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Optimizing Surface Ablation Deflection in the Presence of Realistic Asteroid Topography and Rotation

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EXTENDED ABSTRACT

Surface ablation can be used for hazardous asteroid deflection (Melosh et al, 1994) through heating of the surface by using mirrors to reflect sunlight or directly with lasers. In either case, the impulse from ablated material acts in the asteroid surface normal direction. In order to optimize the deflection to maximize the minimum orbit intercept distance (MOID), the ΔV should generally be aligned with the asteroid's orbital velocity direction (Kahle et al, 2006; Carusi et al, 2002), which efficiently changes the semi-major axis. Thus to maximize the deflection, material should be ablated from portions of the surface when the normal is aligned with the orbital velocity direction. If the asteroid were a sphere, this would be simple because the ablating spacecraft would simply target the leading (or trailing) point of the asteroid surface. However, for realistic asteroids the variation in topography means that this technique will be inefficient as the surface normal is generally not aligned as desired. Furthermore, since asteroids are rotating bodies, the orientation of the topography with respect to the orbital velocity is constantly changing.

This paper has two purposes. First, we will quantify the actual decrease in efficiency of an ablation deflection strategy if the topography is not taken into account. This will be done for three representative small asteroids for which shape models are available - Golevka, Itokawa, and Bennu - which are shown in Fig. 1. Efficiencies for strategies targeting only a single point on the asteroid, or for those which illuminate a swath of the asteroid surface (Schweickart et al., 2004) will be presented.

Figure 1 - Shape models of asteroids Golevka (left), Itokawa (center), and Bennu (right) used in this study.

The second purpose of this paper is to develop a control strategy to mitigate these effects if the shape is known. Initially this consists of optimizing the set of points on the asteroid surface to target that are most closely aligned with the desired impulse direction over the spin of the asteroid. This set of desired ablation targets will then be fed into a simulation which models the spacecraft and asteroid dynamics to determine constraints on the spacecraft system. Various spacecraft-asteroid relative orbit configurations will be investigated, starting with the ideal case of the spacecraft at a fixed point relative to the asteroid center-of-mass, and culminating with a full integration of the spacecraft orbit to assess the possible orbits and their associated fuel requirements for achieving a desired deflection.

Recommendations on system requirements to achieve successful ablation deflection in light of these realistic asteroid shapes will be included.

Golevka

The Near Earth Asteroid Golevka is an Apollo, discovered in 1991 by E. F. Helin at Palomar, and a detailed shape model was subsequently produced from radar observations [Ostro et al, 2000], which is shown in Fig. 1. The spin pole direction was found to be at λ=202° and β=-45°. Due to the complicated topography of this shape and the fact that the spin axis is not oriented perpendicular to its orbit plane, the relative angle between the surface normal at the trailing edge and the orbital velocity changes both with spin angle and heliocentric orbit position.

According to past studies on using ablation techniques, the heating is typically targeted at a fixed point, generally the trailing point (opposite the velocity direction) on the asteroid in order to maximize the velocity change. If this strategy were used on a real asteroid, however, there would be both a loss of efficiency in the thrust directed in the velocity direction, and a non-zero thrust generated in the perpendicular directions due to the topography of the asteroid. In order to illustrate this, we arbitrarily picked two points in the year to demonstrate the change to the expected thrust direction – when the pole longitude is 0° and 60° from the heliocentric orbit radius vector. The facets seen over one rotation in these cases are pictured in Fig. 2.

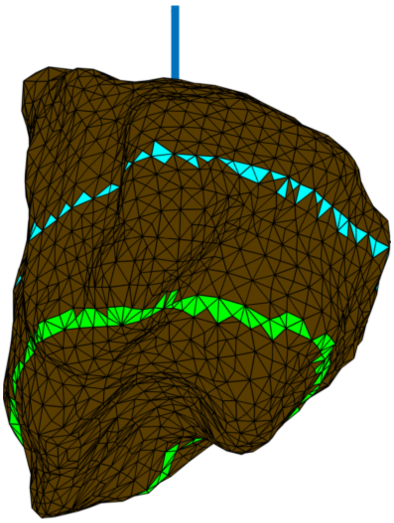

Figure 2 - Facets seen from 0° (cyan) and 60° (green) pole longitudes. Spin pole is blue.

The angle between the ablated surface point and the desired thrust direction is shown in Fig 3 for these two cases. Similarly the component of the thrust in each of the three directions is shown in Fig 4. Each of these results is shown for one revolution of Golevka. If these are averaged over the revolution, we find that for the 0° case the thrust in the desired direction is 91.07% of that predicted with the spherical assumption, and approximately 3% of the thrust is directed in the perpendicular in-plane direction, while 1.5% of the thrust is directed out of plan. For the 60° case the thrust in the desired direction drops to 86.14%, and approximately 1% of the thrust is directed in the other two directions.

The drop in effective thrust of approximately 10% is clearly undesirable. In order to counteract the effect of the topography, the entire viewable surface must be investigated to try to minimize the angle between the desired thrust direction and the surface normal at a given orientation throughout the year.

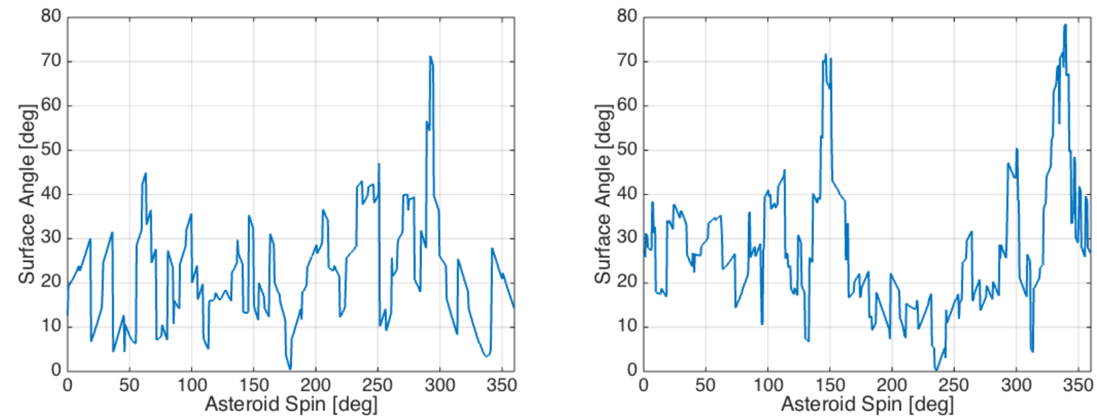

Figure 3 - Surface angle for 0° (left) and 60° (right) longitude over one spin revolution of Golevka.

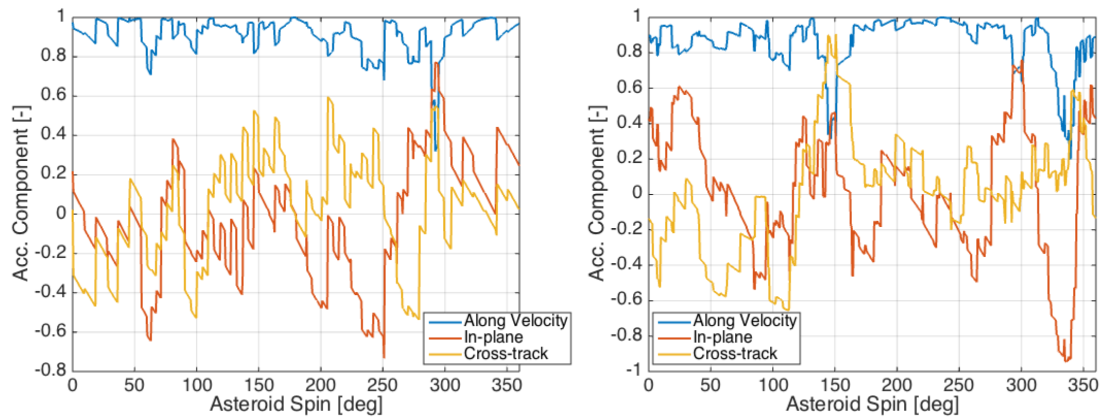

Figure 4 - Proportion of acceleration in each direction for the 0° (left) and 60° (right) pole longitude over one spin revolution of Golevka.

Two examples of the surface angles plotted on the shape model at arbitrary times during Golveka's orbit are shown in Fig. 5. In the first case, we can see that very low surface angles can be found, however they are far from the nominal target, which would appear at the center of the body. In the second case, the minimum angle is near the expected center of the body, however it is on the order of 10°. Thus even if perfect targeting is available for the ablation methodology on the surface of the asteroid, the thrust can't be guaranteed to always line up with the desired direction since we can't control the topography of the asteroid.

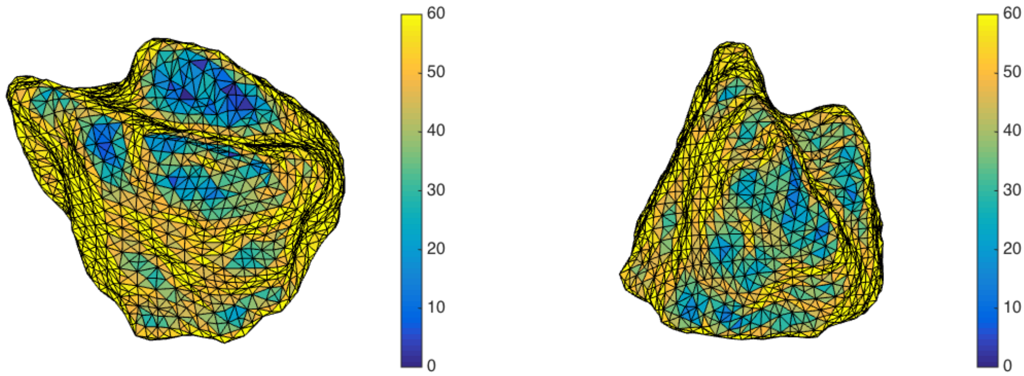

Figure 5 - To examples of surface angle on the Golevka shape model as viewed from the trailing position in the orbital plane (up is aligned with the heliocentric angular momentum, and right is aligned with the radial direction). Minimizing this angle aligns the thrust in the desired direction.

To investigate this more completely, the minimum surface angle at every orientation of Golveka throughout the year was found, as is shown in Fig. 6. This figure indicates at all points throughout the year (via the pole longitude, which increases monotonically over the orbit) what the minimum possible targetable surface angle is at all points over a revolution of Golevka. The left illustration in Fig. 5 is indicated by the left red box in Fig. 6; the right illustration of Fig. 5 is the right red box in Fig. 6. The average of the minimum surface angle over a spin period at any point in the orbit is between 1.7° - 3.3°. Therefore, if it is possible to steer the ablation heat source to an arbitrary location on the surface at any given time, the efficiency can be increased to almost the ideal level.

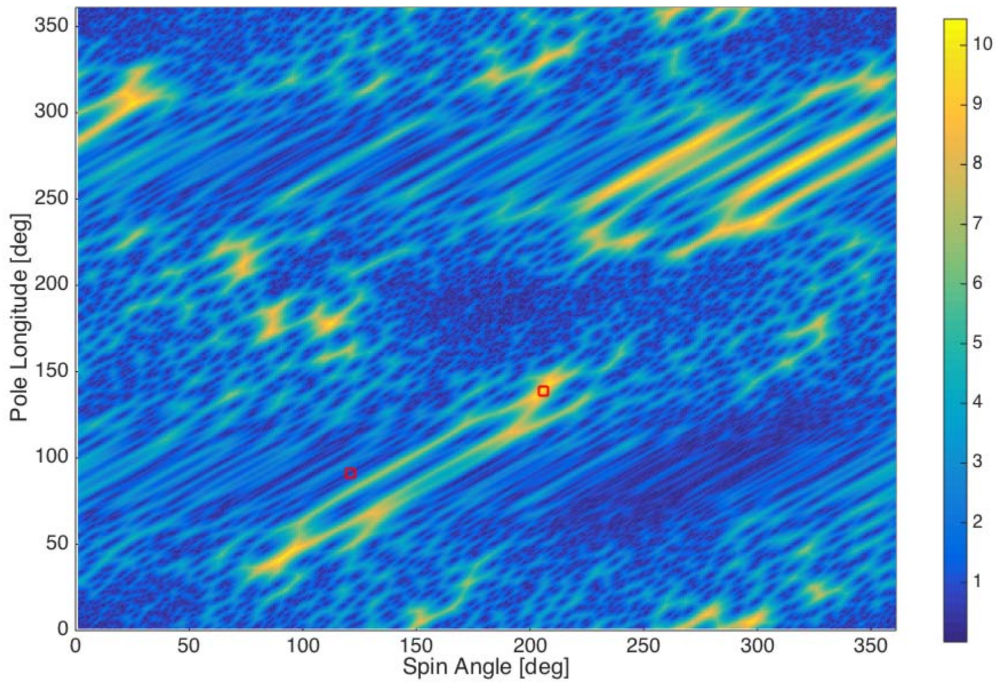

Figure 6 - Contour plot of the minimum surface angle for all Golevka orientations throughout a heliocentric orbit.

The remainder of the paper illustrates how the various level of loss of efficiency translates to a loss of deflection ability, as well as the application of the similar analysis to the asteroids Itokawa and Bennu.

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