
Rosetta

→ "HAPPY CHICKENS FROM FRESH EGGS"

Innovative technologies for mission operations

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Flying a successful mission means having the right technology ready for use at the right time. ESOC's Advanced Mission Concepts and Technologies Office is entrusted with infusing new and effective technology into ESA's mission operations.

Recognising the need to encourage and exploit new concepts and technologies, the Advanced Mission Concepts and Technologies Office, called Advanced Technologies Office for short, was established in 2001 to foster innovation in the field of information technology, with a strong focus on artificial intelligence (AI). The chosen paradigm is: innovate, demonstrate and transfer into the operational arena, with the needs of mission operations at the forefront.

'Chicken and egg'

One issue that had to be tackled immediately was to define an effective and low-cost approach toward achieving technology maturity through a pragmatic and consistent implementation framework. Mission managers do not want to be handed what they might call the technological 'fresh eggs' for implementation in their new missions.

At the same time, mature technological 'chickens' do not appear by themselves – they have to be incubated, hatched and fledged. Resources for producing 'eggs' are available, but the transformation into happy, mature 'technology chickens' is not as linear and natural as it might be on a farm.

Using new technologies involves certain risks: the time for a technology to mature is often longer than desired; or it is possible that a particular technology will not mature in time. Very few stakeholders are ready to allocate funds for this process, which is particularly true in the traditionally conservative domain of spacecraft operations.

In order to reduce the 'egg-to-chicken' development time so to speak, and to mitigate risks, a set of tactical measures has been implemented. The first was to make maximum use of available resources existing in-house: the expertise of operations engineers and accumulated data from ongoing missions. The engineers drive the identification of usage cases matching the new operations concept or workflow to be validated.

Mission control engineers are also a valuable and essential resource for validating any new prototype at a practical operational level. Live mission data become the benchmark against which the innovative algorithm or application is validated.

Another important element that helped to facilitate the process of introducing innovation was the use of proven working methodologies suitable for the process. So-called 'agile' software development approaches, such as 'extreme programming and egoless programming', were evaluated and adopted where possible. In fact, high-risk projects with dynamic requirements are perfect candidates for 'agile' methods, and egoless programming proved to be instrumental in establishing an open collaborative environment across stakeholders and within the development team. This has proven crucial for successful teamwork.

The innovation process at work

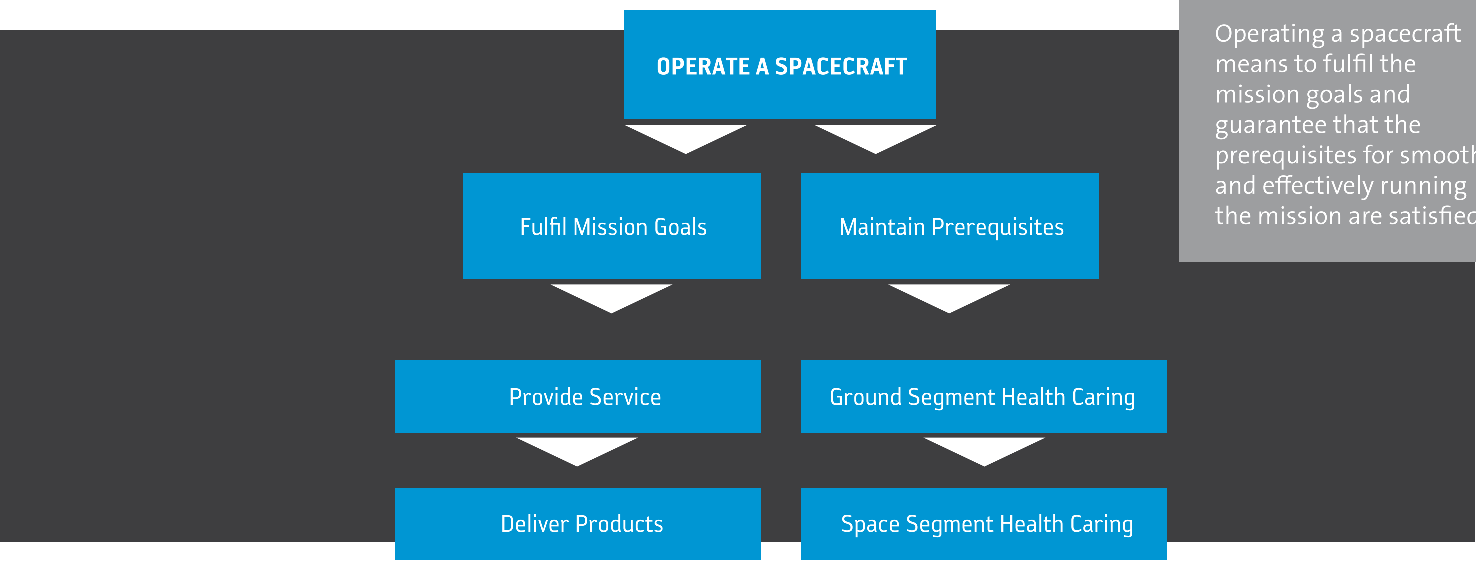
There are several motivators for introducing innovation into mission operations. The first is the goal of continuous improvement to provide progressively better and more cost-effective mission operations services, at an acceptable risk. Practically, this implies the design, implementation and validation of new operations concepts and workflows, with associated enabling tools and technologies.

For instance, the automation of recurrent manual operational tasks is a promising area. Examples are spacecraft monitoring and alarm filtering for an unmanned ground station pass, the generation of pre-formatted operations reports with data and graphics, operations activity logging and complicated planning and scheduling tasks. No one proposes replacing human expertise with machines, algorithms or automation but, through such innovation, the duties of specialised flight control personnel are raised from the (often routine) execution of manual processes to the more interesting supervision, investigation and optimisation of automated processes.

This not only makes better use of the engineers' expertise and intelligence, but they also remain trained and ready to intervene in non-nominal situations or when a final decision must be selected from several proposed solutions provided by a decision support system.

A second class of motivators is derived from the challenges presented by future missions. Exploratory missions, such as those in the Aurora programme, and their successors require that critical or tactical decision processes be relocated from ground to the space segment following a step-by-step transition of automation and autonomous functions from ground to space, with thorough validation of the process on ground beforehand.

This is associated with a significant increase in onboard autonomy compared to currently flying spacecraft.



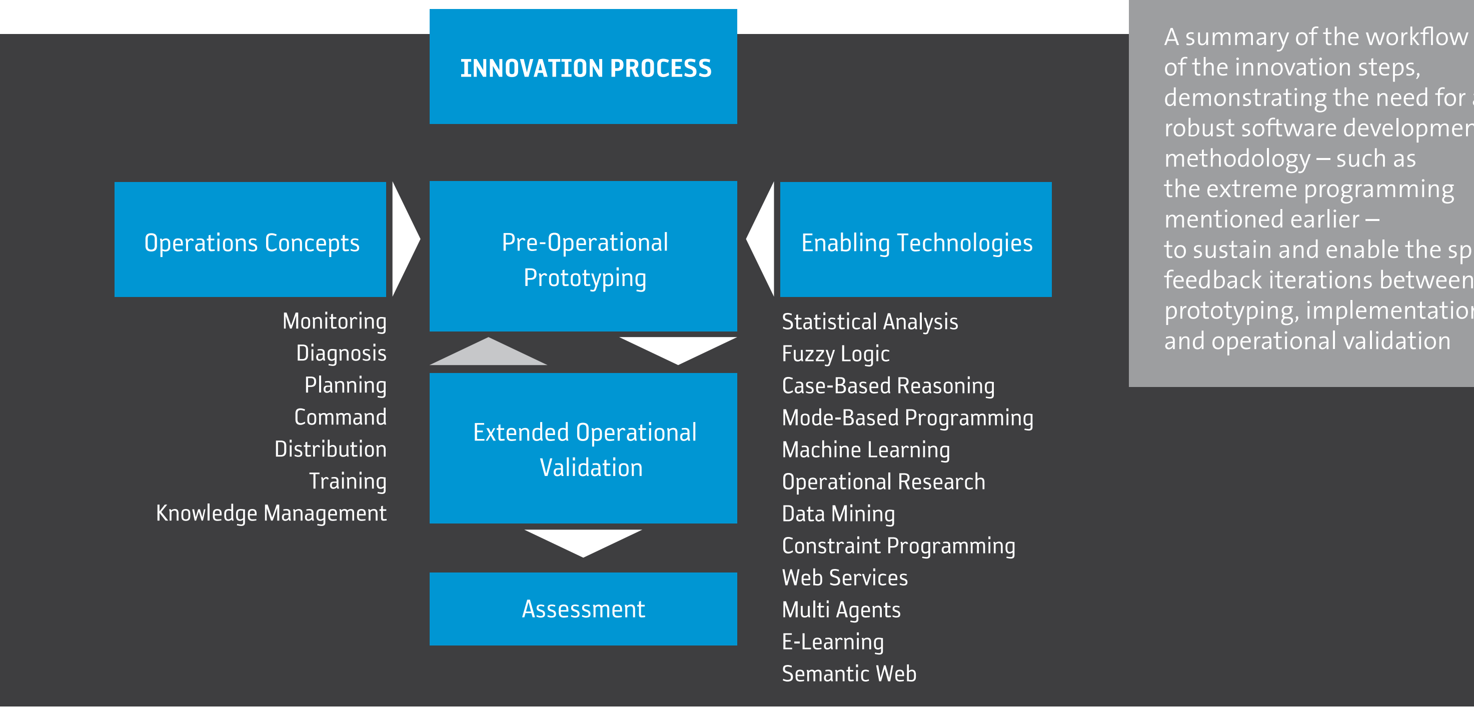
Operating a spacecraft means to fulfil the mission goals and guarantee that the prerequisites for smoothly and effectively running the mission are satisfied

Missions involving multiple elements, such as Earth observation or navigation constellation missions and rover fleets, as well as cooperative operations concepts, require significant enhancements in the flight planning and scheduling process. Today, this process still involves a lot of manual work. However, in order to ensure a good science return in such mission scenarios, tools that support the generation of optimised and robust plans will be required.

Continuing the route of exploration missions, there will be even cases where autonomy is the only technology enabling these missions, typically when the operational increments exceed the reach of the onboard sensing equipment between two communication windows. In the case of fleet missions, there will be so many degrees of freedom involved that it will be very difficult for humans to generate good plans in short time. AI algorithms are suitable to support these planning processes and they are able to generate optimised, conflict-free and robust plans.

Support Tools). This software package enables easy and safe (non-invasive) access, in near-real time, to spacecraft and ancillary data, and therefore permits the exercise and validation of prototype applications using online data. MUST is also the first example of prototype software to be transferred to actual operational infrastructure.

This innovation process affects the most relevant operations processes: monitoring, diagnosis, planning, commanding, training and knowledge management. The implementation of the innovation process makes use of a suite of available and suitable technologies. Most of them belong to the AI branch, such as case-based reasoning, 'fuzzy logic' or artificial neural networks. In addition, statistical analysis, operational research, e-learning and semantic web are among the complementary suite of technologies involved in the process.



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A summary of the workflow of the innovation steps, demonstrating the need for a robust software development methodology – such as the extreme programming mentioned earlier – to sustain and enable the spiral feedback iterations between prototyping, implementation and operational validation

As mentioned above, the Advanced Technologies Office has adopted the 'Innovate, demonstrate, transfer' approach. The innovation is defined by the requirements driving future mission scenarios, which are already identified by the Future Studies Section. Next, demonstration consists not only of a study of possibilities and recommendations, but also of practical implementing prototype applications that are validated under real conditions, i.e. the prototypes are applied to currently flying missions and to real data.

The transfer of validated technologies and concepts takes place by making available to ESA and industry the prototype applications, as well as consolidated requirements and blueprints, ready for operational reimplementation.

The demonstration and validation of technologies and concepts has been greatly facilitated by the Advanced Technologies Office-developed MUST (Mission Utilities and

In fact, the users, represented by mission control engineers, become part of the development team. Their contribution during the engineering phase is fundamental to keeping the focus on the essential part of the functionalities to be implemented. During validation, mission control engineers use the new prototype in parallel to the standard available operational tools.

The result of the process is a technological and operational assessment of the suitability and maturity of the technology with respect to implementing the particular innovative operations process, as well as a 'blueprint' for the validated solution – typically, algorithms, source code and executable code. This blueprint package is then transferred to the Ground Systems Engineering department, responsible for the implementation of the mission operations infrastructure and becomes a starting point for a formal operational implementation in support of a future target mission (or family of missions), as well as a valuable source in the applications library, reusable by any other mission.

Adhering to this technology infusion process is not always easy for the people doing the actual work. The job is demanding because novelty always brings unforeseen difficulties and challenges. At the same time, it is exciting and interesting. It requires strong teamwork, commitment, an open mind able to think 'outside the box' and a readiness to question one's own assumptions for the better. This is where the egoless programming style, mentioned previously, is essential.

Our core team at the Advanced Technologies Office comprises young information technology and artificial intelligence experts in various branches, consisting of a mix of on-site contractors, research fellows and young graduate trainees. In addition, the Advanced Technologies Office maintains close contact with external experts at universities, research institutes and innovative companies across Europe that provide their contributions through contracts financed by various ESA research and technology programmes. Currently, the Advanced Technologies Office oversees 13 ongoing projects with another nine under preparation.

> **"This work needs strong teamwork, commitment and an open mind able to think 'outside the box'."**

In order to successfully introduce innovation, it is necessary to coordinate activities with other organisational entities across ESA. The Advanced Technologies Office cooperates at a technological level with ESA's Advanced Concept Team, several other ESTEC-based sections, including the Robotic section and the Space Environment and Effects section, as well as with relevant sections within the Ground System Engineering Department.

At the strategy level, coordination takes place with the Future Studies Section, the Mission Operations Division, and with external teams, such as the Strategy and Architecture office in the Directorate of Human Spaceflight.

The Advanced Technologies Office also interfaces with supporting and coordinating research and networking activities funded by the European Union, and it participates in and helps organise specialised conferences and forums, such as the biennial 'SpaceOps' event; some of these focus on areas outside aerospace.

Case studies and achievements

Fuzzy logic

Fuzzy logic was the first technology to be assessed by the Advanced Technologies Office. It proved valuable for the diagnosis of failures and was deemed suitable for modelling the flight control engineers' experiences with specific unit degradation and anomalies. The fuzzy logic-based Gyro Monitoring Tool for Envisat has been in use since 2002, providing the capability to detect and diagnose early deviations from nominal behaviour, even if the telemetry is apparently normal. The same technology was also applied to the management of the Ulysses nutation anomaly.

SMART-1 automation

In 2003, immediately after the launch of SMART-1, the flight control team faced a series of anomalies that forced them to work well beyond normal working hours. As a consequence, an urgent request came to the Advanced Technologies Office and in less than two months a client-server tool was designed and implemented to allow remote monitoring and performance analysis of the spacecraft, as well as alarm notification via SMS. The new service greatly helped reduce stress and fatigue on the operations teams, who could then decide from home what to do in case of anomalies, without necessarily travelling back to the control room at ESOC. This also helped mitigate the risk for potential human failure/misjudgement.

The system was dubbed 'MUST', and after a re-engineering process based on pair programming methodology it was deployed to almost all ESA missions. MUST has since become the Advanced Technologies Office's standard platform for the implementation and validation of other advanced applications.

Mars Express planning

Another interesting project was automating a daily manpower-intensive task dealing with spacecraft downlink operations of stored science and housekeeping data.
An AI-based constraint satisfaction programming technique was implemented to generate the Mars Express downlink plans. Called MEXAR2, this tool has been in use since October 2005 providing valuable support to the Mars Express mission planners at ESOC. The generated plans are optimised and robust and provide a better capability to absorb last minute changes, allowing increased science return and contributing to reduced ground station usage. MEXAR2 was the first case in which AI technology was used to help solve the planning and scheduling problem.

MEXAR2 won the best application paper award at the ICAPS 2007 in Providence, Rhode Island, as well as a public recognition to ESA in a keynote speech at the iSAIRAS conference in Los Angeles in 2008. MEXAR2 is now paving the way – with the Advanced Planning and Scheduling Initiative – for further AI prototyping applications in mission planning for the science planning segment of Mars Express

→ Innovation at work

Examples of innovation and prototyping success

DigiLog – a web-based electronic logging system for operations

Most missions, as well as the ESTRACK Control Centre, still use paper logbooks. While this may be flexible, it lacks the possibility to make further electronic use of the information contained in the books. Using an electronic logging system not only makes it possible to search, filter and sort the information, but also to link the logging system to other applications, e.g. to mine stored information, to generate pass reports automatically or to export information automatically, for example to mission scientists.

GEMS – a messaging system currently under development

This system will provide a gateway for other applications to automatically send messages, e.g. alarms and notifications, to a configurable list of recipients via SMS and email. For example, if an anomaly is detected by a connected application, it would use GEMS to send an alarm to the operator on call. If the issuing application supports the functionality, GEMS will even enable the operator to trigger actions, e.g. restarting a machine. If the operator on call does not answer within a given time, the message is automatically forwarded to the next person in the list of recipients.

Fuel Saving

In the area of optimisation, an experiment was done applying a multi-objective genetic algorithm for the fuel consumption optimisation of the reaction wheels bias manoeuvre, implemented at perigee of the space observatory spacecraft. The algorithm was validated with the Integral and XMM-Newton. The result was a fuel saving up to 35% for the manoeuvres with respect to the simplex algorithm approach.

CERTAIN – a system that monitors and reports the health status of a spacecraft during unmanned periods

For missions with a 'dimmed-lights' operations concept. The system analyses telemetry data based on a set of rules defined by operations engineers and generates reports summarising the current status of the spacecraft. This will allow the engineers to get a quick overview of the current status, for example after a weekend.

Reporting

A lot of time is spent throughout ESA writing reports, including mission operations reports. Depending on the mission, reports are generated in weekly, monthly, quarterly or other intervals. Such recurrent reports always contain the same graphs, tables or other elements; the only difference is that they are updated with the newest data. Using state-of-the-art business intelligence tools, the Advanced Technologies Office created a system that largely automates the generation, as well as the distribution of these reports. In addition, the reports can be edited, viewed and downloaded from a web browser, therefore limiting the number of e-mails sent back and forth during the writing and distribution of the report.

ATHENA

A tool that automates the post-processing of telemetry data following specific procedures, for example to validate alarms and events. The procedures are entered into Athena as a set of rules directly by the flight control engineers. It then processes the latest data automatically and provides the results, therefore saving considerable time and effort.

Search Engines

Finding information is an issue in all large organisations, including ESA. Information is distributed in various databases, document management systems, web sites, files on personal computers, etc. It is a very time consuming task to find specific information or documents without knowing somebody who has it. To avoid reinventing the wheel, the Advanced Technologies Office is assessing various commercial off-the-shelf technologies and tools for searching easier and faster, e.g. semantic web and search engines such as 'Google in a box'.

Rover Monitoring & Control

In collaboration with the ESTEC robotics group, the Advanced Technologies Office is assessing the capabilities and challenges related to remote monitoring and control of a robot rover, in view of future missions such as ExoMars.

Virtual Flight Control Team

When people use online market places, such as eBay, they make use of software agent technology – usually unknowingly so. These agents carry out negotiations with other agents on behalf of the user, so that the user is spared exposure to complicated rules, algorithms and technical details. Software agents could also be used to take over parts of the spacecraft monitoring and diagnosis task. The Advanced Technologies Office is assessing the capabilities and usefulness of software agents for these purposes.

Auctions for Science Activity

Another Advanced Technologies Office project based on popular systems like eBay aims to use auctions to allocate time slots and resources to scientists. Each scientist responsible for a payload will have a budget of tokens (virtual money) with which he or she can 'buy' the time slot and the resources required for an observation. However, if another scientist requests the same resources at the same time (therefore causing a conflict in the plan), both of them have to bid against each other. The one bidding more will win the observation. This will allow the overall mission plan to be optimised in the sense that if an observation can be performed during a subsequent orbit, the scientist concerned will not bid many tokens because she/he is flexible enough to do the observation later. However, if a scientist has a unique opportunity for an experiment, he will be willing to pay more for it. This system will help circumvent the current complex and sometimes personality-based science activity negotiations.

E-Learning tools

These have matured over the last few years and sophisticated systems are now available. Operations team activities are a perfect example where it makes sense to use an e-learning system to train, retrain and possibly certify people. Knowledge is captured and transformed to e-learning training content. This includes multimedia animations, videos and interactive software tutorials. In addition, tests can be created to assess the knowledge of the trainees. The Advanced Technologies Office is implementing an e-learning system for the ESTRACK Control Centre, representing a first step into the 'e-learning world'. If useful, the system could easily be extended to other domains, such as spacecraft operations.

Data Mining – for classifying and forecasting anomalies

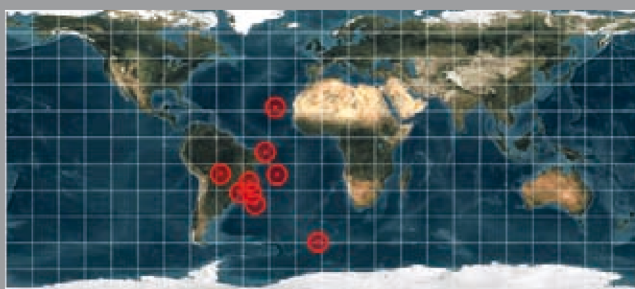
ESA has access to a wealth of data from the history of all its missions. Each current and past mission has an archive of telemetry and auxiliary data, as well as a database containing anomaly reports. Through data mining, it is possible to classify anomalies and even perform root cause analysis as well as to map patterns in the telemetry data to anomalies and therefore predict anomalies in the future. The latter process has already been tested and proven for several problems, including spacecraft leaks during certain manoeuvres and degradation of spacecraft components under certain conditions.

and SOHO, and for the long-term mission planning of Integral and Herschel.

Space weather

The Space Environment Information System (SEIS) is another project that responded to the needs of flight control teams. This system imports, processes and makes available through a data warehouse, data related to the space environment, e.g. radiation levels, as well as related critical telemetry and events data. The harsh space environment can have adverse effects on the performance and health of spacecraft, significantly reducing any mission's science return.

Normally, flight control teams are blind to spacecraft environment effects outside measurements generated from their own sensors, and they rely on other sources to estimate the current dangers, for example from a solar flare.



↑ An example display of the SEIS Reporting and Analysis Tool. This screen shows data from the French DORIS satellite system used for the determination of satellite orbits

SEIS gathers all relevant space environment data, taken from multiple spacecraft as well as ground sensor networks, into one single source.

The system provides two client applications, a real-time monitoring tool and an offline data analysis and reporting tool. SEIS has supported the Integral flight control team since October 2005, and an improved multi-mission version – named SEISOP – is currently under development.

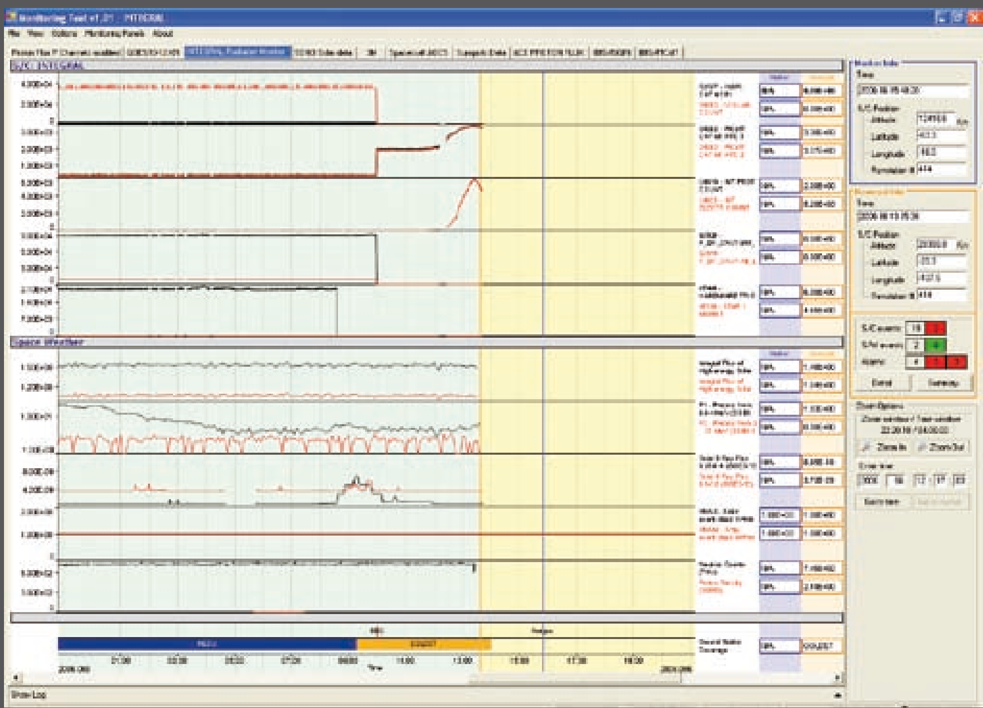
These prototype applications have been or are currently being developed in order to evaluate technologies and concepts against future mission requirements. However, because of the particular way in which the Advanced Technologies Office applies the technology infusion process, not only will future missions benefit from new technologies and proven concepts, but flight control teams of current missions will also reap rewards. They are actively recruited into the prototyping phase, providing feedback and validating the software in their (real) environment. This allows them to make use of the software early on and to benefit from the provided functionalities. Several flight control teams have been able to save time and resources in their daily activities due to the use of such prototype applications.

A considerable number of papers have been published to report on the results gleaned from the implemented prototypes, including publications in the IEEE's Intelligent Systems and in the *Encyclopedia of Decision Making and Decision Support Technologies*. A lot of positive feedback and appreciation has been received from the European academic world due to our success at bridging the gap between AI technology and its exploitation in space mission operations.

Prospect for the near future

A major goal for 2008–10 is consolidating and reinforcing operations technology networking within ESA, with outside research institutes and with European space industry. ESOC's recently established Research and Technology Management Office will be instrumental in this respect.

The Advanced Technologies Office will actively seek such collaborations within ESA and remain available to share and transfer experiences from the operational level as well as to work on joint inter-directorate prototyping projects. Various ideas have already been suggested in a wide range of application fields in ESA where AI could be introduced. Innovation will also continue to be fostered together with various European and international research institutes, particularly to encourage young researchers. We are particularly enthusiastic about a new collaboration started recently with GENSO (Global Educational Network for Satellite Operations), based on a new concept of networking low-cost ground stations in support of student missions worldwide.



← An example display from the SEIS Monitoring Tool for the Integral Space mission, indicating various parameters of 'space weather'

Conclusions

Over the years, we have confirmed a strong need for the benefits and efficiencies that are delivered through the Advanced Technologies Office innovation and prototyping process for both current and future missions. Both require light desktop software applications that are quickly developed and that address a specific problem they are facing. Our team offers this expertise, thus relieving active flight control teams from the workload of doing additional software development themselves.

Thanks to significant progress in technology, those responsible for missions and flight operations are starting to accept artificial intelligence. The benefits in the mission operation processes, primarily cost containment, increased science returns and resource optimisation, give a clear endorsement for the use of AI in future missions. We foresee that ongoing prototyping will sustain the technology infusion process, and joint research projects between those concerned with operations technology and space segment technology will further speed the process in the future, enabling European research institutes and industry to participate in the development of advanced technologies for space operations.

We also realise that being close to the users is of prime importance for our activities. This is why many of our projects are conducted on site and in close collaboration with the teams involved (after all, the best farmers visit their hen houses every morning to check on hatching progress?).

Given the needs and opportunities, as well as the past successes, it is clear that multiple benefits will result from the ongoing strengthening and formalisation of the Advanced Technologies Office workflow and of its collaboration within ESA. This will accelerate the infusion of beneficial technology, helping ESA remain at the forefront of technology application and supporting all the teams working to make our missions successful.

Further reading

Artificial intelligence boosts science from Mars, 29 April 2008
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Innovative Technologies in support of Mission Operations: Experiences and Perspectives, 2 February 2007 | OPS-G Forum presentation files
http://www.esa.int/esaMI/Operations/SEMI7C7H07F_0.html

Sophisticated ESA space weather tool under development, 2 February 2007
http://www.esa.int/SPECIALS/Operations/SEMGSSSMTWE_0.html

ESOC 'Skunk Works' Strong on Innovation, 5 July 2005 | MP3 Audiocast
http://www.esa.int/esaMI/ESOC/SEMYW36DIAE_0.html

Global Educational Network for Satellite Operations (GENSO)
http://www.genso.org/

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Egoless Programming, G.M. Weinberg, Egoless Programming, *IEEE Software*, Jan/Feb 1999