Science Goal Driven Automation for NASA Missions: The Science Goal Monitor

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Abstract

Infusion of automation technologies into NASA's future missions will be essential not only to achieve substantial reduction in mission operations staff and costs, but also in order to both effectively handle an exponentially increasing volume of scientific data and to successfully meet dynamic, opportunistic scientific goals and objectives. Current spacecraft operations cannot respond to science driven events, such as intrinsically variable or short-lived phenomena in a timely manner. For such investigations, *we must teach our platforms to dynamically understand, recognize, and react to the scientists' goals.* While much effort has gone into automating routine spacecraft operations to reduce human workload and hence costs, applying *intelligent automation to the science side*, i.e., science data acquisition, data analysis and reactions to that data analysis in a timely and still scientifically valid manner, has been *relatively under-emphasized*.

The Science Goal Monitor (SGM), being developed at NASA Goddard Space Flight Center, is a prototype software tool being developed to determine the best strategies for implementing science goal driven automation in missions. *The tools being developed in SGM improve the ability to monitor and react to the changing status of scientific events.* Such tools will be enablers for spacecraft autonomy.

Introduction of flexible scheduling and autonomously reacting to science driven events implies a certain amount of automation. There are a number of challenges inherent in infusing autonomy, especially into an existing environment that was not built for autonomy. *By developing and testing a prototype in an operational environment, we are in the process of establishing metrics to gauge the success of automating science campaigns.* In this paper we discuss the challenges encountered and the lessons learned so far into the project.

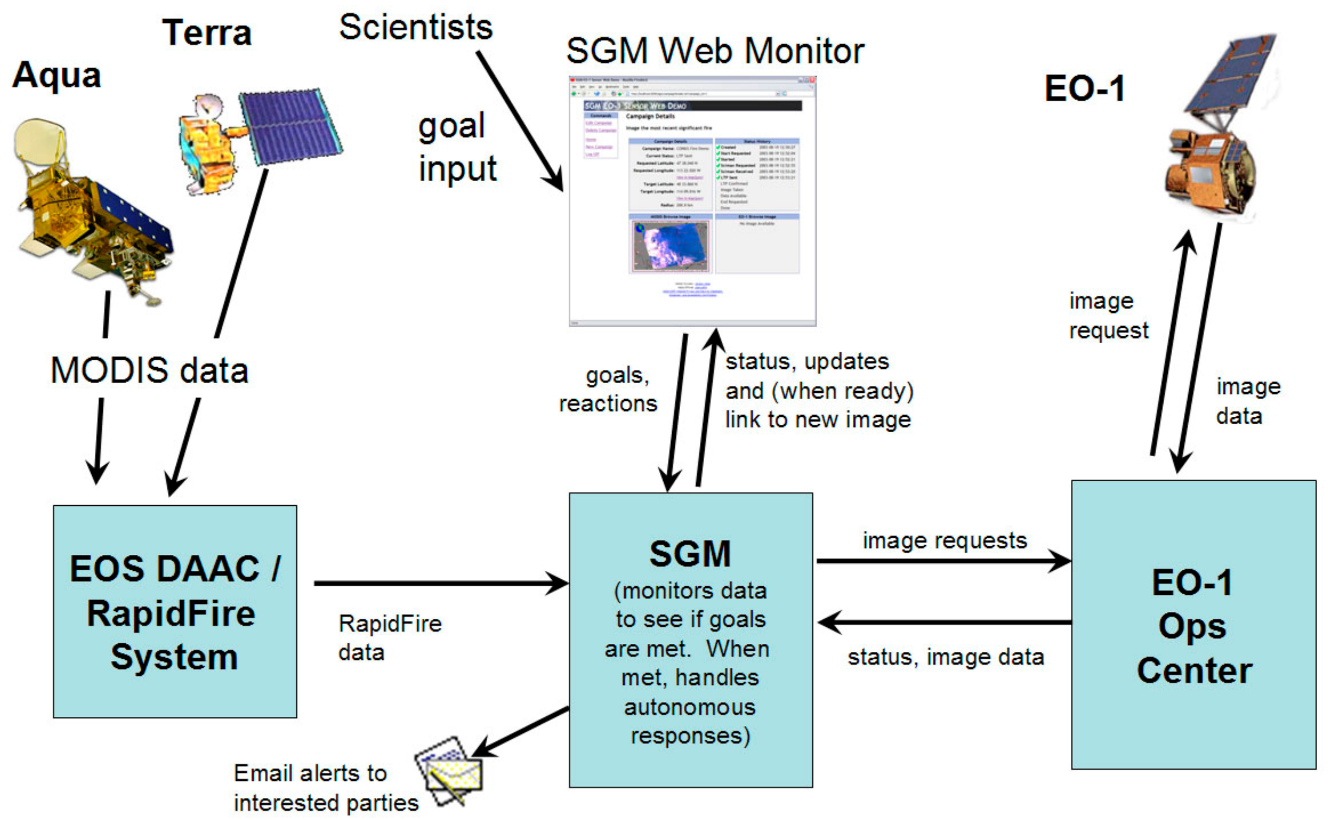
Introduction

NASA science missions have traditionally operated on the assumption that we can only manage scheduling priorities and scientific processing on the ground with significant human interaction, and that all scientific data must be downloaded and archived regardless of its scientific value. However, increases in onboard processing and storage capabilities of spacecraft as well as increases in rates of data accumulation will soon force NASA operations staff and scientists to re-evaluate the assumption that all science must be done on the ground. In order to take advantage of these new in-flight capabilities, improve science return and contain costs, we must develop strategies that will help reduce the perceived risk associated with increased use of automation.

There are several factors that are essential to address if we are to even consider the possibility of reacting autonomously to science driven events in space-based observing. These include: (1) the ability to schedule observations flexibly, (2) the ability to capture science goals in a machine interpretable format to make event driven decisions, and (3) the ability of the observatory to adapt dynamically and autonomously to a changing schedule or set of observing priorities. Further, both scientists and engineers must understand what capabilities are needed onboard for success. Further, metrics must be developed to realistically understand the potential increase in science returns and the risks involved in onboard analysis, and the costs to develop a production-ready system (both software and hardware).

The Science Goal Monitor

The Science Goal Monitor (SGM) is a prototype software tool being developed by NASA's Advanced Architectures and Automation Branch to explore strategies for implementing science goal driven automation in missions (http://aaa.gsfc.nasa.gov/SGM). It is a set of tools that will have the ability to capture the underlying science goals of an observation, translate them into a machine interpretable format, and then autonomously recognize and react in a timely fashion when goals are met. SGM provides users with visual tools to capture their scientific goals in terms of measurable objectives and autonomously monitors the data



SGM data flow for EO-1 forest fire demonstration

stream in near-real time to see if these goals are being met. Our prototype is designed for use in a distributed environment where some analysis might be performed onboard a spacecraft, while other analyses might be performed on the ground.

In the SGM system, scientists specify what to look for and how to react in descriptive rather than technical terms. The system monitors streams of science data to identify occurrences of the key events previously specified by the scientist. When an event occurs, the system autonomously coordinates the execution of the scientist's desired reactions between different observatories or satellites. SGM is designed to be adaptable to many different types of phenomena that require rapid response to fast temporal events such as gamma ray bursts or hazardous events such as forest fires, floods and volcanic eruptions.

For space-based observatories, any form of dynamic autonomous reaction, except to ensure the physical safety of the satellite, has always been resisted. This is partly because, until recently, the computing power deployable in space has been extremely limited, but also because of a fear of the technology. Scientists have strongly believed that only human analysis can determine the best scientific use of their instruments. In order to alleviate this fear, the SGM team is focusing on collaboration with a ground-based consortium, the Small and Moderate Aperture Research Telescope System (SMARTS), to prototype and test dynamic scheduling capabilities. This collaboration will allow us to better understand and measure the risks and rewards of dynamic scheduling and improve the likelihood of successfully using it on space-based missions.

The SGM team is also collaborating with a number of scientists in the Earth Science domain to show how dynamic science analysis and autonomous multi-sensor coordination can be used in the field. We have recently completed a series of prototype Earth Science demonstration tests with SGM using NASA's Earth Observing-1 (EO-1) satellite (http://eo1.gsfc.nasa.gov) and Earth Observing Systems' Aqua/Terra spacecrafts' MODIS instrument (http://modis.gsfc.nasa.gov).

Earth Science Collaboration

Our demonstrations so far have been relatively simple to show the basic capability of SGM. They show the promise of coordinating data from different sources, analyzing the data for a scientifically relevant event, and autonomously updating and rapidly obtaining a follow-on scientifically relevant image in a number of different science domains, such as:

Forest Fire: In the forest fire demonstration, SGM served both as a science analyzer and a multi-mission coordinator. SGM monitored the daily list of active priority fires from the Remote Sensing Applications Center in Utah (http://www.fs.fed.us/eng/rsac). When a fire was detected in the scientist's specified region of interest, SGM analyzed the recent history of the fire from the MODIS Rapid Fire data in that area to isolate the latest center of activity. SGM then coordinated with the EO-1 planning systems to request and monitor a high-priority high-resolution image of the fire. SGM's web-based user interface provided the user with a live display of the status of his/her image request and automatically linked to the new EO-1 image when it became available. The SGM coordination and analysis provided new data to the US Forestry Service within 48 hours, compared to a typical lead-time of up to 14 days for preplanned observations.

Volcanoes: For the volcano scenario, the scientist specified a prioritized list of volcanoes to monitor for new eruptions. SGM then monitored each volcano site using data from the MODIS instrument. When an eruption was detected, SGM coordinated with EO-1 to automatically request a high-resolution image of the volcano area. If more than one eruption was detected, SGM selected the highest priority site for the follow-on EO-1 observation. The user received the high-resolution image via the SGM web front-end.

Floods: For flooding, we interfaced SGM to data from the Dartmouth Flood Observatory (http://www.dartmouth.edu/~floods), which monitors various rivers and wetlands around the world. QuickSCAT scatterometer instrument is used for monitoring. SGM monitored this data for flooding alerts concerning a user-specified river. For our demonstration, the Brahmaputra river in India was selected. SGM detected an alert and, as in the fire and volcanoes scenarios, sent a request for a high-resolution image acquisition to EO-1. Future flood scenarios will use ground in-situ sensors to predict potential flooding before it occurs, which will drive subsequent EO-1 observations of the target area.

Lake freezing: The University of Wisconsin maintains a series of buoys in Sparkling Lake that measure surface water temperature. The goal of this scenario was to monitor the data from those buoys to determine when the lake's first freezing occurred, then to take an image of the lake area as soon as possible to characterize the lake environment during the time of transition. SGM monitored the buoy readings for several days and triggered an EO-1 observation as soon as the temperature readings showed the lake to be freezing.

In the Earth Science domain we are now identifying new science scenarios that will have more complex reasoning. For example, by accessing real-time weather data from the GOES satellite, SGM can coordinate with EO-1 planning to obtain cloud free images to maximize the scientific value of the image obtained.

Astronomy Collaboration

A major focus of SGM is to enable astronomical observatories, ground-based or space-based, to respond more quickly to unpredictable astronomical events such as gamma ray bursts, cataclysmic variables, super novae etc. Such astronomical events occur without warning. A requirement for better understanding of these science phenomena is to obtain further observations as soon as the event is detected. An additional requirement, if an observatory interrupts its plan of observations to observe the event, is that the observatory needs to dynamically adjust the rest of the observing schedule to minimize the impact of the disruption to its original observing plan.

Thus far, the SGM and SMARTS collaborative teams have been working on setting up tools to allow SGM to communicate with the observing queue in a live, dynamic basis. We have been modeling our initial scenarios and are just starting to consider the problem of dynamically scheduling an observatory's observing plan. NASA's ASPEN scheduling system (Chien et al. 1999) developed at NASA's Jet Propulsion Laboratory will be used generate the observing plan.

Challenges and the Lessons Learned with regards to Human Interaction with Automation

A frequent pitfall that has occurred in exploring autonomous goal driven developments at NASA and especially in the astronomical community has been striving to accomplish too much too soon. With the SGM project we are taking a different approach. We are dividing up the problem of flexible scheduling and autonomously reacting to science driven events into a number of smaller achievable goals. Therefore in our first phase we are focusing on automation of relatively simple tasks. A related objective in the early automation phases will be to automate the more mundane and static activities, so that when a dynamic event occurs, the scientists are free to focus on the higher-end subjective science analysis for which they have studied and trained.

In the Earth Science demonstrations we have automated the mundane tasks of (1) monitoring data, (2) generating the technical details for the follow-on observation, (3) requesting the follow-on observations, and (4) tracking the status of the observation. The demonstrations showed that relevant science events can be accurately detected and that the details of the follow-on observations can be correctly captured and transmitted to the appropriate location autonomously. Further, the demonstrations show that existing assets, which were not built with autonomy in mind, can still be coordinated.

The next problem is the task of developing a dynamic schedule or observing plan. Rapidly or semi-autonomously responding to scientific events can be very disruptive to the spacecrafts' observing efficiency. This is especially true in the space science domain. In the SMARTS collaboration we are focusing on this aspect of the project. The observing schedule is currently developed manually on a daily basis by juggling various requirements and priorities of the different observing programs. Once the nightly observing begins, the schedule remains static. If a disruption occurs (such as cloud cover, instrument failure etc.), once observing resumes the operators simply skip observations whose scheduled start time has passed. In our first phase of enabling autonomous scheduling, we are focusing simply on improving the science returns for re-scheduling the remainder of a single night after a disruption. Dynamically rescheduling the observing plan over a short timescale will be very useful in the context of onboard scheduling. This is a far simpler challenge to model, execute, and compare against the static schedule. Once this is accomplished, we plan to introduce additional science evaluations that may initiate a change in the schedule based on recently (seconds to hours) occurring science events.

The Human-Computer Interface

It is not possible to capture all conceivable science goals in natural language and convert them into machine interpretable format, given the current state of natural language technology. However, there is a subset of science problems that we can capture and reproduce. One example is to capture goals to represent an effective strategy for observing time-variable phenomena. For time-variable phenomenon, goals can be defined as measurable objectives with contingency plans for follow-on work. Hence, in SGM we are confining to science problems that are time-variable. SGM interfaces with the science data stream to determine if a goal is met; and then notifies the relevant person/scheduler regarding changes in priorities.

When this research began, our intent was to develop a flexible user interface that allowed the scientist to specify a wide range of science goals. We developed a prototype that used visual programming concepts to provide a set of graphical building blocks with which the user could construct goals. While it was very flexible, the overwhelming reaction was that it was much too difficult to construct science goals. We discovered that the majority of science goals could be represented by a set of adjustable templates. This led to the abandonment of this first prototype and caused us to rethink our approach. Instead of a generic infinitely flexible user interface, we would instead present the user with a list of observation templates that the user could customize. Each template defined a typical kind of observation that the user might want to perform. These templates included parameters that the user could alter, but otherwise the template structure was fixed. While this approach did not allow the scientist to express all possible science goals, it did satisfy the majority of them, and since the system was quite easy to use, reaction to this new approach was very positive.

Knowledge Capture

Once we established that we would structure the system using a menu of science templates, we sought to build those templates in cooperation with our scientist users. This primarily consisted of a series of face-to-face interviews with the scientists, followed by emails to clarify particular issues. The first task consisted of identifying the set of science phenomena that we would support in our prototype. This included astronomical objects such as gamma ray bursts, X-ray binary sources, supernovae, etc., and Earth Science related events such as forest fires, volcanic eruptions etc. For each type of object, we developed a story for what the scientist was observing and how they would go about observing it. Each story contained branches where different things would occur if certain criteria were met in the science data. One challenge was coming to an agreement on the story, particularly because the different scientists that we interviewed did not always agree. It was very much an iterative process where we collected each scientist's version of the story, identified differences, and then clarified those differences with each scientist. In some cases this pointed to the need for a user-adjustable parameter where each scientist might tweak a value in the story. Fortunately, this was not a great problem; since the differences between the scientists' stories was generally relatively minor.

Perhaps the greater challenge has been in deciding which processes should be automated, and which should remain manual. Certainly those that require exact mathematical computation should be automated, but when we considered aspects that involved human decision-making, there were some concerns amongst the scientists. For example, in assigning priorities to observations for the purpose of optimizing the total observing run, a scientist will consider many factors. Some, such as the target location, are easy to capture. However, in this case the user is essentially determining the scientific worth of an observation, which is fundamentally a subjective task. We decided to attempt to automate as much as possible, but insert the human in the automation loop so that the human can provide their own subjective input into the process where necessary. An additional benefit of this strategy was that it alleviated the concerns of the users. The purpose of the system was not to automate and thus replace their jobs, but instead to automate only the tedious aspect of their jobs, freeing them to concentrate on the more interesting aspects.

Automation Challenges for Legacy Spacecraft

Since we are testing our prototype using operational environments, we have a number of automation challenges that would not exist if the environments were built with autonomy in mind.

Automation of Manual Tasks in an Existing Environment

NASA mission software has historically followed very conservative development and implementation methodologies, hence there are a number of routine tasks that require manual intervention. Further, each mission typically includes various bits of custom software to do different things, which is very labor-intensive to automate given that there are few standard interfaces to these tools. To change an existing system into a completely autonomous system is therefore not possible with the limited funds available. One must look at the full spectrum of automation possibilities and find the optimal level that will provide the most capability while minimizing disruption to current operations. Also, the work required to implement the new automation will likely need to be done by the existing mission engineering staff given that they are the ones who know the mission operations software, and are unlikely to trust outsiders to make changes to their existing mission operations software.

In our case with the EO-1 mission, we worked with the EO-1 engineers to add some level of automation on top of their largely manual operations software. We quickly ran into barriers, however, that limited the kinds of interactions we could achieve in the SGM software. This was largely due to their reluctance to disturb the existing processes. Automation that was layered on top of their existing system was generally accepted. However, the limit of such automation is directly related to the flexibility of the existing system design. In our case, the EO-1 operations system lacked several bits of fundamental information that we needed to achieve more advanced SGM tasks. To add those bits of data to the EO-1 system would have required modifications to the core EO-1 operations, something that the EO-1 engineers were unable to do with existing funds.

Change in Mission Operation Strategy

One desired outcome of detecting science events is the modification of the observing plan/schedule for the spacecraft. However, legacy missions' operations are not flexible enough to accommodate unexpected changes while maintaining a consistent plan and schedule. The inflexibility of a mission operation schedule does not affect autonomy as such but it dramatically restricts how proactive a system can be. For example, science objectives require that a target be observed, once an event is detected an autonomous system inserts the observation in the next available schedule. Now suppose the event is short-lived, because of the inflexibility of the operations schedule the autonomous system cannot dynamically change the schedule and could miss capturing the event entirely. Thus, the response time of any automated system built on an existing legacy system is largely bound by the response time of the legacy system. This can be a major problem if rapid changes are desired. Even though the legacy software may be able to handle more flexible scheduling, if the mission operation policies do not allow for that level of flexibility, it will not be possible.

In most cases, introducing flexible scheduling does not require an onboard scheduling system. Most existing spacecraft do not have sufficient onboard processing or storage capability to handle onboard scheduling. A flexible ground scheduler can handle modifications to the schedule and upload new plans to the spacecraft as necessary. However, depending on the temporal requirements of the science, this may not be sufficient. There will always be a response time advantage in making decisions onboard versus on the ground. In cases where every second counts, for example gamma ray bursts in astronomy, the ability to make decisions onboard is an enormous advantage. NASA's Swift spacecraft (http://swift.gsfc.nasa.gov) will do just that. Swift is designed to detect and observe gamma ray bursts. It contains onboard decision-making software that can analyze data and make near real-time decisions when a gamma ray burst is detected. Future spacecraft will either have onboard schedulers or will have enough processor and storage resources to allow for one, so considering what automation should be done onboard versus on the ground will become much more important in the near future.

Socio-political Challenges

Clearly, the capture of science goals to automate the operations of a spacecraft is not just a leap forward in automation, but a wholesale change in the operations paradigm. In developing an automated system like SGM we face skepticism not only from flight software teams; scientists themselves remain leery of expert/automation systems and are not yet convinced that their unique goals can be effectively and accurately captured and executed.

Recent GSFC's Advance Architectures and Automation Branch studies suggest that automation has yielded success in operations staff reductions, particularly for small, simple missions, but there remain barriers that impede further progress for complex, high profile missions such as Terra and HST (Cooter et al. 2001, Maks et al. 2001). Missions, especially complex high-profile missions, are more culturally and politically averse to risk when it comes to automation. The trade-off between scientific gains for successful risks versus the damaging publicity for failed risks is difficult to ignore.

We were very aware of these issues when we began this effort. Our strategy has been to start with a much more limited scope and lower risk level of automation, then to expand from there by adding additional automation as the comfort level of the users increased. In addition, by ensuring that humans remain in the automation loop throughout the process, we reduced the fear of automation making human tasks obsolete.

We have also done our best to understand the cultural barriers that we faced from our scientist users and to recognize their particular concerns. In both the Earth Science and Astronomy, scientists need to react dynamically to time-sensitive science events that directly affect the quality of the resulting science data. Yet, their reaction to an autonomous dynamic system is very different. Astronomers, for example, observe very faint objects, and so every photon that they capture is considered valuable. The idea of shortening the exposure time or canceling an observation is a particularly sensitive issue. Hence, when a science event is detected, disrupting a schedule has to take into consideration the observation that is presently occurring. Priorities for the various observations have to be considered while developing the dynamic schedule. Another consequence of being photon starved is that any form of onboard processing or compression is not easily accepted. The scientists are willing to consider some very simple onboard processing to detect events, but the raw data cannot be deleted. All the data (raw and processed) must be transmitted to the ground stations, affecting communications and onboard storage needs. Earth scientists, by contrast, have enormous amounts of data, and in fact have the problem of too much data. Further, they also have many more assets that can access their targets. Hence, scientists in this domain are much more conducive to considering dynamic automation strategies.

Conclusions

Developing a spacecraft with flexible scheduling, which can autonomously react to science driven events is not just a leap forward in automation, but a large change in operations paradigm. There are a number of challenges that need to be overcome to change the present NASA mission operation strategies. The Science Goal Monitor project is a proof-of-concept effort to address these challenges.

In SGM we are developing an interactive distributed system that will use onboard processing and storage combined with event-driven interfaces with ground-based processing and operations, to enable fast reaction to time-variable phenomena. We are currently developing prototypes and evaluating the effectiveness of the system. Although we have not completed our project, we have had some success. Our dynamic science analysis and autonomous multi-sensor coordination has been highly appreciated in the Earth science domain and scientists are looking forward to attempting more complex problems.

Acknowledgements: This work is funded by NASA Code R under the Computing, Information and Communications Technologies (CICT) program.

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