

Onboard Science Techniques to Optimize Science Data Retrieval from Small Spacecraft. J. Lightholder, D.R. Thompson, W. Huffman, J. Boland, S. Chien, J. Castillo-Rogez, Jet Propulsion Laboratory, California Institute of Technology, (4800 Oak Grove Drive, Pasadena, CA 91109, {jack.a.lightholder, david.r.thompson, justin.s.boland, steve.a.chien, julie.c.castillo}@jpl.nasa.gov).

Introduction: As small spacecraft begin to travel beyond low earth orbit, mission planners are likely to encounter platform constraints that may adversely affect operations and instrument design. These include limits to instrument aperture, low communications bandwidth, and attitude control. Compensatory software based strategies for mitigating these limitations have recently been introduced in order to make efficient interplanetary small spacecraft a reality. These strategies move the zero-order science data analysis, traditionally completed on the ground, onboard the spacecraft. Moving the science analysis to the spacecraft allows for significant reductions in required bandwidth for sending crucial scientific data products. These techniques have additional potential for integration into larger interplanetary missions for increasing overall mission science return.

Goal: Developing software solutions to optimize science return in resource constrained missions is the focus of this work. The Near Earth Asteroid (NEA) Scout mission, launching in 2018 with the Space Launch System Exploration Mission 1, will demonstrate these capabilities as critical mission components.

This 6U CubeSat propelled by a solar sail will perform the reconnaissance of a near earth asteroid via multispectral imaging in the visible. Onboard science techniques are being implemented for detection, navigation towards, and observation of the target. Several unique challenges of the small platform make this objective challenging. First, the encounter will take place at about 1 AU from earth where the downlink rate afforded by the CubeSat is a mere 1 kbps. In addition, the small mass and large solar sail makes stable pointing difficult, so that the Attitude Control System (ACS) will be challenged to achieve the pointing precision needed for long camera integrations to detect the target when in range. Finally, the cubesat platform also requires low instrument mass, compounding the detection challenge. Novel onboard science data analyses will permit image coalignment and coaddition, improving the effective sensitivity without bandwidth requirements of downlinking large image sequences. Automatic coalignment provides resilience to cosmic ray artifacts as well as ACS-induced drift.

Methods: In order to be practically deployed on flight hardware the NEAScout Science toolkit must have a small working memory footprint as well as min-

imal power requirements. The techniques can broadly be categorized as (1) image radiometric calibration and (2) target detection. Each of these processes is completed onboard the spacecraft, permitting efficient downlink of the finalized scientific data products.

Radiometric Calibration: Flight calibration of optical instrumentation is not a new challenge. However, to optimize volume, cost, and complexity, a shutter has been omitted from the NEAScout Science Imager. While this poses challenges for the collection of dark current and flat fielding frames, the Agile Science toolkit includes an image co-addition software capability which works as a median filter across an image set. Dark current reference frames can be generated without the use of a shutter by taking a collection of zero second exposure images and using co-addition to create a single high fidelity reference frame for dark current subtraction. This process simultaneously eliminates single image events such as cosmic rays. Flat fielding is handled with pre-launch laboratory calibration in conjunction with non-illuminated pixel querying in flight. By querying these non-illuminated pixels, radiation degradation of the detector can be characterized and adjusted for. These areas will be characterized for stray light preceding launch and will act as a reference to characterize radiation decay. Detector specific radiometric calibration characterization routines have been written into the science software with coefficients updated automatically in flight based on the results of preceding flat field and dark current investigations. The generation and processing of calibration data in flight eliminates the need to send these frames to ground for scientific calibration under nominal science operations.

Target Detection: Strategies for early target detection utilize software functionality to support the limited aperture camera equipment available to small spacecraft platforms. Small aperture systems on a spacecraft with minimal pointing accuracy would challenge traditional optical navigation on these platforms; they would reduce single-frame image sensitivity to below the level needed for timely detection of a wide range of small, dark primitive body targets. We address this challenge with software strategies for early target detection that are appropriate for the limited aperture camera equipment available to small spacecraft platforms.

The first step in target detection is to increase the fidelity of the acquired data. This is accomplished with image coaddition on at least ten images taken in rapid succession. For the NEAScout target at nominal detection distance, these images must carry a signal to noise ratio of 5. The brightest point sources persistent across all images (bright stars) are then identified as image anchor points. The row/column shift between any two images can then be determined by calculating the shift in centroid for any reference star between two images. We search for the optimal cross-correlation over a finite search window based on the expected travel distance of the starfield. Once these shift parameters are known for each image pair, the images are aligned and pixel values are combined. Coaddition is then performed on the aligned stack, increasing the signal to noise ratio to 7 [1]. In addition to increasing the fidelity of the data, the combination strategy uses a triplet-median method that filters single-pixel anomalies such as cosmic rays. This also reduces memory requirements because it is never necessary to store more than a few frames in memory at one time.

A more ambitious objective is to detect the target onboard, so that only the target row and column image coordinates need be downlinked. This involves two coadded image stacks acquired with a time difference permitting a shift in the target across the stationary starfield. Applying a pixel value subtraction between the aligned images will eliminate the background starfield, leaving only the target as an illuminated point source. The coordinate of the point source centroid is then recorded as an onboard data product for later use [2].

Onboard instrument calibration and target detection allow for controlled testing of onboard autonomous systems. The results of these processes, and their intermediary data, are stored onboard to be queued for downlink as needed. Because of the size of resulting data products, they can easily be downlinked for terrestrial validation by the spacecraft team.

Implementation: In order to be practically deployed on CubeSat-class flight hardware the Agile Science toolkit must have a small working memory footprint as well as minimal power requirements. The computer and data handling (C&DH) subsystem onboard NEAScout was in part designed to enable agile science processing. It offers dual core processing with 134 MIPS in full duplex and peak power < 7W.

Testing: The NEAScout software continues to meet mission expectations as the flight ready distribution undergoes testing. Testing involves both synthetically generated data and past mission data available on the Planetary Data System. These include the New Horizons data from the Long Range Reconnaissance

Imager (LORRI) upon approach to Pluto [3]; the Rosetta mission encounters of Steins[4] using the wide angle camera and 67P using the navigation camera [5]. Coaddition achieved anticipated improvements in SNR as more images were analyzed. Applying the detection algorithm to raw (uncalibrated) mission data, target detection rates over 95%. Failures are typically due to the unavoidable case of a target obscured by a point source in the star field, resulting in the target being subtracted away with the background star field. This condition can be detected in the resulting data product, which will not conform to mission specific expectations with respect to brightness and general target area. The process for reacquiring the target is to repeat the analysis process with another coadded image stack, taken at a different time. The occurrence rate of this boundary phenomenon pathological case is related to the density of background stars in the reference frame. This can be controlled with exposure time of the images, a mission specific parameter which can be determined before launch or adjusted in flight.

Conclusions: As smaller spacecraft conduct interplanetary travel, communications bandwidth, ACS-induced drift, power and instrument volume constraints will increasingly hinder the volume of scientific return. Here, novel software addresses the problems of limited ground contact on interplanetary missions as well as the inherent physical limitations imposed by small spacecraft platforms. A unified software solution addresses both problems with minimal software infrastructure overhead.

More generally, moving well-defined data analysis onboard the spacecraft allows for more efficient and effective human interaction while preserving the critical decisions for the human controllers. By reducing the data volume required to downlink for practical scientific decision making, operations teams can access the scientific return of a mission in significantly reduced timescales when compared to the status quo defined by larger missions' science downlink strategies.

References: [1] Huffman W. et al. (2015) The Astronomical Society of the Pacific [2] Thompson D. et al. (2012) *SpaceOps* [3] Cheng A. (2014) NASA Planetary Data System, 2014 [4] Hviid S. et al. (2011) ESA Planetary Science Archive [5] Geiger B. (2015) NASA Planetary Data System