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# Agile Science: Using Onboard Autonomy for Primitive Bodies and Deep Space Exploration

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## Abstract

Future missions to primitive bodies will have limited time to explore these unknown targets. Because of long round trip light times, missions requiring ground control seldom change objectives dynamically or rapidly respond to new science opportunities. In order to address this issue, we are developing flight software for onboard science target detection and onboard response enabling closed loop autonomous action by the spacecraft. These response methods must be able to predict future opportunities to view the newly detected target using predicted spacecraft trajectory, target position and rotation, and future illumination conditions. The necessary geometric reasoning for observation planning has traditionally been performed on the ground by highly skilled operations personnel. We describe the software under development to perform this reasoning onboard and its application to future primitive bodies missions.

## 1 Introduction

To date, many deep space encounters are short flybys that use pre-scripted data collection sequences. This can negatively impact science yield, since it is not generally possible to precisely anticipate the pointing needed for narrow-field of view instruments. Operators cannot always speculatively predict the location of the features of greatest scientific interest prior to an encounter. For example, asteroids are mostly covered by thick space-weathered regolith that obscures the interior composition, so the occasional exposed areas of the substrata are high-value targets of opportunity for follow-up imaging and spectroscopy. Flybys generally cannot exploit such targets because their positions cannot be anticipated in advance. Additionally, with insufficient time for ground in the loop control it is impossible to reacquire or correct bad data caused by instrument errors, suboptimal exposure settings, or deviations from the predicted trajectory. Other rich and underexploited opportunities include the detection and study of transient or unexpected events such as outgassing and time-variable comet activity – a temporal dimension to the solar system that remains basically unexplored.

Spacecraft autonomy can help address these challenges. Onboard pattern recognition can vet data quality and analyze context images for features of opportunity. This can inform onboard resource-aware planners or procedural responses that can respond immediately if needed. In this manner, the spacecraft can reacquire bad data or target high-value features for additional data collection. The timing of the analysis and response is critical, since observations are constrained by spacecraft observation geometry, illumination, energy resources, and competing science activities. While previous work has evaluated components of the pattern recognition and response in isolation, no previous study of which we are aware has evaluated the entire system-level performance under realistic time constraints with flight-relevant hardware.

We are currently developing a real-time testbed to evaluate detection and response software in a flight-like environment. The evaluation testbed simulates flyby and encounter trajectories together with realistic images drawn from archival datasets of previous encounters with primitive bodies. The flight computer, a RAD750, performs basic image analysis and response operations according to priorities dictated in advance by science team operators. We describe the results of initial experiments including the performance in meeting desired science objectives and the quantitative tradeoffs between processing time and science yield.

## 2 Primitive Bodies Exploration: Challenges and Opportunities

Exploring primitive bodies presents a number of challenges. First, the science features and events being detected include varied and subtle signatures:

- Plumes and outgassing events can be very faint and

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may appear in orientations that are challenging to detect (e.g., a plume erupting towards the spacecraft).

- Illumination may be poor due to the Sun's position (e.g., lighting behind the target).
- The morphology of the target may also present illumination challenges. If the target body has a very irregular shape, the exact illumination and observer viewing geometry may not be easily predictable.
- The target body may have unknown geology, making estimation of reflectance and other parameters more challenging.

In addition, primitive bodies exploration often involves challenging timescales. Target bodies in the asteroid belt imply round trip light times to the Earth of approximately 1 hour. Given flyby durations of approximately 1 hour, ground analysis and response to downlinked science data by a ground team is not generally possible. Moreover, navigation in the vicinity of primitive bodies is challenging due to many unknowns:

- The gravity field of the target body is typically not well understood in advance. This poor gravity model will add uncertainty to any projected trajectory.
- The rotational axis and period may only be partially known.
- Gas fields (e.g., for a comet) and out-gassing events for comets and asteroids are unpredictable and can change the science environment as well as the spacecraft trajectory (due to changes in drag) with little or no warning.
- Unknown satellites may be present. It may not be known if there are satellites prior to arrival. Satellites are both science targets and spacecraft safety hazards.

In general, there have been few close proximity encounters with primitive bodies, and our experience with these objects is limited. There are few images or instrument datasets collected from a range close enough to reveal distinct surface features. This is particularly important in the context of the diversity of primitive body objects.

Agile science techniques are applicable across a wide range of primitive body missions/concepts either currently flying or under study. Figure 1 (top) shows the many unknowns that primitive bodies missions encounter. Figure 1 (bottom) shows the many relevant agile science technologies for each of the target primitive bodies missions.

| | | Missions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Asteroid / inert | | | | | Comet / active | | | | |
| | | Dawn-style mapping | Hayabusa II | OSIRIS-Rex | Trojan Tour | Chiron Orbiter | Rosetta | Comet Hopper | CSSR | CNSR/CCSR | Coma Sampler |
| Mission and science unknowns | Morphological units | x | x | x | x | x | x | x | x | x | x |
| | Surface composition, mineralogy | x | x | x | x | x | x | x | x | x | x |
| | Localized targets (boulders, crater walls, etc) | x | x | x | x | x | x | x | x | x | x |
| | Satellites | x | | | | | | | | | |
| | Plume activity, distribution over space and time | | | | | | x | x | x | x | x |
| | Gravity field | x | | | | | | | | | |
| | Location of site for sampling/landing | | x | x | | | x | x | x | x | |
| | Surface conditions at sample site | | x | x | | | x | x | x | x | |
| | Rotation rate and pole location | x | x | x | | | x | x | x | x | x |
| | Spacecraft performance / faults | x | x | x | x | x | x | x | x | x | x |
| Applicable ground ops technologies | Single-cycle trajectory/observation selection | x | x | x | x | | x | x | x | x | x |
| | Fast instrument data processing | x | x | x | x | | x | x | x | x | x |
| | Fast instrument data interpretation | x | x | x | x | | x | x | x | x | x |
| Applicable onboard technologies | Trajectory replan (fault or hazard recovery) | | x | x | | | x | x | x | x | x |
| | Observation replan (opportunistic targeting) | x | x | x | x | | x | x | x | x | x |
| | Morphological pattern recognition | x | x | x | x | | x | x | x | x | x |
| | Spectral pattern recognition | x | x | x | x | | x | x | x | x | x |
| | Plume/change detection | | | | | | x | x | x | x | x |
| | Satellite detection | x | | | | | | | | | |
| | TRN / optical navigation for prox. ops | | x | x | | | x | x | x | x | |
| | Onboard planning / execution for prox. ops | | x | x | | | x | x | x | x | |

Figure 1: Mission Unknowns for Primitive Bodies (top) and Relevance of Agile Science Technologies to Primitive bodies Missions (bottom).

## 3 Agile Science Scenario: Flyby

Our driving scenario for onboard autonomy ("Agile Science") is a primitive body flyby. Consider the 2010 Rosetta Orbiter flyby of the Lutetia asteroid. The timeline of the flyby is shown in Figure 2. With a relative velocity of approximately 15 km per second, the flyby lasts less than an hour, far too short a time to involve the ground in the loop to command the spacecraft, since round trip light times are approximately one hour.

Traditionally, flybys would be painstakingly planned by operators using their best estimated locations of expected targets of highest science interest. These ground-planned observation sequences would be executed "open loop" based on timing alone. *Critically, due to round trip light times, early acquisitions of science data would not be able to inform later observations.*

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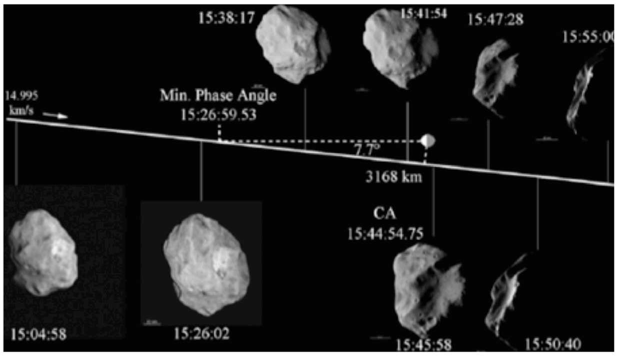


Figure 2: Lutetia 12 flyby as a use case for Agile Science smart flyby: ~ 1 hour of imagery, ~ 15km/s flyby velocity, closest approach ~ 3000km.

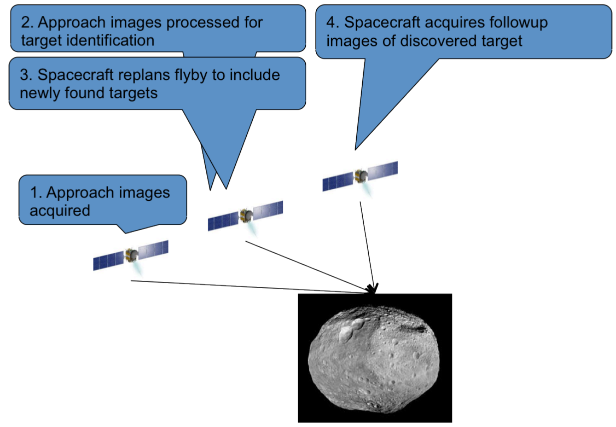


Figure 3: Onboard Autonomous Target Detection, Prioritization, and Response.

In the Agile Science paradigm, the spacecraft and flight software enable onboard analysis of acquired science data to inform subsequent spacecraft actions. Specifically, the procedure would be to:

- Acquire science data
- Analyze science data onboard, detecting pre-specified features of interest
- Generate new data acquisition/target requests using priorities pre-specified by the science team
- Assimilate new target requests into the operational plan as appropriate based on prioritization.

This paradigm is illustrated by the operations scenario shown in Figure 3.

## 4 Onboard Autonomous Target Detection

An important aspect of the Agile Science methodology is the ability to analyze data autonomously onboard the spacecraft to detect high priority science targets [Thompson et al. 2012, Fuchs et al. 2014]. While the general concept of Agile Science applies to a wide range of instruments, initially we have focused on imaging instruments. These instruments are central to most space missions, and commonly available as navigation cameras on nearly all modern spacecraft. Moreover, they provide a wide field of view and are capable of localizing detected targets with high precision. Finally, they can detect a wide range of different targets which enables us to exercise a range of target detection and follow-up scenarios. For primitive bodies exploration there is a wide range of science phenomena that can be discovered upon arrival at the target that warrant follow-up observations, including:

- Point source detection for target or satellite searches
- Outgassing and plume detection
- Searches for specific materials or surface morphologies.

Figure 4 shows two promising onboard processing analysis products. The left image shows the detection of high albedo areas in an image of the Hartley asteroid, as acquired by the Deep Impact spacecraft. Detection of high albedo areas is achieved by computing the convex hull enclosing the target's horizon points and then

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classifying the pixels whose intensities differ substantially from the median intensity of the pixels within the convex hull. These bright albedo areas are of high science interest because they often indicate the presence of volatile substances or, in the case of regolith-covered asteroids, fresh mineralogy unearthed by impacts or mass wasting. Such targets are candidates for high-resolution imagery or point spectroscopy.

The right panel shows a detection of a plume in an image of Enceladus acquired by the Cassini spacecraft. Here the system determines a polygonal mask defined by the aforementioned convex hull. Bright regions within an annulus surrounding the mask are candidate plumes. Plumes are of high scientific interest, and the spacecraft could respond by increasing its imaging rate or using narrow field of view instruments to target the plume directly.

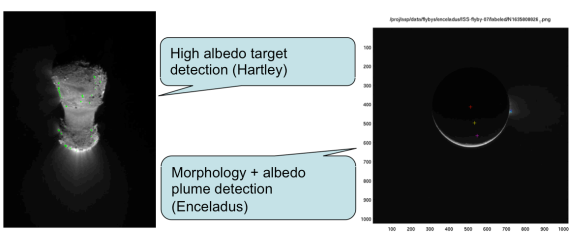


Figure 4: High Albedo Region Detection; Plume Detection

The onboard detection algorithms produce images with a (possibly empty) set of detections. Next, targets are selected based on priorities defined in advance by the science team. For example, a new target may be generated only if a plume appears in several consecutive image frames. As another example, a bright albedo algorithm may only produce a target if the area of bright albedo exceeds a given threshold of brightness and exceeds an area (size) threshold. The output of the target detection algorithm is a set of prioritized targets in the acquired imagery.

## 5 Geometric Computation

The target identification process produces a set of targets that are associated with priorities as well as specific line and sample locations in the image frame. This coordinate in image space must be transformed into a target space coordinate (e.g., lat/lon, altitude on target body). Next, calculations based on the spacecraft trajectory must be combined to determine legal viewing times (accounting for solar position, rotation of the target body, etc.). This will produce a set of possible re-imaging opportunities. Each of these can be considered a tuple of:

<opportunity-type-ID, priority, start time, end-time>

which is associated with a required spacecraft pointing (via the opportunity type) and associated observation and target location. These observation opportunities are then passed to the onboard response system as new requested science goals with appropriate prioritization. An important point is that this geometric reasoning involving the relative positioning and trajectories of the target body, spacecraft, sun, and other bodies is traditionally done in a time and knowledge intensive ground-based observation planning process. One of the unique aspects of this work is to migrate this functionality onboard the spacecraft.

For many of these geometric calculations the SPICE library [NAIF] is the common standard used for spacecraft operations. In our implementation we have used a combination of libraries from SPICE as well as some custom code. One element of future work will be to ensure that these calculations can fit within limited flight software computing resources.

Once the timing of the re-observation opportunities has been computed they can be passed to the procedural or model-based response system which then attempts to schedule follow-up observations as warranted by the science priorities. Figure 5 shows this process of mapping the targets from the image space into a known frame of reference (such as the target body) to determine when the spacecraft position, illumination, and target body position and orientation allow for follow-up imagery.

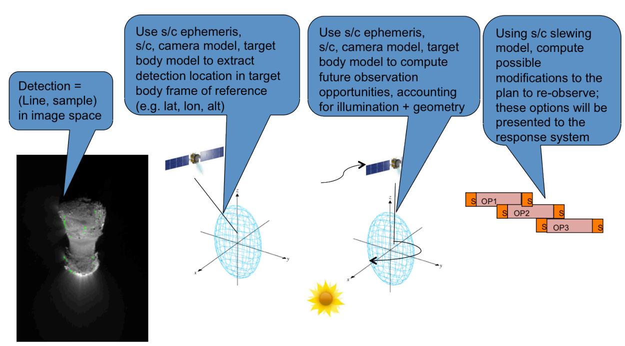


Figure 5: Geometric processing is required to determine valid response imaging opportunities

## 6 Procedural and Model-based Onboard Responses

We have implemented two response systems: an ad-hoc response system and a model-based response system. For the current Agile Science procedural software prototype we utilize an ad-hoc scheduler and the Core Flight Software procedural response system. The ad-hoc scheduler takes the pre-defined responses defined by the science team and determines which highest priority responses should be executed. These responses are scheduled in a priority-first fashion using a greedy, heuristic, non-incremental scheduler. The scheduled responses are then mapped to sequences in the core flight software sequence engine [Weiss 2013] enabling a modest range of alternative responses.

As a second, more general, response implementation we have used the CASPER system [Chien et al. 2000, Knight et al. 2001]. In this approach, detections from observations may spawn new goals posed to a model-based planning system, specifically the CASPER embedded planning system. The goals are posed to CASPER with priorities, and CASPER uses its plan optimization capability to attempt to achieve the greatest number of highest priority goals. This approach has the benefit of being able to generate entirely new observation plans that achieve the highest priority science goals while respecting operations constraints. However, model-based planning is harder to verify and validate, and it also requires more onboard computation than a procedural response.

## 7 Related Work, Future Work, and Conclusions

The Agile Science project has currently implemented integrated detection and response prototypes using both procedural and model-based response in a Linux.workstation environment. The primary effort for 2014 is to bring these software prototypes into an embedded software simulation VxWorks environment.

Considerable prior work has investigated spacecraft autonomy using procedural and model-based methods.

- The Autonomous Sciencecraft (ASE) [Chien et. al 2005] utilized a planner (CASPER) in concert with the Spacecraft Command Language (SCL) executive and has been used for primary operations of Earth Observing One 2004 to the present (2014).

- V AMOS [Worle and Lenzen 2013] is an onboard executive in development by DLR that validates branching plans on the ground and then selects execution branches onboard for operational flexibility.

- GOAC [Frratini et al. 2013] is a goal-oriented architecture developed by ESA for future onboard use.

- The Remote Agent [Muscettola et al. 1998] utilized the batch planner RAX-PS and the procedural executive ESL [Gat 1997] to control the Deep Space One mission for 48 hours in 1999.

- T-Rex [Rajan et a. 2013] is a planning and execution architecture that has been deployed for control of autonomous underwater vehicles.

- SCL [Prumo et al. 2009] in addition to ASE has been used on the Tacsat-2 mission to offer on-board procedural rule-based automation.

We have presented the Agile Science approach to onboard autonomy. Agile Science can enable dynamic science for primitive body missions. Many science events can be detected via instrument data processing techniques that are amenable to on- board computation.

We have demonstrated a capability to perform:

- Target Detection: Target extraction and geometric computation required for re-observation opportunity analysis

- Response: Modification of the existing observation plan to incorporate the new observation if warranted by science priorities

- Execution of the new plan

This capability is currently implemented in a Linux/workstation software testbed and is being matured to a VxWorks/embedded platform on the path to eventual operational use.

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