IMPROVED ESTIMATION OF THE HAYABUSA SPACECRAFT TRAJECTORY AND LIDAR TRACKS E. G. Kahn[1], O. S. Barnouin[1], C. M. Ernst[1], [1]The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD, USA (eliezer.kahn@jhuapl.edu).

Introduction: The original trajectory of the Hayabusa spacecraft while hovering over the asteroid 25143 Itokawa possessed several inaccuracies that made it initially very difficult to reconstruct the topography of the asteroid from the lidar range measurements and estimate the gravitational forces of the asteroid [1,2]. An important improvement to the estimate of the spacecraft trajectory was calculated by fitting parabolas to the Hayabusa spacecraft housekeeping data collected at two minute intervals [2]. These data simultaneously provided the centroid location of the asteroid in the field of view of the wide-angle camera aboard the Hayabusa spacecraft, and a range measurement to the asteroid surface [3]. Despite significant improvements in the results, errors of several meters in the measured range persisted. In this paper we describe an algorithm to further improve this first estimate of the spacecraft trajectory as well as the location of the lidar tracks by making use of a high resolution Itokawa shape model [4,5] to shift the trajectory so that the lidar points better match Itokawa's topography.

Method: The lidar data collected by the spacecraft curves and winds around the asteroid in complicated ways as the spacecraft hovered over the rotating asteroid. We note, however, that for short lidar tracks, only a simple translation is enough to shift the track so that it better matches to the surface of the asteroid. The algorithm, therefore, begins by first dividing up the location of lidar points derived by [2] into small tracks of several hundred points each such that the resulting track does not wind too far around the asteroid so that a simple translation is sufficient to correct it. As was found to be sufficiently accurate in [2], we assume the pointing information derived originally from the spacecraft is correct so that only the position of the spacecraft needs to be improved.

Then for each small lidar track the following procedure was performed. Denote the set of lidar points in the track as S (the source points). For each lidar point in S, a point on the asteroid near it was computed by intersecting with the highest resolution shape model of the asteroid [5] a ray originating from the spacecraft position (using [2]) in the direction of the lidar point. These intersection points now form a second set denoted as T (the target points). A point-matching scheme (described next) was then used to find the optimal translation that best matches the source points S to the target points T. This optimal translation was then applied to the original lidar points S as well as to the spacecraft positions to produce the improved data. This procedure was repeated for each lidar track.

The point-matching scheme used is a variation of the well known Iterative Closest Point (ICP) algorithm [6] which we briefly describe here. This algorithm seeks to find a transformation that best aligns the source points S with the target points T. Typically the transformation can include translation as well as rotation, though in this case, we restricted the transformation to translation only and assumed the pointing information in the original dataset is correct. The algorithm begins by first translating set S so that its centroid is at the same location as the centroid of set T. Then it iterates between the following 2 steps:

- For each point in S, find the closest point in T.
- Minimize the sum of squared difference between sets S and T using the correspondence computed in step 1.

The algorithm terminates when there is no longer any reduction in the sum of squared difference computed in step 2 or a maximum number of iterations is reached. The reader is referred to the literature for more information about the ICP algorithm.

We note that an alternate approach is to recompute the target set T at each iteration of the ICP algorithm by recalculating the intersection points using the current estimate of the spacecraft position. In initial tests, however, we found that this sometimes caused the target set T to stray too far away from the source points which would then result in an unrealistically large shift in the spacecraft trajectory, especially when no significant topography was present on the surface of the asteroid to provide an anchor. We therefore only computed the target set T once for each track prior to each ICP run. We plan to further explore this approach at a later date using both laser altimetry data collected at asteroids 25143 Itokawa and 433 Eros by using longer tracks that are more likely to encounter significant anchoring topography.

Finally, we note that in order to make sure that the corrected tracks joined smoothly with each other, we made sure that there was sufficient overlap between adjacent tracks and after running the ICP algorithm for each track, we then averaged together the regions of overlap.

Results: We tested the algorithm using several approaches. First we computed the error in range using the estimated spacecraft trajectory averaged over all lidar points both before and after running the algorithm.

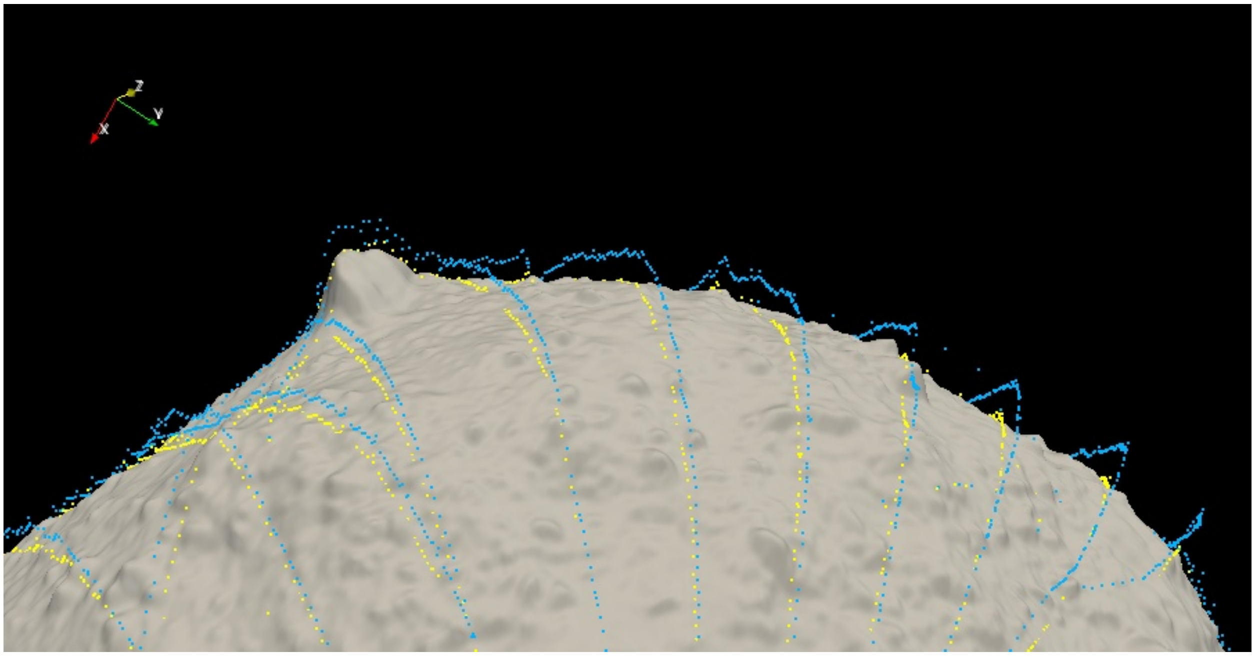

Figure 1: The original (light blue) and improved (yellow) lidar data acquired on Oct 15, 2005 with the Itokawa shape model. The yellow points are noticeably closer to the asteroid.

We obtained a reduction of about 4 meters, from about 7.4 to 3.5 meters.

However, a reduction in the range error does not necessary imply a reduction in the spacecraft position error. Fortunately, we were able to obtain highly accurate positions of the Hayabusa spacecraft at several hundred points in time during Hayabusa's orbit of Itokawa derived using Stereo-Photoclinometry, or SPC, [4] that provides accurate estimates of spacecraft positions during the process of creating the Itokawa shape model using the images acquired by Hayabusa's AMICA imager. We therefore computed the error between the corrected positions of the spacecraft as computed by this algorithm and the positions of the spacecraft as computed by SPC. We excluded from the calculation points at times that coincided with gaps in the lidar data as well as points for which the error was already very large to begin with (over 100 meters). We found a modest reduction in error by about one meter, from about 11 to 10 meters. This is not surprising given the highly noisy nature of the original data.

Finally, we plotted the optimized lidar tracks on the shape model and visually inspected the lidar tracks to make sure they look acceptable. The plot in Figure 1 shows some lidar tracks acquired on Oct 15, 2005 and is typical of how the algorithm performs. The original lidar data is shown in light blue and the corrected lidar data is shown in yellow. Notice that the yellow points are closer to the asteroid shape than the light blue points.

Conclusion and Future Work: This paper has presented an approach for improving the estimate of the Hayabusa spacecraft trajectory and lidar tracks by using a high resolution shape model of the asteroid and a point-matching scheme for better matching the lidar tracks with the shape model. Future work includes improving accuracy further and testing the approach on NEAR's Laser Rangefinder data of Eros and possibly other missions, as well as further exploring the alternate approach of recomputing the target set T at each iteration of the ICP algorithm by recalculating the intersection points using the current estimate of the spacecraft position.

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