Why Introducing Innovative Technology in Operations?

Alessandro Donati[1] and Reinhold Bertrand[2]
European Space Agency, ESOC, Robert-Bosch-Strasse 5, 64293 Darmstadt, Germany

Jose Antonio Martinez-Heras[3]
Black Hat, Spain

and

Nicola Policella[4]
Solenix, Switzerland

. **The term innovation brings to mind the idea of “doing things differently” while the space operations discipline, being conservative by nature, is very attentive to scrutinize and validate any new attempt to modify the status quo. It is also true that imperative drivers, such as cost reduction, performance and new requested capabilities, are creating preconditions for implementing a new way of "doing business". The paper addresses first the motivation for changing specific operational processes, putting in evidence the source of the new requirements - programmatic, budget constraints, political agenda - and their temporal impact. In the second part both benefits and risks are analyzed with considerations related to the impact of innovation in the operational processes - planning, monitoring, diagnostics, training, etc. - in the capability of improving the efficiency of the current workflow and empowering new tasks and new workflows - such as autonomy operations. Risk analysis considerations include safety, investment cost, schedule, return on investment and training. Concrete examples related to recent innovative research and technology activities at ESOC, such as automatic novelty detection in telemetry streams, automated diagnostics and correlation analysis across telemetry and onboard autonomous controller are then discussed to substantiate what has being stated before. Considerations on opportunities and threats in relation to the external environment - such synergy with innovation carried out in other industrial sectors - like automobile and telecommunication - and the current world financial crisis, are then presented before the conclusions with a way forward.**

I. Introduction

The objective of this paper is to summarize the motivations for successfully introducing innovation in mission operations, based on innovation experience matured in the last ten years[1]. ESOC played a major role here, however the innovation process affected also other ESA centres such as ESAC, for science operations and ESTEC, in the robotics.

Motivation is a sort of engine that can make things happening. Several patterns exist to finally succeed in the innovation process. However, in mission operations the patterns are very narrow, dictated by the recognized statement that “failure is not an option”. Awareness of what one is planning to do, and of its consequences, effective communication and sharing will help to gain support and keep the track along the narrow pattern.

Motivation is inspired by long term scenarios and visions, however it can get wider consensus only if it takes into account also short term needs, of currently flying missions. The latter is instrumental to allow successful validations of innovative processes and technology, ahead of the future.

[1] Advanced Mission Concepts & Technology Manager, Mission Operations Dept..
[2] Head of the Research and Technology Management Office, Ground Systems Engineering Dept.
[3] Senior Technologist and Software Engineer, Advanced Mission Concepts & Technology team.
[4] Senior Technologist and Software Engineer, Advanced Mission Concepts & Technology team.

The first section will cover aspects that helps building up solid motivations such as considerations on past, current and future missions, to identify both trends and disruptive evolutions, expectation from future operations scenarios, the reality of the limited available resources and the richness of available spin-in opportunities.

The second section is related to benefits from innovation and to associated risks and risk mitigation approaches.

The last section gives a high level overview of selected examples, in the area of monitoring, diagnostics and planning.

II. Motivation for Innovation in Operations

Innovation can be justified either by the fact that enabling technology is available (technology push), by strong requirements coming from mission operations of currently flying or of future spacecraft and rovers (application pull), or from strategic directions from management.

A. Past, Current and Future Missions

Missions bring new operational concepts, on-board technology made jumps in evolution since the first satellite was put in orbit, observability is dramatically improved across the years. A synthesis of the trend of the number of platform and payload parameters being reported to ground makes clear that the operator cannot anymore perform regular analysis across telemetry time series and the classical out-of-limit approach seems to be not sufficient anymore to cope with the complexity of today’s spacecraft.

A demand for intelligent transfer of housekeeping telemetry, particularly for deep space missions, will provide the capability to use the available limited bandwidth, not only with the classical data compression approach, but with a “semantic” compression able to provide the right granularity of the samples, where it is required.

Another aspect in trend is the slow but progressive transfer of functions to onboard autonomous modules. Failure detection isolation and recovery was among the first functionality for onboard. Still it is going through evolution with sophisticated diagnostic functions that will be soon put onboard.

The way a spacecraft is commanded has also evolved from direct commanding to time-tagged, up to the most recent adoption of On-Board Control Procedures (OBCP). Future envisioned evolution will be from a traditional procedure-oriented approach towards a goal-oriented command approach, delegating the authority for planning, scheduling and execution to the target element, operating in space or on a remote planetary surface.

B. Visioning Foreseeable Future Scenarios

If we look at operational scenarios in the medium and long term range, we can easily detect strong demand for further onboard autonomy functionality. In the area of platform operations it can be envisaged an intelligent autonomous capability to perform onboard re-planning and re-scheduling to cope with unforeseen contingency, requiring fast reconfiguration without disrupting the mission objectives’ production. This will override, for certain situation, the necessity to put the spacecraft in safe emergency mode.

Payload operation will also require additional onboard autonomy, particularly when a scientific opportunity shows up and needs to be exploited, with short-term reaction, without intervention from ground. This is called opportunistic science, and is equally applicable to rovers mission on Mars or on the Moon, as well as to earth observation satellites looking at the natural and human-made phenomena on the surface of our blue planet.

Moreover, the ground segment itself faces increasing demands for increasing autonomy, not only to reduce operations cost, but also to enable future operations ground segment networks integrating non-homogeneous ground stations and communication links in one single control system.

Such examples of future trends and expectation are included in the current Research and Technology Development Roadmap, driving the R&T activity at ESOC.

C. Response to Urgent Needs

So far we have briefly discussed cases with emphasis to the future. Currently flying missions represent also another very reach inspiration and justification for introducing innovation, particularly during the routine phase and also when the spacecraft is aging. These cases can represent often an easy door for making the first steps of the innovation, if we focus on the resolution of the concrete case and, at the same time we keep an eye to the medium & long term scenarios. In this way today’s innovative solutions can become the building blocks enabling and supporting the future scenarios.

This was the case – in our experience – of designing and developing the innovative and simple MUST[2,3] architecture and technology in support of the operators dealing with recurrent anomalies in Smart I, immediately after launch, in September 2003. It took only two and half months – from concept to deployment – to get the first operational prototype of MUST running in support of the stressed and tired Smart-I flight control team. They got fast and remote access to key telemetry parameter, in near real-time, on-demand and available either on PC or mobile. The tool was supporting initial capability for manual correlation analysis and statistical information enabling the operators to take key decisions even if they where not in console.

D. Costs and Risks

Operations costs is always there and the ESOC centre was and is very keen in improving the efficiency, reducing the on-shift positions or introducing the concept of family of missions, therefore grouping them in families sharing the same control area and operations expertise.

Innovative technology has and can further provide a boost in redesigning specific workflow and therefore reducing further the operations costs and the temporal satellite degraded state. Examples include the electronic logging, the automatic production of operational reports, in their initial draft format, the process of doing troubleshooting when an anomaly occurs and so on.

It is important to consider that cost should always be treated together with the accepted level of risk. What is mentioned above is valid assuming to guarantee, at least, the same initial level of risk, therefore without jeopardizing the possibility of degradation or failures.

Another recently introduced class of missions, called NGS – Not Guaranteed Services missions – will consider to make use of innovative technology and, at the same time, a relaxed level of availability and reliability. This will be applied to small size missions, initially focused on technology validation.

E. Availability of Spin-in Opportunities

The technology for mission operations we are discussing in this article belongs to artificial intelligence and advanced computer science. Machine learning, AI planning & scheduling, data mining, data compression are all disciplines developed mainly in support of applications for defense, mobile communication and automobile industry. Space represents a too narrow market to directly drive these technologies. However, space can well represent a very interesting segment to spin-in and to validate them. And this is what was happening in the operational experience matured so far at ESOC. No need of big investment in developing the adequate and enabling technology. Intelligent spin-in of existing mature technology can be a good start to develop innovative applications and deliver solutions to demands coming from either a flying mission or a new operations concept under feasibility study.

III. Benefits and Risks of Innovation

The process of introducing innovation in space mission operations can be represented by a circle between technology experts (T) and operations engineers (O). Synthesizing the experience matured in introducing innovation in mission operations, this circle represented in Figure 1 needs to have qualities to work properly and give maximum benefits and minimal risks. Very good *communication*, particularly (T) have to listen and understand very carefully the stated and implicit needs of (O). The risk of imposing a solution (pure technology push) can disrupt the entire process and jeopardize costs, on the long run.

Figure 1. Technologist & Operations Engineers Circle

Mutual *trust* is a second value that can grow with time and with the responsiveness of (T) to real issues being solved. When the dialog is open and trustworthy in both directions newly proposed enabling technology can further stimulate (O) in identifying different innovative workflows that were not thought before because of known difficulty to implement them. See below the example of “googling” telemetry time series, related to Dr.MUST[4]. Another important aspect that needs to be taken into consideration is that often it is easier and more effective starting to do the technology *infusion* on specific cases. Generalization will come later and the best “advertisement” is done by (O), that already validated and used, with satisfaction, the introduced novelty. The majority of the innovations experienced so far by the Advanced Mission Concepts and Technology team were focused on the routine operations phase.

A. Better Workflows, New Workflows

Technology infusion can lead to improve the efficiency of currently existing workflows. Examples include the daily, or weekly, or monthly reporting, the monitoring for novelty detection, the daily scheduling of on-board memory dumping, the space weather assessment and reporting.

Necessity for new workflows is also picking up. One example is represented by closing the circle between the satellite design, implementation and testing, before flight, and the in-flight performance assessment. Data fusion between testing data and inflight data will soon enable fast performance assessment of critical components and feedback to the manufacturer for future design improvement.

Another example is the new requirement to fuse too much sparse data and not sufficiently integrated information extracted from the data. The fusion of data coming from spacecraft, from ground stations, from the mission control system behaviour in MUST and the novelty detection algorithm (see below in sect. IV.B) enables now the flight engineer or analyst to base his or her decision making process also on additional information now made available.

B. Mitigating Risks... and Costs

The introduction of novel tools in operation can be also viewed as element of disturbance and source of additional risk. For this reason the initial approach, followed so far, is "non invasive", that means data and information is automatically extracted or inferred, however we have always human-in-the-loop for checking and authorizing the use of the output of the modified process, e.g. a new optimized schedule, before uplinking.

Confidence is gained only after an extensive operational validation. Costs are also positively affected, in reality – an example was the MEXAR-2 downlink scheduler for Mars Express, with a cost reduction on the long run of 50% of the initial scheduling process – or, virtually, by making better use of precious resources such as the planning engineer.

IV. Examples of Recent R&T Activities at ESOC

A selection of works performed in the recent past represents examples of solutions matching the needs of the operations community and, at the same time, building blocks for future goal based operations scenario.

A. Diagnostics: Dr. MUST

Anomaly investigation is part of the routine diagnostic task of flight control engineers. When an anomaly is detected (e.g. when a particular parameter crosses a noticeable threshold), it is common practice to search along the telemetry history for similar behavioural patterns in order to characterize the anomaly. By analyzing the time periods when the anomaly happened in the past, we may be able to identify its causes and eventually prevent it from happening again in the future. The anomaly investigation process can be very labour intensive: many different parameters need to be analysed to identify possible correlations with the observed anomaly.

Although DrMUST has been designed with the goal of supporting anomaly investigation; it can also be used to perform system or subsystem characterization. This process helps engineers in identifying potential areas of concern when operating the spacecraft in different modes.

Dr. MUST offers two main functionalities: *pattern matching* allows to find similar patterns in a given telemetry parameter from a large time period (in the order of years). When an anomaly is noticed, it is useful to understand if it is really a new anomaly or if it happened before (and went unnoticed). The pattern matching functionality of DrMUST allows to find when behaviours similar to a give one happened in the history of a certain parameter. Since behaviours are never exactly the same, the pattern matching functionality needs to allow for certain flexibility to recognize similar behaviour. The enabling technology is the usage of speech recognition techniques as they allow to recognize the same word even if spoken by different speakers.

Correlator allows to find the telemetry parameters that are involved in a relevant time period (e.g. anomaly) from a large number of parameters (in the order of tens of thousands). The search for *correlations* is made under the following assumptions: a) parameters related to the anomaly behave similarly in all same- anomaly periods; b) parameters related to the anomaly will behave differently during anomaly and nominal periods. The solving approach consists of scanning every parameter and suggesting to the users those parameters with a similar behaviour during anomaly periods and different behaviour during nominal periods.

The Venus Express flight control team gave the following operational assessment: "Dr. MUST allows "googling" through spacecraft data and searching of similar occurrences or correlated occurrences. The performance is impressive: queries run very quickly compared to manual searches".

DrMUST assists in tasks which are very labour intensive of data analysis and enables a different more efficient diagnostic workflow. Before, it was required that the engineer would guess or hypothesize which parameters could have a credible correlation to a specific behaviour and then would perform the analysis to prove the hypotesis. DrMUST finds these correlations for the engineer even the ones he had not thought about.

Dr. MUST is a MUST[13] Client in the sense that it uses time series data provided by the MUST repository. However, it can be easily adapted to work with any kind of time series data.

B. Monitoring: Novelty Detection

The most widely extended approach for automatically detecting anomalous behaviour in space operations is the use of Out-Of- Limits (OOL). The OOL approach consists of defining an upper and lower threshold so that when a measurement goes above the upper limit or bellow the lower limit, an alarm is triggered. Then engineers will inspect the parameter that is out of limits and determine if it is an anomaly or not and decide which action to take.

While OOL alarming has its benefits, it suffers from the following limitations:

- Some behaviours are anomalous even if they are within the defined limits.
- OOL are not defined for every parameter. Engineers only define OOL for a subset of parameter for which they want to receive alarms if they exceed the limits. Therefore, OOL is not systematic in the sense that it does not cover every parameter.
- Quite often engineers receive OOL alarms that are completely expected. A typical example is the OOL defined for the Automatic Control Gain (AGC) during a pass. At Acquisition of Signal (AOS) and Loss of Signal (LOS) the AGC goes outside limits. However, it is expected to happen and at every pass these two OOL alarms will be raised.
- It requires effort to adapt OOL thresholds to useful values as the mission goes through different phases or simply ages.

The Novelty Detector project has been developed to cope with the current OOL limitations. Its main goal is to automatically detect anomalies and report them to engineers for further investigation. The Novelty Detector characteristics are the following:

- Systematic: it scans every parameter in search for novel behaviour.
- Realistic: it takes into account that parameters can behave nominally in several different ways.
- Robust: it does not make any assumption on what kind of behaviour or how many different behaviours a parameter will have.
- Versatile: it works with any kind of parameter. No prior knowledge required: the only inputs required are a time period that makes sense (e.g. orbital period) and examples of nominal periods.

The aim of the Novelty Detector is to automatically identify anomalies. However, we did not reach that far yet. At this stage we can only detect new behaviour. In this sense we can state: “What is happening today in parameter P never happened before”. In most of the cases this signals an anomaly, but could also mean a new nominal behaviour.

The Novelty Detector has been validated both with Venus Express and XMM anomaly cases. For both missions, the Novelty Detector managed to detect the anomaly way before the out of limits checks did. In some cases, these anomalies were not even detected by the out of limits.

The Novelty Detector is currently being integrated with the XEWS system (XMM News) to automatically detect potential anomalies for the XMM-Newton mission. XEWS will report the Novelty Detection findings automatically to flight control engineers.

C. Advanced Planning and Scheduling

Introducing innovation in an operational environment is a challenging process. This is even more true in the context of mission planning where the operators are responsible for the satellite’s management and safety. Here mission planning tools should support operators to continuously (and safely) plan the different spacecraft operations (from payload operation to maintenance activities and data downlinking).

The strategy we pursed to support innovation in mission planning context was based on an approach that would preserve mission planners’ control as well as foster their contribution to and intervention in the solving process. In fact mission planners in charge of spacecraft operations need to understand every step of the solution and maintain authority on any decision.

This goal was achieved by using AI techniques like constraint programming, timeline-based planning, and model-based knowledge representation. AI based tools lets planners work at a higher abstraction level while it performs low-level, often-repetitive tasks. It also helps them produce a plan rapidly, explore alternative solutions, and choose the most robust plan for execution.

A first example is Mexar2[15,12] a tool used on the Mars-Express mission (since February 2005) to support operators to manage the on-board memory and to plan data downlinking. Like other successful applications[17] from NASA and the Jet Propulsion Laboratory Mexar2 has demonstrated AI's suitability for mission planning at ESA-ESOC in Darmstadt. Since its introduction, Mexar2 has reduced the mission planning team's workload for generating a feasible downlink plan by half compared to the previous method. The science data is generally available on Earth as early as possible after its generation, and overwritings of the science packet stores are minimized. Finally, mission planners now have an easy-to-use interface supporting graphical output and what-if analyses.

Mexar2's success[12] has fostered ESA's confidence in exploiting AI technology for planning and scheduling. This Advanced Planning and Scheduling Initiative (APSI) was initiated to deeply inject AI technology in the mission planning process.

APSI had the general and ambitious aim of bridging the gap between advanced planning and scheduling techniques and the spacecraft operations environment. Overall, the project aimed to address and validate reusable functional library modules for use in future mission planning and scheduling systems.

The main result of the APSI project consisted in an experimental framework[11] for the development of AI-based planning modules, in order to increase the automation and the efficiency of the planning process. The framework is based on:

- The identification of typical space domain planning problems;
- A library of techniques and a set of functional AI modules applicable to the modeling and resolution of these problems;
- A general architecture for the development of experimental planning tools;

The capability of the APSI framework has been so far tested on different cases supporting the development of different prototypes/tools[8,6,7]. A first example was the development of tool, MrSpock[8], which support the Long term planning process of Mars-Express. The goal is to generate of a pre-optimized skeleton Long Term Plan which will then be subject to cooperative refinement between the spacecraft operators and the science planners. More recently APSI was used to develop a planner which is the core component of an autonomous controller for future space rover missions.

The implementation of the prototypes demonstrates two key points. First, the advantage of employing an AI model-based approach, in which the relevant features of the domain are described in a high-level declarative language allowing harnessing the versatility of general modeling and solving capabilities. The second feature which enables fast prototyping is the capability of designing ad-hoc components and including them in the domain specification.

V. Conclusion

Innovation in mission operations is an essential contributor to enable the execution of future demanding missions. At the same time operations can become safer and cheaper by enabling new workflows or improving existing ones.

Space operations can make good use of innovative technology also to satisfy short term needs from current flying mission. Enhanced monitoring, automated pre-diagnosis, automated conflict-free optimal mission planning and scheduling. This approach – if implemented keeping in mind long term vision of future operations concepts – can, at the same time, creates the building blocks for a solid set of enabling – and proved – technology for enhanced autonomy operations. These building blocks, once validated on ground, can become precursor for on-board implementation, paving the way to faster track for on-board goal-based operations, when needed. The discussed non-invasive approach takes also into account to keep risk derived from new technology infusion under strict control.

In summary innovative technology in mission operations gives answers to both short term and long term demands and expectations.

A second consideration is the spin-in opportunity from fast technology evolution driven by other industrial sectors such as mobile communication and automobile. In this case the question is different: why not? Available innovative technology, adapted for space operations needs, can give substantial benefits at reasonable costs.

Third, more subtle aspects, is the reality that everything evolves in nature. Giving opportunity to introduce innovation in mission operations helps to keep experts motivation and quality improvement virtuous circles alive, for a more affordable space access in the future. Participatory approach in the innovation process is instrumental for fast dissemination and diffusion across and beyond an organization.

The authors expect to get connected with other colleagues, around the world, sensitive to the process of innovation in space operations as well as with a dream to pursue in mission control what already mentioned by Leonardo Da Vinci: “simplification is the last sophistication”.

The technologist should have not only the capability to “invent” and exploit innovative technology and methods to meet demanding requirements. He or she should have a complementary parallel short term and long term horizons that mutually help to give refined direction of the research and short term validation of the building blocks.

The authors expect to open a sort of discussion forum on the subject and are interested to share and learn other different experiences and approaches as well point of views on the “Why”.

References

[1] Donati A., Baumgartner A., Happy Chickens from fresh eggs - innovative technologies for mission operations, E1SA Bulletin, Nov. 2008

[2] Martinez-Heras J. A., Baumgartner A., Donati A., "MUST: Mission Utility and Support Tools", Proceedings DASIA 2005 Conference, Edinburgh, UK

[3] Baumgartner A., Martinez-Heras J. A., Donati A. & Quintana-Claramunt M., "MUST - A Platform for Introducing Innovative Technologies in Operations", iSAIRAS 2005, Munich, Germany

[4] Martinez-Heras, J.A., Yeung, K., Donati, A., Sousa, B., Keil, N.; “DrMUST: Automating the Anomaly Investigation First-Cut“, In the IJCAI-09 Workshop on Artificial Intelligence in Space. Pasadena, California, USA, July 17 - 18, 2009

[5] Donati A, ESA Strategic Building Blocks for AI P&S Infusion in Space: Current Status and Perspectives, IWPSS 2009, Pasadena

[6] Pralet C. and Verfaillie G., AIMS: A Tool for Long-term Planning of the ESA INTEGRAL Mission IWPSS 2009, Pasadena

[7] Lavagna M. and Castellini F., Advanced Planning and Scheduling Initiative’s XMAS tool: AI for automatic scheduling of XMM-Newton long term plan, IWPSS 2009, Pasadena

[8] Amedeo Cesta, Gabriella Cortellessa, Simone Fratini, and Angelo Oddi, MrSPOCK: a Long-term Planning Tool for Mars Express. IWPSS 2009, Pasadena

[9]] E. Rabenau et all. The RAXEM Tool on Mars Express - Uplink Planning Optimisation and Scheduling Using AI Constraint Resolution, IWPSS 2009, Pasadena

[10] E. Rabenau et all. Using an Artificial Intelligence Tool to Perform Science Data Downlink Planning as Part of the Mission Planning Activities of Mars Express, IWPSS 2006, Baltimore

[11] Cesta A. et all. Developing an End-to-end Planning Application from a Timeline Representation Framework, IAAI2009, Pasadena

[12] Cesta, A., Cortellessa, G., Fratini, S., Oddi, A. and Policella, N.. An Innovative Product for Space Mission Planning -- an a posteriori evaluation. In ICAPS-07. Proceedings of the 17th International Conference on Automated Planning and Scheduling, 2007

[13] Martinez-Heras, J.A., Donati, A.; “Making Sense of Housekeeping Telemetry Time Series”, In the IJCAI-11 Workshop of Artificial Intelligence in Space. Barcelona, Spain, July 17, 2011.

[14] Itakura F. (1975) Minimum prediction residual principle applied to speech recognition. IEEE Trans Acoustics Speech Signal Process ASSP 23:52–72.

[15] Cesta, A., Cortellessa, G., Denis, M., Donati, A., Fratini, S., Oddi, A., Policella, N., Rabenau, E. and Schulster, J.MEXAR2: AI Solves Mission Planner Problems.In IEEE Intelligent Systems, 22(4):12-19, 2007

[16] A.K. Jonsson et al., “Planning in Interplanetary Space: Theory and Practice,” Proc. 5th Int’l Conf. Artificial Intelligence Planning and Scheduling (AIPS 00), AAAI Press, 2000, pp. 177–186.

[17] M. Ai-Chang et al., “MAPGEN: Mixed-Initiative Planning and Scheduling for the Mars Exploration Rover Mission,” IEEE Intelligent Systems, vol. 19, no. 1, 2004, pp. 8–12.