Mission Automation and Autonomy: In-flight Experience Derived From More Than 8 years Of Science Operations In Orbit About Mars

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For long-lived missions such as Mars Express, operating at considerable distances from Earth, the paradigms of autonomy and automation are especially pertinent. The concepts are quite distinct, but are often confused. Moreover, there appears to be little uniformity of approach regarding the implementation or application of each one to spacecraft operations. In this paper, we seek to compare/contrast these paradigms, based in part on experience gained with Mars Express, and review of automation methodologies implemented by other ESA science missions. For mission autonomy, we identify the reasons behind attempts to extend the Mars Express operations concept far beyond that originally envisaged in the design phase or at launch, and consider the mechanisms by which this evolution was achieved. For mission automation, we review the ground segment elements developed to support the Mars Express mission, and compare/contrast automation methodologies (specifically the mission planning system and automation in the control room) for this and other operating ESA missions. We identify the relative merits of, and limitations in, these automation methodologies, and justify the direction taken by Mars Express based on specific mission needs. We review lessons learned from the reviewed approaches, and identify possible future directions which could be taken in automation (specifically with regard to enhanced ground segment flexibility).

I. Introduction

Mission automation and autonomy are paradigms which are relevant to all spacecraft in design, development or routine operation. The concepts are distinct, but are related in the degree to which they reduce the level of (and need for) direct human interaction in spacecraft monitoring and control.

Autonomy: Can be defined as the ability of a system to take decisions and perform actions based on pre-defined stimuli. In spacecraft operations it is established in the early mission design phase, and is encapsulated within the flight software. It is a concept that the Flight Control Team (FCT) inherits at launch, albeit one that they can tune (indeed even extend) during the mission life to improve safety and robustness or enhance science return.

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Automation: Is more a process or methodology, seeking to perform activities in a manner removing or reducing the need for human interaction. This process comprises many diverse elements, some of which may not be in place at mission launch. The management and implementation of an automation concept is within the remit of an FCT or science planning team. It is one which may undergo frequent (even substantial) evolution as the mission ages, science priorities change, or as the operations concept evolves based on in-flight experience. Moreover, mission automation can be realised in many ways by design of, and modifications to, the supporting ground segment.

The two concepts can be complementary in that limitations in on-board autonomy can be partially mitigated by developments in automation. Moreover, on-board failures can necessitate, or be circumvented by, ground operations that are only feasible through the application of automation methodologies.

However, there appears some confusion regarding these concepts, and considerable diversity of approach in the development of methodologies designed or developed to address them. These constraints have limited the benefits to be realised by any particular mission based on the experience of its predecessors, particularly so with respect to automation, where a generic methodology at the European Space Operations Centre (ESOC) is noticeably lacking.

Mars Express is a useful case study for concepts of autonomy and automaton. The mission design incorporated considerable autonomy primarily directed towards mission safety (e.g. a complex Failure, Detection, Isolation and Recovery [FDIR] methodology), whilst its complex mission profile has required the development of a correspondingly complex level of mission automation. The ongoing dynamic evolution of this operations concept has resulted in considerable modifications of, and extensions to, both on-board autonomy and the tools developed to support on-ground automation far beyond the scope envisaged prior to launch. However, Mars Express is not unique. The European Space Agency (ESA) currently operates a number of other science missions with a diverse range of operations concepts and mission needs, each one displaying its own (usually differing) measure of autonomy and concept of what constitutes automation (and what benefits are to be gained by its application).

It is therefore a question whether development of a generic automation system (to fulfill the needs of numerous missions) is a realistic, indeed desirable, goal and if so exactly what this system should comprise. It is a specific objective of this paper to compare and contrast the methodologies applied in a number of ESA missions, and to identify whether results derived therefrom can usefully be applied for the benefit of missions to come.

II. Autonomy and automation– a definition of terms

In an attempt to alleviate some of the confusion surrounding the concepts of autonomy and automation, we first propose to define a classification scheme to distinguish between the various elements of any operational system which functions fully, or in part, without human intervention. Three complementary levels (termed *elements* in the remainder of this paper) are proposed, namely *mechanisation*, *regulation* and *autonomy*. They are all envisaged to be components of the overall operational system (including both on-board and on-ground aspects), and can globally be considered various manifestations of mission automation.

As with any classification scheme, the distinction between the levels is somewhat arbitrary. However, our objective here is merely to define an analysis methodology which could:

1) Help to distinguish between the main elements of "automation" as applied to spacecraft mission operations.
2) To assess the suitability of the implemented methodology for its intended application.
3) Identify a framework within which easily to compare/contrast the differing approaches of various missions.
4) To define a context within which to identify any future automation improvements in the space domain.

Table 1 summarises the terms introduced above, in the context of both space and ground segments, presenting examples typical to most spacecraft operational systems, and which will be discussed further in this paper.

DOMAIN	Mechanisation	Regulation	Autonomy
Space segment	On-board command	On-board monitoring	On-board control
Objective(s)	Ensure integrity of loaded commands, and their execution at the specified time	Apply functional control to ensure mission conforms to appropriate operational (e.g. safety) constraints	Ensure mission is robust to failure
Example(s)	A mission timeline	Attitude and thermal control	FDIR
Ground segment	Mission Scheduling System	Mission Planning System	On-Board Software Maintenance
Objective(s)	Command schedule generation/partitioning for uplink	Activity flow control, maximising mission return within defined mission constraints	Retain the ability to modify the software to enhance mission return + address safety issues

Table 1: Definition of terms used in this paper.

III. Autonomy and automation in operation

A. Automation drivers - The Mars Express experience

1. The operational need for automation (and autonomy)

The Mars Express mission displays a number of operational characteristics typical to science missions which make the need for both on-board autonomy and on-ground automation essential. These are summarised below (a more detailed discussion can be found in Shaw etal [ref 1]):

- Long one-way light travel times: A one-way light travel time of up to 21 mins obviates interactive human operations (and potential intervention in the case of anomaly) in all but the most critical of operations.
- Multiple pointing's per orbit: During each orbit Mars Express can perform as many as 3 dedicated pointing's per orbit to support observations by the 6 payload instruments. Ensuring that the instrumental requirements of each pointing do not violate the underlying mission operational constraints (and that all parallel instrument operations are mutually compatible) is ensured by on-ground automation (both *mechanisation* and *regulation* elements playing a role here).
- Eclipses and occultation's: Mars Express experiences eclipses and occultation's behind Mars typically every orbit in seasons of typically 6 months duration. This inevitably places demands and constraints on both the power and thermal sub-systems, especially in view of the limited power available on-board (Porta et al [ref 2]). Mission automation (both *regulation* and *autonomy* elements) help to ensure that the demands are managed, and all appropriate constraints satisfied.
- Complex ground station coverage: The Mars Express mission benefits from the support of an extensive ground station network, but one displaying a complex and highly variable allocation profile. Management of this coverage is impossible by human operator alone, and is a task performed by station scheduling and mission planning components in the ground segment (both *mechanisation* and *regulation* elements) – see Rabenau etal [ref 3].
- Data storage and recovery: The on-board storage of housekeeping and science data is performed by a solid state mass memory device (Shaw etal [ref 1]). However, this device has limited capacity before data overwrite. Optimised use of this resource, and ensuring that all data are recovered in a timely fashion after acquisition, is a task of mission planning components in the ground segment (both *mechanisation* and *regulation* elements).

2. An evolving operations concept and mission profile

The Mars Express mission has displayed (since launch) a complex and highly evolving mission profile. This arose in part because of the need to support a number of diverse mission phases: Immediate post-launch operations, near-Earth commissioning, a dynamic cruise phase, orbit insertion, in-orbit commissioning, radar antenna deployments.

However, the demands of operational constraints (identified only in-flight), changing science priorities, the execution of dedicated tests, and varying ground segment capabilities have all played a role in requiring continued review of the mission operations concept. These are summarised below:

- A solar array mis-wiring, detected during the cruise phase, resulted in the mission having to operate a full science programme at a maximum of 72% of the original foreseen power budget. Additional *regulation* was implemented on ground to plan energy management to achieve maximum possible performance; *autonomy* being improved on-board by adding new power monitoring applications to safely operate with 0% margin instead of 30%.
- The recovery of science data as originally envisaged (performed by a parallel reads from data acquired for all instruments, and relying on the priority handling within the on-board software [OBSW]) could not be realised owing to performance issues affecting the solid state mass memory. *Autonomy* of the interaction between the mass memory and central computer was enhanced by OBSW changes to both units. *Mechanisation* was implemented on-ground by defining the recovery of the science data as serial dumps interleaved with data acquisition - a task originally done by humans but one proving too complex and error prone.

- Potentially significant variability can occur in the data volume generated by payload instruments (partly resulting from varying illumination conditions, and therefore varying degrees of effectiveness of the data compression techniques used by those instruments). These variability's are essentially impossible to predict in advance, but have a significant impact on data return mechanisms. This has been mitigated by introduction of a *mechanisation* element to estimate over-generation rates. [A future step would be to add a *regulation* layer automatically to generate the additional data dump commands and schedule them in free slots. This was considered, but not implemented to date, because of an unfavorable trade-off between extra complexity and infrequent need.]
- The irregularity of the possible daily ground station coverage (a consequence of the 7 hour orbital period, coupled with observations, eclipses and Mars occultation's), combined with a variable downlink data rate of between 28 and 228 kbps, quickly revealed an inadequacy in the original single ground station operations concept. The original single ESA station in Australia has since been augmented by support from several other 35m and 70m dishes. A strong *mechanisation* element (allowing one to identify all possible passes at any time by overlaying resources on Earth and constraints at Mars) was the decisive initial automation step. *Regulation* layers were progressively introduced, first manually and then in software, to optimise station usage, minimum/maximum pass duration, time between passes, and prioritisation of certain types of ground antenna. *Autonomy* (to react to late changes or detect special contact opportunities) is retained by the human planners.
- The mission was requested to support changes in both the science pointing frequency (initially a single nadir pointing per pericentre passage in each orbit, extending to 3 pointing's out of 10 possible types) and pointing duration (initially from 36min to more than 68 mins). These changes reflected the gradual evolution of science priorities from a survey to a target-oriented emphasis. *Mechanisation* in the ground segment has been key to coping with this quantitative change in density and diversity of pointing's. However, this mechanisation could have produced invalid outputs – and resulted in risky operations - had the development not been accompanied by tight *regulation* of the planning: Formalisation and software implementation of rules for instrument, energy, pointing and data management, to confirm or reject the multiple possibilities long before their implementation on the spacecraft. Here on-board *autonomy* offers the ultimate protection.
- The Mars Express orbit was initially defined to follow a frozen ground track, allowing for well-defined advanced science planning. However, the change of science emphasis towards more targeted observations, and the realisation of the high fuel cost of maintaining such an orbit, resulted in the change to a free drift orbit, albeit one regularly maintained by wheel off-loadings.
- Periodic validation of the space-to-space radio link between Mars Express and National Aeronautics and Space Administration (NASA) landers are undertaken, with observations utilising a dedicated pointing profile which require inclusion in the normal planning process. Originally conceived as unique activities (requiring no automation), a toolkit was subsequently developed to offer *mechanisation* of preparation for the radio-link sessions. This was in response to a NASA request for ESA to provide a backup relay, activated on-demand in case of emergency, but required to be ready for activation during any possible contact period throughout the several month mission of the 2008 Phoenix lander to Mars.
- Dedicated campaigns were performed to support an imaging search for the Mars Global Surveyor spacecraft, and several close fly-bys have been conducted of the moon Phobos. By virtue of their rarity and unique character, the level of automation possible here is limited, resulting in a significant additional workload on the FCT. Such ad-hoc campaigns also run the risk of considering, late in the planning process, constraints usually pre-checked long in advance for more automated operations.

3. *On-board anomalies*

Since October 2011, when on-board anomalies observed from the solid state mass memory called into question the fidelity of the nominal mission timeline, the backup mission timeline was called into use. Unfortunately, size limitations in the available storage space in random access memory in which this backup timeline is located resulted in a factor ~25 net reduction in storage capacity of time-tagged commands, requiring a substantial revision of the commanding operations concept in an attempt to reduce the daily commanding volume without adverse impacts on the science conducted.

This issue was addressed by a review (and modification) of both on-ground *mechanisation* and *regulation* automation elements, and on-board *autonomy* elements. It will be summarised in Section D below, with a more detailed discussion being presented in Lakey etal [ref 4].

B. Evolution of on-board and on-ground autonomy for Mars Express

The options available to the Mars Express FCT to modify or enhance on-board or on-ground *autonomy* are discussed in this section (addressing both *regulation* and *autonomy* elements identified in table 1 above).

1. On-board monitoring and control

The existing failure management mechanisms on Mars Express are sufficiently extensive, and their inter-dependencies sufficiently complex, that in-flight modification was quickly excluded from further consideration. Rather, the initial Project decision to avoid the use of on-board command procedures was reconsidered.

Prior to the activation of on-board command procedure (OBCP) technology, the Mars Express FCT relied upon the following components to effect on-board autonomy:

1. **Command files**: Stored on the solid state mass memory, and merely containing groups of commands executed in sequence, without recourse to any branching or decision making.
2. **Application programs**: Encoded within the OBSW, activated by an external trigger (e.g. out-of-limit [OOL] or anomaly condition) and potentially including extensive decision making and flow control. Management of concurrent active application programs (a situation which could occur in exceptional circumstances) was of particular concern on Mars Express in view of the risk it posed to mission safety, particularly during safe mode recovery – Shaw etal [ref 5]. To date, application programs are utilised to monitor the on-board power status (and management during eclipses), for the establishment of a stable radio frequency configuration, for management of heater cycling and monitoring of the tele-command (TC) reception chain.
3. **On-board monitoring**: Simple sub-components of the FDIR mechanism, offering the ability to monitor telemetry (TM) parameters, and react to those parameters exceeding defined limits (or to the generation of specific events) by the execution of a specific command. As with command files, they make no recourse to any significant decision making.

However, in the light of the automation drivers listed in Section A above, it was realised that these autonomy functions were insufficient to continue (safely) complex routine operations without additional development of OBCP's. The prime motivating factors, and directions taken, during such development were summarised in Choukroun et al [ref 6], but of particular appeal were the following:

- The possibilities offered by OBCP's to extend/enhance potential recovery actions of an ageing spacecraft without recourse to complex OBSW modifications.
- The ability of such procedures to function at any time scheduled in the mission timeline, offering the potential for more timely intervention in case of an on-board anomaly.
- The opportunity to execute routine, repetitive tasks at the appropriate scheduled on-board time, but making more efficient use of available resources (e.g. number of stored files on the solid state mass memory, number of required commands, or variations in command timing) than possible by use of command files.

Utilising expertise already available in the FCT's of Venus Express and Rosetta (missions sharing the same hardware and software architecture to Mars Express) facilitated the rapid establishment of an OBCP coding, testing and validation environment on Mars Express. To date, OBCP's have been developed to:

1. Extend the available FDIR in case of failure of the transponder,
2. Perform the daily re-routing of housekeeping data between file stores on the solid state mass memory.
3. Execute changes in the TM visibility (on-ground or as stored on-board).
4. Perform routine switch on/off activities for the majority of the payload instruments and heaters.
5. Perform complete instrument operations, but removing the need for input command parameters.
6. Support the (otherwise very labour intensive) safe mode recovery process by management of the communications configuration and application program activation strategies.

Such a significant change of emphasis in the operations concept has required the establishment of a rigorous definition, validation and implementation methodology, supported by additional levels of configuration control. This is described in detail in Shaw [ref 7], and summarised in Lakey etal [ref 8].

By virtue of their potentially significant autonomy, OBCP's not only offer significant benefits, but also risks, if implemented in mission critical areas. It is often impossible to validate all possible system dependencies or interactions that a complex OBCP might undertake, when testing with a spacecraft simulator on ground.

Therefore, a conscious decision was made on Mars Express specifically to avoid OBCP development in the areas impacting on-board software maintenance (OBSM) and in the reconfiguration of a failed unit (with the exception of the transmitter, which was considered a special case).

2. On-ground (software) autonomy

The remaining *autonomy* domain available for development by a flight control team is that of on-ground OBSM.

However, from 2007 Industry support was no longer readily available on Mars Express to define OBSW modifications, nor to provide an environment sufficiently complex and reliable with which to test them. The combined Mars Express, Venus Express and Rosetta FCT's thence demonstrated the ability to undertake some OBSW development, validation and implementation (Shaw [ref 9] and references therein). However, the scope of any software change has been consciously limited to simple patches (e.g. those modifying the contents of data structures, the management of threshold, filters or flags values and their checking, or simple code module deactivation). Any changes which required full software re-compilation, or involved timing issues , inter-task communications or requiring data access across address states, were considered beyond scope.

To date, therefore, limited OBSW development has been undertaken for Mars Express. However, the potential need for any such development is under continual review. Indeed, a minor software modification is currently under consideration to improve the robustness of the core software in the event of interface failure between the prime on-board computer and the solid state mass memory.

C. On-ground automation for other ESA missions – concepts and mechanisms

For many spacecraft, especially Earth observation missions, other drivers may exist above and beyond those identified in Section A above. Three of the most common are:

- **Limited pass duration**: With visibility durations of as little as 5 mins, there is insufficient time for interactive human operations. A measure of automation must be implemented to ensure that the essential operational activities are performed in the available time.
- **Repetitive operations**: Short visibility durations often result in the need to perform far more repetitive operations (and sequences of operations) than would be the case for a mission such as Mars Express. The management of planning, scheduling and executing such activities would be a task of both the space and ground segment (both *mechanisation* and *regulation* elements in table 1 above).
- **Minimisation of outage** (and therefore rapidity of automated recovery) for missions which seek to build a continuous – i.e. uninterrupted - or timely data archive for their user communities.

How such automation can be achieved varies from mission to mission, often reflecting the direct needs of that mission and often requiring definition and implementation within a short timescale. In this section, we review the approaches to automation adopted by a number of ESA missions:

1. An Earth observation mission (ENVISAT).
2. Two science survey missions sharing a common platform architecture (XMM/Newton and INTEGRAL).
3. A solar system network mission (the four CLUSTER II spacecraft).
4. A family of solar system missions displaying a commonality of OBSW, avionics architecture and ground segment (Rosetta, Venus Express and Mars Express).

In the majority of missions cited above, *automation has primarily been directed towards support for operations in the control room*. These are discussed in further detail in the present section. By contrast, in Section D below we discuss approaches to "offline" automation i.e. prior to control room commanding.

1. Automation in the control room – the mission concepts

It is first instructive to define what operations on-ground automation is sought to support or complement. The means by which such automation can be implemented is addressed in sub-section 2 below.

ENVISAT: On-ground automation offers the possibility for multiple spacecraft control (in this case with ERS-2), and to conduct routine activities for each of the typically 13 daily commanding pass (each of 10-12 min duration). These activities are based on a well-defined plan, typically involving one primary activity per ground station pass (see Mesples etal [ref 10]). Moreover, automation allows operators to perform timely recovery following well-known - recurrent - payload anomalies (in parallel to possible on-ground diagnosis and further analysis), and for periodic operations which require extensive TM verification (which would be impossible by human interaction within the available commanding period).

CLUSTER II: The prime objective here was specifically to automate recovery following eclipse exit, particularly to execute in a timely manner the large number of TM checks which a human operator would otherwise be required to perform. In this case, the operations are well-known, but are mission critical as the spacecraft may be required to operate during eclipse at a sufficiently minimal power demand as to require almost all units being switched off. The time required to facilitate the recovery of even a single spacecraft (several hours) demands automation support when up to 4 spacecraft may need to be controlled in unison. The automation tools do not replace the need for specialist engineering support, merely complement it by providing efficiency and error-reduced operational support by execution of dedicated automation procedures (Foley etal [ref 11]).

XMM/Newton and **INTEGRAL**: These missions operate in fully real-time, with essentially constant ground station visibility and no concept of on-board data storage and retrieval. As such, at mission definition, there was no requirement for significant on-board autonomy. In case of failure, the platform was designed to be "fail safe" - until direct ground intervention - for a period of up to 5 days. This autonomy has been extended on XMM to the payload instruments, mainly via post-launch OBSM activity. On-ground, the definition of the mission real-time commanding timeline is fully automated within the dedicated mission planning system (and is therefore not a control room activity). However, during routine operations, ground automation has been further extended to enhance monitoring of some major on-board failures and/or to detect high radiation levels (to which the payload instruments are particularly sensitive). On activation, the ground automation mechanism facilitates the uplink of automatic command sequences without the need for operator intervention.

Venus Express and **Rosetta**: The automation concept here has been tailored to support nominal ground station contact periods, and specifically excludes contingency recovery operations (de Sousa etal [ref 12]). In the case of Venus Express, the concept is an addendum to a mission planning system similar in basic design (though different in implementation) to that of Mars Express. The automation system envisages status checks of the various ground segment components, configures the appropriate settings for the mission control system, and monitors the spacecraft TM throughout the contact period. Uplink of the routine time-tagged commanding profile for the coming days, commanding of routine science data recovery, and logging of data outages, are also performed.

2. Automation realisation in the control room – mission case studies

In this sub-section we review the mechanisms by which some of the featured ESA missions have sought to realise on-ground automation. For each mission, we present the methodology adopted, and attempt to identify the benefits and limitations of the adopted approach. Finally, we review the responsiveness of the adopted approach to contingencies, and attempt to quantify (where possible) the "return on investment" gained by automation.

2.1 **ENVISAT**

Realisation: This has been facilitated in the following ways (see Mesples et al [ref 10] for further details):

1. Use of a mission planning system to compile the daily commanding profile for both payload instruments and spacecraft attitude/orbit control, uplinked to the spacecraft three and two times per day respectively and including additional checking of the fidelity of the attitude and orbit control commanding prior to uplink.
2. Development of an operations automation system which, based on user inputs and the outputs of the mission planning system, generates a commanding schedule.
3. Construction of a station visibility plan (of activities to be executed in real-time), derived from the mission planning schedule, based on timing of events within the mission orbit event file - done on a weekly basis.
4. Interfacing of the visibility plan with dedicated automation procedures developed within the Flight Operations Plan via a command executor. Automatic procedure execution is thenceforth the means by which spacecraft commanding during the contact period is conducted.
5. Establishment of monitoring, linked to the executor, which reacts to events within the mission control system (likely originating on-board) by activating commanding from a dedicated recovery procedure.
6. Implementation of a priority scheme allowing for the parallel commanding both by the automation system and a spacecraft operator, with the latter taking priority in the event of conflict. The operator has the ability to lower the priority of TC's dispatched by the automation system (whose functionality is then paused) or to terminate automated execution completely should the need arise.

Benefits gained

1. Plans for spacecraft commanding are defined in a timely fashion, and nominal operations are conducted within sufficient margin of the available commanding opportunities.
2. Routine and repetitive tasks are conducted with the minimal human operator input, improving reliability.
3. Timely automated recovery of frequently observed anomalies is possible with limited (or potentially no) direct human intervention.
4. The output of the scheduler (by virtue of being linked to events and ground station visibilities rather than absolute times) can be used to re-generate a new pass plan is case of late changes.

5. An extension of the nested logic implicit in many flight operations procedures allows the possibility quickly to identify to the operator the recovery procedure to be used in case of anomaly.
6. The human operators are now able routinely to support other missions (with the similar operational monitoring and control methodology) in parallel to ENVISAT.

Limitations of the cited approach

1. The approach is very labour intensive, in that it requires independent assessment of that subset of procedures in the flight operations plan most amenable to translation into automated equivalent procedures. It then requires translation of these procedures, a potentially significant task given that the automation system is much more deterministic in its checking than would be a human operator, and only applies margin when explicitly requested to do so. By definition, only the most routine activities can be supported in this way.
2. A list of on-board anomalies or OOL’s needs to be established and maintained, and significant effort has to be expended in mapping the entries in this list to applicable recovery procedures (or command sequences within such procedures). For the mechanism to be of value, there must exist a 1:1 mapping between each anomaly/OOL and an applicable recovery procedure, and thus each recovery procedure (or command sequence) must be fully compatible with the automation system.
3. The scope of the envisaged system does not allow execution of activities which follow a complex logic flow (and thus task execution). The adopted approach cannot therefore support complex or highly variable commanding tasks, and it can only perform automated recovery for a pre-defined subset of all possible on-board anomalies (or detected OOL’s) which could arise.
4. The introduction of the automation system has not removed the need for a spacecraft operator (merely that the operator is now more dedicated to spacecraft monitoring, and reporting in case of anomaly).
5. The mission control system complexity is enhanced by the need to manage a priority system of dual commanding by both automation system and spacecraft operator.
6. By virtue of the intended scope of the automation system, it does not support the routine reporting of each pass, nor does it seek to simplify the methodology for recovery of data outages.
7. The overall automation concept entirely relies on the availability of a good communications link during each ground communication pass.

Contingency handling

1. In the event of unavailability of the most critical daily ground station passes (i.e. those in which attitude and orbit control commands would be uplinked), back-up passes are identified. However, only two such passes per day are available, making the mission susceptible to a significant ground station outage.
2. In case of anomaly, the automation system loads the required recovery procedure into the executor either for automatic execution, or interactive execution by a human operator. However, on first anomaly detection, the operator is still required to review the downlinked event lists, and can only sanction the recovery methodology after the routine pass commanding has been completed.

“Return on investment”

No explicit figures are available for the trade-off between investment required for, and benefits gained from, mission automation. However, it was considered that a significant improvement in the quality of the flight control procedures resulted from their review to support automation. Moreover, more timely response was derived to the limited number of repetitive anomalies most commonly observed in routine operations. More complex operations are conducted rarely, and are therefore treated on a case-by-case basis.

2.2 **CLUSTER II**

Realisation

Automated procedures are developed in the Flight Operations Plan, and interface with the mission control system using the same interface as developed for ENVISAT (Foley etal [ref 11]). However, the automation scheduler function is disabled for CLUSTER.

Benefits gained

Within the intended scope of the automation methodology, the long and complex operations required to support mission re-activation after eclipse exit require less human interaction, and are considered more robust to potential human error.

Limitations of the cited approach

1. As with ENVISAT, the approach is labour intensive in automated procedure production and validation, and displays equivalent constraints to those identified in Section 2.1. By definition, only those specific activities defined by the scope of the automation concept can be supported in this way.
2. A more dynamic modelling of the current status of the on-board mission timeline was identified to optimise the commanding loading profile. The automation system, as currently implemented, does not support such modelling. If implemented, this would be a step towards *regulation.*
3. The mechanism for data transfer between the development and operational environments is labour intensive, and is not optimised for more generic automation of routine spacecraft activities.
4. Currently the automated eclipse recovery procedures are only executed by user request at scheduled times, and not based on ground station trigger events (such as acquisition or loss of signal). This is an example of *mechanised* automation.
5. Because the scheduler functionality is disabled, external files (such as event and mission planning files) cannot be used to populate any station visibility plan.
6. By virtue of the intended scope of the adopted automation methodology, routine commanding at each acquisition of signal still requires the presence of a spacecraft operator.
7. Where more than 2 OOL's are identified in the downlinked TM buffers, manual operations are required to recover the additional OOL's, obviating the possibility for the automation system to respond in an automated and complete fashion to all detected OOL's.
8. Currently event recognition/response is not supported - the approach supports little or no *autonomy*.

Contingency handling

Where any observed spacecraft anomaly matches two or more related OOL's (processed by the event monitor function within the automation system), the core anomaly information and appropriate recovery actions are identified. The subsequent recovery actions must be performed manually.

"Return on investment"

No explicit figures are available. It was considered that the effort required to develop a CLUSTER variant of the scheduler in use for ENVISAT outweighed the benefits to be gained from its usage, and as a consequence this was not included in the adopted automation concept.

2.3 **VENUS EXPRESS**

Realisation: This has been facilitated in the following ways (see de Sousa etal [ref 12] for further details):

1. Station schedules (tracks and appropriate bit rates) and weekly science requests are input to the mission planning system (subject to the applicable constraints of power, thermal and data rates). Tags are assigned to activate appropriate automation procedures at each commanding opportunity, and the resulting lists of commands split into daily sub-units before transfer to the mission control system. The output master request file is then submitted to the automation system.
2. The automation system itself comprises a scheduler (to manage procedure execution), an executor (to run the procedures and validate responses/outputs) and an event monitor (to monitor events from the mission control system). The system can request, and then schedule, tasks in the mission control system to perform each of the objectives outlined in Section C.1 above. Schedule execution can be started, stopped, paused or aborted by user interaction.
3. The executor task operates by sending directives to the mission control system (e.g. to load a stack of commands, re-order them, or dispatch them to the spacecraft).
4. A routine pass monitoring automated procedure checks for the availability of spacecraft TM and establishes the appropriate TM/TC settings.
5. A routine pass execution automated procedure initiates automated recovery of on-board science and housekeeping data (triggering failure reports if these activities are not completed in the specified timeout period). It then uploads to the on-board mission timeline the commanding profile for the coming days, and finally checks that the number of commands loaded on-board is consistent with those sent (based on a mission timeline loading profile modelled in the mission planning system).

Benefits gained

1. The derived schedule of activities can be directly loaded into the automation scheduler function, and thus provides a direct interface to the automation procedures to be used for pass execution.

2. The system automatically ensures completeness and self-contained integrity of the derived daily command products, such that if one element is missed, this does not adversely impact the subsequent element.
3. Automated logging of routine pass activities is facilitated by the automation system.
4. Because the automation system can store both spacecraft-generated events and on-ground planning events, timely correlation of one against the other is possible. The system is thus able to predict certain spacecraft conditions (i.e. events or OOL's) as a consequence of planned events. Examples include acquisition/loss of signal, occultation and eclipse entry/exit, transmitter on/off times, ground station carrier up/down times.

<u>Limitations of the cited approach</u>

1. As with ENVISAT and CLUSTER, automated procedure production and validation is labour intensive, and displays equivalent constraints to those identified in Section 2.1. To date only 4 procedures have been created to support automation.
2. By definition, only those specific activities defined by the scope of the routine pass monitoring and execution procedures can be supported in this way. The methodology cannot cope with any contingency or anomaly.
3. The intended scope, namely setup prior to pass execution, and routine monitoring (e.g. of the status of the automation task itself) during the contact periods, all require the presence of a spacecraft operator throughout the pass. Although the concept undertakes a considerable number of real-time status and pass/fail checks, it merely transfers the responsibility for execution from the operator to the automation task, but does not obviate the need for the presence of that operator. It therefore focuses on *mechanisation* of the checks, not on *autonomy* of response.
4. Although the dump of critical events from the spacecraft is automatically scheduled at the start of each commanding window (if required), this task runs only once. Any event raised during the pass must be monitored by the operator on console, and its impact assessed in real-time, or it will be dumped only the following day. This dump of critical events is *mechanised* for a first request, but not *regulated* further.
5. The uplink concept is optimised to a mission with daily 8-10 hours commanding possibilities on a single ground station, and has only 1 redundant uplink opportunity in the event of ground station failure. This approach would require modification for a mission with shorter, or more variable, ground station visibilities. The adopted *mechanisation* approach is therefore unable to cope with inputs of variable dimension (in this case ground station allocation), making intrinsic assumptions about the regularity of available resources.
6. The concept generates a unique commanding element always assuming the same initial conditions (Earth pointing, transmitter on, all instruments off). Such a quantisation would be more difficult to ensure or enforce for a mission with a more demanding operations concept, e.g. one which would support dual Earth communication and data acquisition.
7. The system has a strong emphasis on "in-pass automation", possibly driven by the heritage from those real-time missions (e.g. Earth observation) that first made significant use of this technology. When applied to a "store-and-forward" (essentially non real-time) mission like Venus Express, the constraints imposed by the available toolset induce a real-time bias and overhead that may be incompatible for other missions (particularly when reviewed against the costs of a need-driven, mission-specific implementation of automation).

<u>Contingency handling</u>

The methodology does not support any contingency handling. In the event that any of the tasks fail, or the completion success flags are not received, the procedure terminates at the specified point, leaving the operator/user to assess the next action to take. The scheduler, however, continues to operate, such that other automated procedures executing in parallel with (or sequentially following) the failed procedure continue to be executed. The failed task can either be terminated, or resumed, at operator request. This is therefore consistent with the *mechanisation* approach to failure, and is not necessarily "fail safe" as would be the case for a more *regulatory* mechanism.

"<u>Return on investment</u>"

No estimates are available - the system is undergoing evaluation and has yet to be implemented operationally.

2.4 **ROSETTA**

The system implemented by Rosetta is essentially similar to (indeed was a precursor to) that adopted by Venus Express, with the exception that the interface to a suite of on-ground automation tools (namely the mission planning system) has yet to be implemented. All the benefits gained from, and limitations in, the applied methodology identified in section 2.3 above are thus equally applicable here. However, contrary to the approach on Venus Express, the plan/schedule definition and import to the automation system requires extensive manual interaction.

As with Venus Express, contingency handling is not managed, with the exception of TM/TC link outage (in which case the automation system stops, leaving the operator/user to assess the next action to take). In all cases of failure, it is assumed that operator intervention will be required to continue manual execution of the tasks which would nominally have been undertaken by the automation system. The spacecraft controller is instructed to stop the automation system in case of any doubt about the fidelity of its status.

The system has thus far been used successfully to support a small number of routine passes (albeit ones with only a modest commanding profile). The return on investment is therefore difficult to quantify, particularly given the currently limited commanding profile while in transit to its scientific target. The prime objective of automation from the Rosetta perspective was to initiate a methodology which could be used by a family of missions with significant commonality (namely Rosetta, Mars Express and Venus Express).

3. A critique of the adopted methodologies

ENVISAT: Earth observation mission, with their limited (but well-defined) uplink opportunities and their repetitive commanding profiles are the missions most likely to benefit from control room automation of the type envisaged for ENVISAT. The adopted approach applies both *mechanisation* and *regulation* functionality pre-pass and in-pass, but the approach is intentionally limited in scope and response to contingency. Moreover, it does not allow for more complex decision making in response to stimuli. This, coupled with a limited on-board autonomy and modest *regulatory* elements on ground, make it unsuited to a mission such as Mars Express.

CLUSTER: The scope of automation in this mission is restricted to support for specific activities, rather than being implemented in all (or even most) operational contexts. It is largely mechanistic in nature, and utilises little on-board or on-ground *regulation* and *autonomy*. The lack of completeness with regard to contingencies, and the cost of generalising this methodology to other areas of routine and non-routine operations, call into question the value of this approach for other missions.

XMM/Newton and **INTEGRAL**: Both in terms of operations and in response to contingencies, automation for XMM follows a largely *mechanised* approach. The limited scope for programmable on-board monitoring and control (e.g. OBCP's) has required that automation be undertaken on-ground (i.e. via OBSW developments), with all the costs and risks inherent in such an approach.

Venus Express: The control-room automation approach is largely *regulatory* by design, and therefore reactive in nature – actions are performed on the basis of observed stimuli. The mechanism thus functions largely in real-time, but merely modifies the activities required of a human operator. Concerns remain about the system behaviour in response to contingencies. Specifically, the fidelity of running tasks may be compromised in the event that execution failure of one task adversely affects the integrity of those which follow, and there must always be concern about the completeness of response to all possible failure cases (even if some measure of future contingency handling would be implemented). These difficulties may be amplified by an under- exploitation of the *mechanisation* potential of the planning and control room processes, which could a priori minimise the needs for the more demanding *regulation* and *autonomy* capabilities. Moreover, the concept of dumping the science data only when TM reception is confirmed in the mission control system is only a partial implementation of an automation concept – to be contrasted with those missions (e.g. Mars Express) in which the data dumps are pre-loaded on-board based on an assumed ground station availability.

Rosetta: The same comments made for Venus Express apply here. Moreover, the relative immaturity of the Rosetta mission planning and scheduling ground segment (compared to those of Venus Express) mean that significant work is still required to fully automate the operations concept of the Rosetta mission. It remains to be clarified how much of the automation in a ground segment for Venus Express, with its more extended timescales, is applicable to Rosetta – given the (likely intense) science phase of the latter mission on arrival at its target.

D. Automation for Mars Express

In this section we summarise the primary elements of the on-ground automation approach implemented on Mars Express. These comprise several elements: The mission planning system, the mission control system and associated tool sets. We defer to section IV below a justification of the approach adopted on Mars Express, as well as an assessment of the success of this approach.

A detailed discussion of the various elements of the mission planning system have been presented in Rabenau etal [ref 3]. Some of the tools are also utilised by the Venus Express mission. This tool set used is unique for ESOC in being the first to make significant use of artificial intelligence methodologies: Supporting the downlink of science and housekeeping data stored on-board, and the uplink of commands for the forthcoming 2-3 day period.

The system continues to evolve as new mission constraints arise. As a consequence, the following elements have been added to, or modified within, the toolset supporting on-ground automation during the last year:

- The ability to support multiple operations by loading unique sequences of commanding operations in successive command files, loaded in reverse order of execution to alleviate timeline loading limitations. Additional checking ensures no concurrent scheduling of activities of the same type.
- Dynamic modelling of the mission timeline contents, taking into account the use of command files with delayed execution times.
- Creation and management of “trigger” files to execute the command files at the appropriate times.
- Generation of an uplink schedule to optimise timeline population, subject to the loading constraints.
- Avoidance of concurrent command uplink with delayed command file execution on-board.
- Independent checks of products included in the schedule to those uplinked, based on spacecraft reports.
- An extension of the artificial intelligence system in use since 2009 to identify the prime and backup uplink windows for all commanding products. The system has now been ‘tuned’ to allow planning of the uplink of the “trigger” files, thus relieving the workload on the FCT and reducing human-error in identification of safe, useable passes for uplink.
- The mission control system has been extended to support automated operations for a Mars lander. To date the spacecraft controller performs consistency checks on the commanding products prior to uplink, but by only a modest investment of effort full automation (from products reception to uplink) could be achieved.

<u>Benefits gained</u>

1. Much of the workload required to generate the commanding profile to be uplinked to the spacecraft is automated, both the *mechanisation* elements (courtesy of the mission scheduling system), and the *regulation* elements (courtesy of the mission planning system).
2. The methodology is able quickly and efficiently to identify inconsistencies in the derived command products in a timely manner, avoiding the need for any late changes immediately prior to uplink.
3. No modification of, or extension to, the existing procedure set in the flight operations plan is necessary.
4. Detailed “what if” analyses can be performed, both for command uplink and data downlink scenarii, to assess the impacts of non-nominal situations. Such an approach has specifically been used following ground station anomalies, and to define the science mission which could be supported in particularly power-limited seasons (as occurred in 2006). The output of such “what-if” analyses is used as positive or negative feedback to run a *regulation* mechanism at the highest level (i.e. mission definition).

<u>Limitations of the cited approach</u>

1. The adopted approach places significant demands on the knowledge of the FCT required to support it. All knowledge acquired by the team must be retained, and the methodology must therefore be robust to personnel changes within the team. Processes implemented in software for automation purposes are rarely black boxes - they need to be maintained.
2. The methodology does not cater for on-board anomalies (or their consequences), and therefore continues to require a regular human presence (i.e. operator in the control room for each station visibility, and - for non-routine operations - specialist engineer(s) in the control room or available on-call).

IV. Justification of the Mars Express approach

Many of the automation drivers outlined in section A above were evident prior to the execution of the routine science mission for Mars Express, or shortly thereafter. It therefore became evident that an automation approach focusing on activities in the control room, as outlined in section C above, was insufficient. Rather, for Mars Express, more emphasis has been placed in on-ground *mechanisation* and *regulation* automation elements in table 1.

The overriding objective of the automation methodology on Mars Express has been to pre-plan as much of the routine commanding of the spacecraft as possible in advance of uplink, incorporating as much margin into the system as possible to take account of possible anomalies in the ground segment (e.g. late ground station allocations/changes, ground station unavailability etc.). This has resulted in an approach which minimises the degree of human interaction required at the time of application, namely during the commanding opportunity itself.

The objective of automation has been to replace tasks previously undertaken manually, but not at the expense of the flight control team complement. Rather, the team members have been released to perform (primarily offline) activities more suited to their skill set. These have included detailed trend analyses (related to unit and sub-system performance and possible degradation), planning for forthcoming mission critical (e.g. power limited) seasons, support for ad-hoc activities such as lander communication campaigns, review of mission readiness for extended science operations, further development of on-board automation mechanisms (via OBCP's or OBSW changes).

However, the adopted approach is sufficiently flexible that it allows manual intervention should the need arise, for example to re-plan data return in the event of significant data over-generation by a payload instrument due to the ineffectiveness of the applied data compression techniques.

For the space segment, *mechanisation*, *regulation* and *autonomy* elements of automation are all assumed to be managed by the mechanisms offered by the spacecraft itself. Specifically, all non-routine (or contingency recovery) activities are considered beyond scope for the automation system. As a result, any on-board anomaly has to be assessed and corrected by direct operator action. A conscious decision has been taken that automation complements, but cannot replace, a human operator (spacecraft controller and/or operations engineer).

"Return on investment"

Detailed figures on the return to investment are to be found in Denis etal [ref 13]. However, a measure of the success of the adopted approach is that it continues to provide routine operational support to the mission despite the constraints and limitations outlined in section A above. Indeed, both Rabenau etal [ref 3] and Denis etal [ref 13] cite an ~20% increase in science return resulting from the increased optimisation of available resources offered by implementation of on-ground automation. On-board data losses (e.g. due to over generation by payload instruments) are believed to be less than 1%, and unrecoverable loss due to commanding problems to be less than 0.1%.

Moreover, these benefits can be realised whilst also achieving significant improvement in the reliability of (and reduction in the time taken to perform) the primary activities of planning, scheduling and execution. Specifically, the following time savings have been observed in planning/scheduling activities for a routine weekly period:

- Data downlink planning has been reduced from hours to minutes.
- Uplink planning has been reduced from a day to 30 mins
- Ground station consistency checking has been reduced from several days to of order 1 hour.
- A 50% reduction has been observed in the time taken to schedule the command uplink.

V. Summary and conclusions

In this paper we have sought to review the concept of automation in the context of spacecraft operations. To this end, we have proposed a nomenclature in which autonomy (be it in the ground or space segments) is understood to be merely one element of mission automation, and that automation is the overriding goal which is sought in an attempt to complement (or even replace) human operator monitoring and control.

We have compared and contrasted the adopted approaches of seven ESA missions covering a broad spectrum of scientific objectives, and functioning under widely differing operational constraints. In the majority of cases, automation has been restricted to support for operations in the control room. In the most complete implementation (ENVISAT), automation comprises a *mechanisation* element to support immediate pre-pass and pass execution activities and product checks, together with a *regulation* element during pass execution. A measure of in-pass *autonomy* is provided by reaction to a well-defined subset of observed OOL's or events, although this still requires significant human intervention. For no other automation system is there significant handling of contingencies or anomalous conditions (be they on-board the spacecraft, or in the ground segment).

The Mars Express mission is rather an exception within the automation approaches at ESOC, in being the mission for which the majority of efforts have been invested within the "off-line" ground segment automation - specifically the mission planning system and its associated tools, coupled with the spacecraft pre-loaded operations and on-board control procedures. This can be interpreted as an emphasis on *mechanisation* and *regulation* in view of limiting the *autonomy* needs at their interface - the control room. This approach has allowed the mission to satisfy its complex and evolving mission operations profile under unique (and often stringent) operating constraints, whilst releasing human resources within the flight control team to undertake longer-term tasks.

After review of the automation approaches in this paper, the following specific conclusions are identified:

1. Experience to date suggests that missions will define their automation system requirements, and tune the adopted approach, to suit their immediate mission needs and constraints. In some cases (e.g. the power situations on CLUSTER II and Mars Express) these constraints cannot be envisaged before launch, or even

at the outset of the routine operations phase, yet their very existence often enforces a substantial modification of their respective operations concepts.

2. There will always exist mission phases likely unique to each mission, for which it may be impractical (or, in the case of mission critical phases, even inappropriate) to utilise mission automation.
3. Some missions (such as Mars Express) display such a widely varying set of mission phases (each with their own unique set of constraints and conditions of operation) that automation efforts may be more effectively directed in on-ground automation through mission planning and scheduling, at the expense of automation in the control room.
4. All missions are subject to evolution of their operations concept due to changing situations and operational circumstances. These may be due to an unusually adverse operational environment, due to unit aging or resource depletion, or resulting from a changing emphasis of the scientific objectives of the mission. Aging and consumables utilisation constraints become increasingly stringent as the mission exceeds its original lifetime and/or as units and instruments approach or exceed their qualification limits. In some cases (e.g. in the case of XMM/Newton), this may result in significant in-flight OBSW changes – envisaged as an on-ground element of autonomy in the present nomenclature. An automation system (to be fully effective) must therefore be sufficiently flexible as to adapt to the varying operational circumstances under which the mission continues to operate.
5. Automation in the control room can place significant demands on the workload of an FCT to support it. This is particularly so for migration of the flight operations procedures to utilise a methodology which is more suited to the more stringent conditional checking imposed by automated tasks. Unless such procedures are developed from the outset with such constraints in mind (to date an approach adopted by no currently flying missions at ESOC), the overhead in porting procedures to automation equivalents is such that only a portion of the entire flight operations plans can realistically be migrated. Although some procedures are in any case only suited for execution by a human operator, this selective approach to migration will inevitably result in an incomplete set of contingency recovery procedures. This in turn will have an adverse effect on the likely ability of the automation system to respond to on-board anomalies in a timely way – ostensibly one of the most appealing aspects of mission automation.
6. Despite the limited scope of the control-room automation methodologies implemented to date, the fact that few are able to address contingency situations (either at all, or only in a very limited subset of all conditions which could arise) suggests that there exists little trust in the reliability and fidelity of the system as implemented. By contrast, on-ground automation (as implemented by Mars Express) is a fully trusted system – indeed one without which the mission would not be able to operate as currently envisaged. This situation has arisen from constant optimisation and development since its inception. It has been guaranteed by multiple validation: Each unique operation generated by operationally validated software is checked systematically by (at least) another software methodology developed, validated and operated independently. This “macro-regulation” is only conceivable and affordable for “off-line” tools. It significantly improves the quality/reliability of the output while being doubly economical: Much less human effort is required for final checks, whilst improved knowledge management is ensured by a wider distribution of responsibilities for the development and maintenance of independent tools within the control team.

Given the above constraints, it appears optimistic to envisage the development of an automation system which is sufficiently generic as to be applicable to all future missions (regardless of mission objectives and operational constraints). Experience to date suggests that automation in the control room (e.g. through automated procedure execution), whilst providing operational support for a routine operational pass , rarely obviates the need for a human operator on console. Specifically, such an approach would not address many of the operational constraints which condition the commanding of, and data retrieval from, a mission such as Mars Express.

Rather, we propose that time and effort would be better invested in automation support for routine operations in the area of ground segment planning and scheduling tools, and identifying commonalities between missions which would rapidly allow a new mission to extend and adapt the methodology adopted by a predecessor. The identification of commonalities within the mission planning systems of Mars Express and Venus Express indicates that such an approach can yield rich rewards. The commonality of approach (executor and scheduler task functions envisaged as extensions of a common mission control system) adopted by ENVISAT and CLUSTER II, whilst limited in scope, indicates that again there exist synergy of needs and resulting implementation that could perhaps be satisfied at institutional level given appropriate automation developments in core infrastructure software.

Of course, for such core infrastructure initiatives to be deemed sufficiently relevant to the needs of the operational community they are intended to support, requires that the same end user community be actively involved in the definition and proto-typing of any such system long before deployment in an operational environment.

VI. Possible future directions in automation

In this section we propose some possible future directions for consideration in areas of particular relevance to mission automation, derived in part from experiences gained in-flight on Mars Express:

1. An output of the mission planning system is a series of command files for uplink, together with an identification of the optimal uplink schedule and visibility periods in which they should be sent. Therefore, the mission profile is entirely predictable. On-ground automation could review all commands sent, and data volumes recovered, and identify inconsistencies between planned and observed commanding profiles, or between predicted and observed data returns, in a more timely manner than is possible to date. [For missions (e.g. Earth observation) for which the commanding profile is also very repetitive, the lack of repetition may of itself indicate an error worthy of further inspection.] The detection of a shortfall in recovered data could then be used better to automate the recovery of such data in a more timely manner prior to over-write on-board. Additional consideration could be made whether the automation tasks could define, and uplink, the corresponding commands necessary to recover these data independently of operator interaction.
2. The human-oriented response to observed OOL's or events is, by its nature, reactive – often there may be insufficient time for the response to make use of knowledge from previous occurrences of the same OOL or event, particularly if that event or OOL is rare and/or the mission is long-lived (such that previous knowledge is lost). An artificial intelligence extension of an automation system could monitor (in near real-time) observed events, OOL's or TM parameters – possibly defined by a grouping which reflects the sub-system or unit to which they correspond. By defining periods in the data archive which reflect nominal behaviour, one could envisage that the automation system could "learn" from past experience, so as to identify subsequent time periods in which the monitored parameters/events are deemed non-nominal, and which are therefore worthy of further analysis by an engineer.
3. Conducting trend analysis by human interaction (either for specific TM parameters in isolation, or by comparison to manufacturer predictions - where they exist) is time-consuming and often subjective. However, it forms a crucial element of the monitoring function as a mission ages, and/or as consumables deplete. An artificial intelligence extension to the on-ground automation system could be used automatically to check TM parameter evolution (for a suitably defined subset of the available TM datapool) against predictions or defined limit ranges. This could be used to identify divergent conditions, and thus potentially allow more timely identification of impending anomalous conditions long before any critical limits are exceeded.
4. Correlation of specific events on-board or on-ground with one or more of the triggers which may have initiated them is often problematic. For example, broken interfaces in the ground segment can result in an interruption of the distribution of mission critical files. An identification if such interruptions is often only partially automated, and late detection of the condition may adversely impact the operations themselves. However, as the mission evolves, and patterns emerge of the trigger conditions and the effects that result from them, a future automation system could use pattern recognition methodologies to flag trigger conditions, and identify in a timely manner possible consequences, potentially allowing operators rapidly to recover normal operations.

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