IMPROVED DETECTION OF A NEAR-EARTH ASTEROID FROM AN INTERPLANETARY CUBESAT MISSION

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Abstract. *This work considers the autonomous detection of a small faint Near-Earth Asteroid using a commercial off-the-shelf camera during the approach phase of an interplanetary CubeSat mission. A standalone user-friendly design tool was created that considers the camera parameters, the asteroid parameters, the geometry of the approach phase and the stacked frame technique to generate a synthetic SNR that meets the target asteroid detection requirements (SNR ≥ 7). Results of the design tool are validated against an image simulator to generate realistic images of the target asteroid during the approach phase of the asteroid rendezvous mission.*

Introduction. In recent years, there has been a focus on developing technology for in-situ resource utilization on asteroids. Two recently accepted CubeSat missions to characterize Near-Earth Asteroids (NEAs), resource-rich bodies, are NASA's NEAScout[1] and ESA's M-ARGO[2]. While CubeSats' low-cost are a tremendous benefit to rapidly testing new technologies, the drawback is the unavailability of cheaper space-rated equipment that are high performing like their high-cost counterparts.

Given an interplanetary CubeSat's camera system and an asteroid of interest, the detection (SNR ≥ 7) of the asteroid at a conservative observational distance during the approach phase, e.g., the distance where the asteroid's $\pm 3\sigma$ positional uncertainty fits within the sensor's field of view (FOV), it may not be possible to guarantee a detection from a single image due to the CubeSat sensor's signal to noise ratio (SNR) being too low. This motivates the research question of how to bound the camera parameter and the required number of images to guarantee the autonomous detection of a small (Diameter<50m) faint (Absolute Magnitude>20) NEA using a commercial off-the-shelf camera during the approach phase of an interplanetary CubeSat mission.

Due to satellite jitter, CubeSat-based imagers are unable to use long exposure times to increase the SNR[3]. One method to increase the SNR is to take many short exposure images and combine them with the shift-and-add technique[4], where multiple images are stacked and corrected with respect to the spacecraft's attitude, to synthetically boost the SNR[3].

As the SNR of a single image depends on the camera sensor and the observational configuration, it is important to develop a fast-prototyping tool which defines requirements at both the camera and trajectory design levels and explores the problem design space during the preliminary design phase. A standalone user-friendly design tool was created that considers the camera parameters, the asteroid parameters, the geometry of the approach phase and the increased SNR from the stacked frame technique to generate a synthetic SNR that meets the target asteroid detection requirements (SNR ≥ 7).

Design Tool. The design tool uses both camera specifications and asteroid specifications as inputs, as depicted in Fig. 1. The design tool uses the input parameters to generate intermediate output plots, which the designer uses to visually determine ranges of acceptable inputs for the final desired SNR. There are four intermediate output plots and one reference plot, based on the three equations that govern the design space. The first equation is the optimal imaging range from the spacecraft camera to the asteroid which includes the $\pm 3\sigma$ positional uncertainty of the asteroid in the camera's FOV: $range = \frac{\sigma * 6/2}{FOV/2}$.

The second is the apparent visual magnitude of the asteroid as seen from the spacecraft camera[5]: $V = H + 5log_{10}(r\Delta) - 2.5log_{10}[(1-G)\varphi_1(\alpha) + G\varphi_2(\alpha)]$,

where $\varphi_i(\alpha) = e^{-A_i(\tan\frac{\alpha}{2})^{B_i}}$, i = 1 or 2, $A_1 = 3.33$, $A_2 = 1.87$, $B_1 = 0.63$, $B_2 = 1.22$, H is the absolute magnitude, r is the distance from the asteroid to the Sun, Δ, is the distance from the asteroid to the observer, G is the asteroid slop parameter, and α is the phase angle in degrees.

The third is the synthetic SNR, SNR', of N stacked images: $SNR' = SNR * \sqrt{N}$.

The plots generated from the three equations are contour plots that depict the relation of the output of the equation, represented by contour lines, with the two independent variable inputs, represented on the axes (Fig. 2). The first plot shows the conservative imaging range from the spacecraft camera to the asteroid as a function of the spacecraft camera's FOV and the linear addition of both the spacecraft and asteroid's positional uncertainties. The second plot depicts the visual magnitude of the asteroid as a function of the phase angle and the previously calculated range to the asteroid. The third shows as contour lines the camera reference parameter epsilon, which is a combination of the aperture diameter in centimeters and the exposure time in seconds. The epsilon parameter is used in the fourth plot, which depicts the SNR in a single frame from the signal received from the asteroid as a function of the camera parameter epsilon and the visual magnitude of the asteroid. The fifth plot shows the synthetic SNR, SNR', as a function of the SNR of a single frame and the number of stacked frames. These plots provide a visual into the

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problem's design space, allowing the user to identify optimal values for the input camera and orbit parameters.

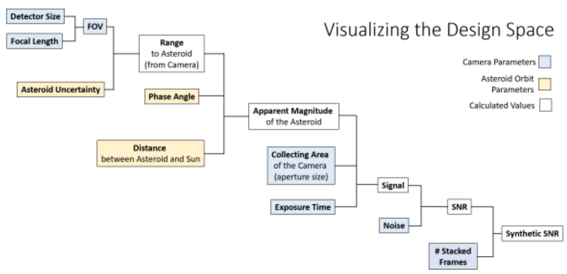

Figure 1. Design tool input parameters.

Results. We provide a demonstration of the design tool for M-ARGO target asteroid 2014 YD. First, we consider the proposed navigation camera, for the M-ARGO mission[6] and show how the design tool improves the final synthetic SNR to ≥ 7 while simultaneously generating the requirements for both camera hardware and the spacecraft orbit approach. We consider four different scenarios of iterative parameter selections as we explore the design space.

The first scenario, represented by a red star (Fig. 2), uses conservative values for a CubeSat camera. An SNR of 0.5 in a single frame at the conservative range to the asteroid is generated, which is not high enough to guarantee a detection of the asteroid. If we consider using the stacked frame technique, it will take ~200 stacked frames to reach a synthetic SNR of 7. This number of stacked frames is unrealistic for the onboard processing capacity of a CubeSat, where the maximum number of stacked frames can be realistically estimated at 10 frames[3].

The second scenario, represented by a green star (Fig. 2), increases the exposure rate from 0.1 to 1 second while leaving all other parameters equal, and returns a single frame SNR of 5.3, and combined with the stacked frame technique, takes only 2 stacked frames to return a detection SNR of 7.

The third scenario, represented by a blue star (Fig. 2), increases the sensor size, and doubles the aperture diameter while keeping the other parameters the same and returns a single frame SNR of 2.5, requiring 8 stacked frames to generate a synthetic SNR of 7. This scenario models the NEAScout mission with the design tool.

In the fourth scenario, represented by a purple star, the asteroid orbit parameters are changed, decreasing the range to half of the optimum range to the asteroid and decreasing the phase angle from 15 degrees to 10 degrees while the camera parameters are held constant, using the original conservative camera. Because of the decreased range to the asteroid, the FOV of the camera no longer encompasses the $\pm 3\sigma$ positional uncertainty of the asteroid. This requirement could still be met by utilizing the scanning technique, where the camera captures four images in a square 'scanning' format to simulate the same coverage of the camera's FOV at the optimum range. The result of using the scanning technique is a single frame SNR of 2.5, which, like the prior scenario, requires 8 stacked frames to return a final synthetic SNR of 7. However, this approach is limited by the pointing error of the spacecraft and the processing power onboard.

The outputs of the design tool are used as inputs to an image simulation rendering engine[7], which generates realistic images of the target asteroid during the approach phase. The image outputs can be stacked to achieve the final synthetic frame.

Fig. 3 depicts a single frame of the second scenario with a 1 second exposure time and the resulting stacked image output to generate a synthetic SNR of ≥ 7. The asteroid is not detectable (indistinguishable from noise) in the single frame but is apparent in the stacked image.

Conclusions. We have been able to demonstrate how the design tool can explore the design space of the detection of the asteroid in a single frame by increasing the synthetic SNR when the $\pm 3\sigma$ of the asteroid's positional uncertainty is included in the FOV of the CubeSat sensor.

The design tool provides the user with output camera hardware specifications, approach orbit, range requirements, and the number of stacked frames necessary for an SNR ≥ 7 for an asteroid rendezvous CubeSat mission design. These outputs can be used as inputs to an image simulation tool which then generates realistic images of the approach phase of the asteroid rendezvous mission from which the stacked image technique can be implemented.

Another application area for the design tool would be increasing the likelihood of detecting NEAs from cis-lunar space, for example, characterizing a space-based telescope for an early-warning asteroid system.

References.

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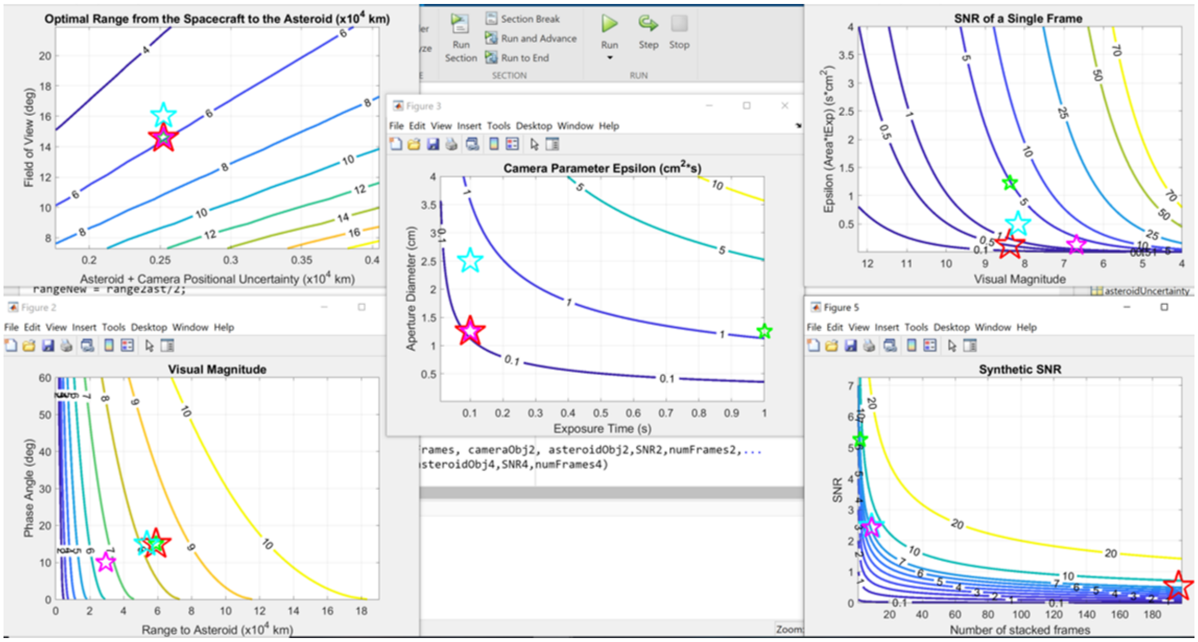

Figure 2. Design tool output.

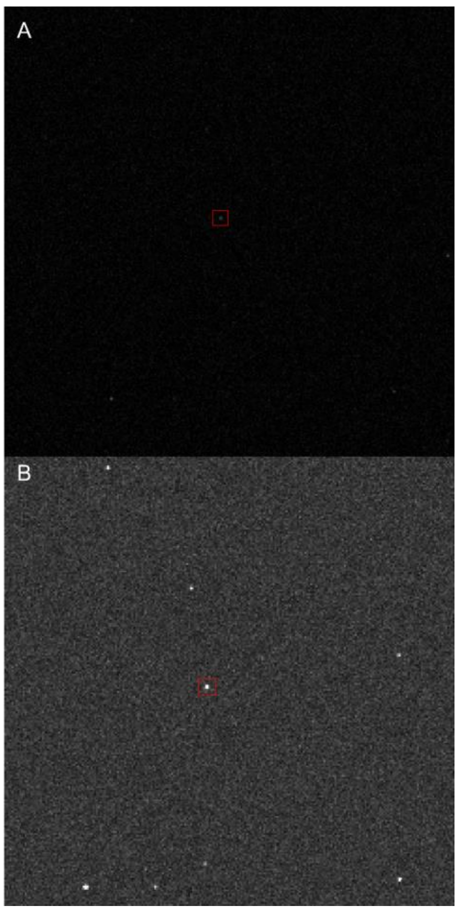

Figure 3. Single frame of scenario 2 (A) and stacked output image (B). The asteroid position is outlined in red.

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