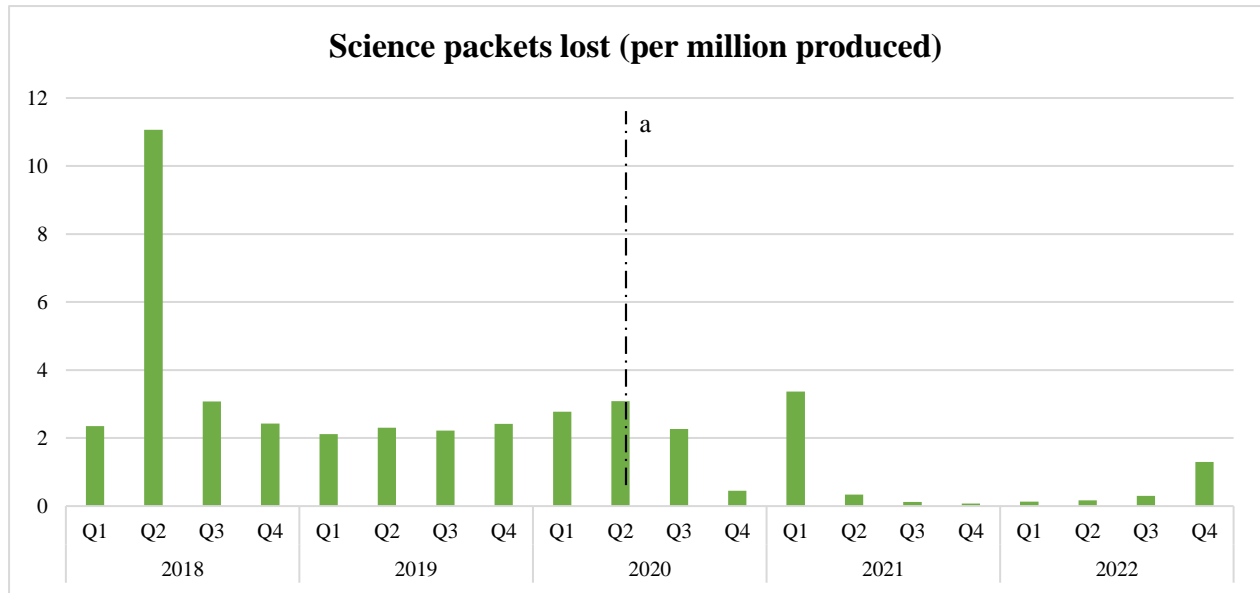


Figure #11 GAIA Packet losses^[7]
[a] 2020-05 Implementation of SDLP procedure

It is important to note that adverse weather conditions are unpredictable and remain one of the most common disruptors to a GAIA contact. The unpredictable nature is evident in 2018 Q2 where several consecutive days of bad weather caused large losses in scientific data. The fact this event happened during the date of the IXG merge is an unfortunate coincidence and cannot be linked to the increased workload of the spacecraft operator.

However, with the exception of a few isolated incidents the SDLP has been tremendously successful in mitigating the data losses during periods of bad weather. The loss of science data over the period 2021-2022 has been reduced by over 66% when compared to the previous period 2019-2020.

6. Discussion

6.1 Impact of automation

The findings from section 3 illustrate the importance of automation when considering merging spacecraft operations. Though there have been substantial improvements in XMM and INTEGRAL automation, the importance of a human operator (SPACON or otherwise) cannot be understated. To fully automate two missions which were never designed to be so, would require immense effort and manpower. Furthermore, any automation would require near

continuous ground coverage, demanding a highly reliable space link. Although many safety-based procedures have now been automated (particularly for XMM), the list of anomalies for both XMM and INTEGRAL which still require an urgent first response remains extensive.

6.2 Data limitations

Although the methods discussed within section 3 provide a clear picture of that automation has had on the operator's role, it is not without its limitations. Many changes to the way each mission has operated over the past years has presented challenges in finding consistent and concise processing methods, resulting in a great deal of both manual and automatic processing, which of course is cumbersome and more prone to error.

Concerning the analysis of telecommanding, it is not possible to identify the source of manual commanding, operator or otherwise. However, as the Spacecraft controller is the prime communicator with the satellite, it can be assumed that most manual commands were sent by the SPACON, with exception of a few critical operations (XMM Tank replenishment, high-level recoveries, SPI annealing etc.).

Regarding the processing of the digital mission log, a great deal of effort was given to ensuring the data quality was of an adequate standard. Nonetheless, the data quality from the extracted logs relies solely on the earnestness of the SPACON and their respective effort to create concise and clear mission logs. Although the reduction in manual procedures is shown, this does not necessarily represent the full picture. Automation can be a great tool to reduce repetitive activities, but with respect to bigger anomalies, there is a need for a more patient and careful response. Due to this, spacecraft recoveries can take anywhere from minutes to days, the data in Figure 05 does not present this information.

With the above in mind, the availability of such a large quantity of data allows for some of these errors to be mitigated. It can be assumed that any errors present in data are consistent and therefore the trends presented herein remain valid.

7. Future work

EUCLID, an infrared space telescope will be merging into the existing astronomy missions (XMM, INTEGRAL and GAIA), which is scheduled to be launched in 2023. The author is keen to carry out a systematic review of challenges, limitations and difficulties of multiple spacecraft operations in his future study efforts.

8. Conclusion

The effect on scientific return for all three missions has been kept minimal and it is conceivable that despite the merge, XMM, INTEGRAL and GAIA will enjoy further improvements in scientific return in the years to come. The effect on INTEGRAL has been kept minimal with the SPACON still having an active role in instrument recoveries. With XMM, automation of the instrument re-join procedures has been a resounding success and GAIA remains unaffected. The tools and procedures put in place to facilitate the merge reduce the risk of all three-spacecraft requiring attention at the same time, allowing the SPACON to completely focus on the recovery at hand.

From the perspective of a spacecraft controller, the current scope and workload as a result of automation, reviewed procedures and operational tools has been kept manageable despite the addition of an entirely new spacecraft. The new operational concept for XMM, INTEGRAL and GAIA has allowed all three missions fly simultaneously with a minimal effect on the science product and with no compromise to spacecraft safety. By all measurable standards, the INTEGRAL, XMM and GAIA merge has been a success and serves as a model for future mission integrations.

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