A Comparison of Close-Proximity Operations at Asteroids and Comets

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The relative tracking and planning costs of close-proximity operations at asteroids and comets are defined and discussed. We consider a suite of four different close-proximity operations that spans a range of useful approaches to obtaining scientific measurements of a small body. Added to this are four different navigation measurement suites, ranging from a basic capability to an enhanced autonomous measurement capability. Four different measures are formulated, consisting of the feasibility of performing a given operation with a given navigation measurement suite, the fixed costs of model development for that operation and measurement suite, the recurring costs of monitoring the spacecraft during that operation, and the cost of planning scientific observations during the operation. This provides a simple characterization that allows comparisons between different approaches and will aid mission designers in formulating measurement strategies for small-body missions. A basic conclusion is that the benefits of additional onboard autonomy lie mostly in increased science return and reduced science planning. Reductions in total tracking costs given additional onboard autonomy capability are modest at best.

I. Introduction

The costs of supporting a spacecraft are analyzed for a number of close-proximity operation options about asteroids and comets. This cost will be a function of the specific operations planned and the suite of navigation measurements that the spacecraft has available. For different combinations of close-proximity operations and measurement options (16 in all), we evaluate four different performance indices that measure the combination's viability, its fixed tracking costs, its recurring tracking costs, and the cost of planning scientific observations for that combination. The analysis is geared towards mission planners who wish to evaluate the costs and benefits of different mission options and instrument suites so these may be balanced against the benefits of the science obtained by implementing these options.

The analysis takes the orbital environment close to a small body into consideration to provide realistic models of the close-proximity operations. Emphasis is placed on the information content needed to support the necessary model fidelity and spacecraft orbit determination and control accuracy for the different options. We show that all the combinations share a number of fixed tracking costs that are

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driven by science considerations as well as modeling requirements. For some scenarios, the inclusion of autonomous measurement capability is essential, while for other scenarios it does not enhance capability appreciably nor reduce tracking costs.

The close-proximity operations options include orbiting in a close (stable) orbit, targeted low-altitude flyovers, precision landing, and low-altitude hovering—all different ways to achieve close proximity to the body. The different "mixes" of navigation measurements and processing are a basic navigation capability including radiometric and optical landmark tracking processed on the ground; the basic capability plus accurate altimetry processed onboard; the basic capability plus global position measurements processed onboard; and the basic capability plus global measurements and surface-relative measurements processed onboard. These options are chosen to fit with current and planned mission designs to small bodies, such as the Near-Earth Asteroid Rendezvous (NEAR) and Space Technology 4 (ST4) missions.

II. Close-Proximity Operations Options

In designing and navigating a spacecraft close to a small body, there are a number of different options from which a mission designer can choose. The specific options used will be a function of the desired scientific measurements, the spacecraft capability, and the amount of operations effort that can be expended in support of the mission. In the following, we identify four different options, each having a different level of complexity and scientific measurement gain, yet each achieving the goal of bringing the spacecraft close to the small body where precision measurements may be taken. The four options discussed here are orbiting in a close, stable orbit; targeted low-altitude flybys over particular sites on the small-body surface; precision landing on the small body; and low-altitude hovering over the small-body surface. There are, of course, other options available to the inventive mission designer, but the current set covers a wide range of feasible types of operations. Each of these options is discussed in more detail in the following.

A. Close, Stable Orbits

As has been discovered in researching spacecraft dynamics about small bodies, the orbital environment about them can be extremely unstable, and it is often impossible to navigate a spacecraft safely in these orbits [5,7,9,11,12]. However, there is one class of orbits that is generally stable and will allow a spacecraft to orbit in an extremely tight orbit about the central body—orbits that are retrograde and near the equatorial plane of the small body. The closest such an orbit can come will be the maximum radius of the body, measured from its center of mass, since the spacecraft is flying in the opposite sense of rotation and, hence, flying over all longitudes. It is, in general, not possible to design a close-retrograde orbit that flies only at a low altitude over a restricted set of longitudes, due to the large secular motion of periapsis. These orbits are generally near-circular. There are some intervals of unstable orbits, but these are easily discovered once a model of the body exists.

In such an orbit, it is possible to obtain high-resolution imaging of the surface and to accumulate other varieties of measurements that rely on relatively close proximity to the body. The drawback of this approach is the relatively high body-fixed speed of the spacecraft and the longitude restrictions, in that only the ends of the asteroid will have the highest-resolution imaging. Despite these drawbacks, this is perhaps the simplest manner in which to bring the spacecraft into close proximity to the body.

The sequence of maneuvers to achieve these orbits consists of placing the spacecraft into an initial orbit at a benign distance and then, by a two-maneuver sequence, dropping into a close, retrograde, near-equatorial, near-circular orbit. In general, the initial orbit will have the same inclination as the final, tight orbit. It usually is possible to generate safe orbits that lie only a few kilometers or less from the ends of the rotating body [5].

B. Targeted, Low-Altitude Flyovers

Another approach to a close-proximity trajectory is to perform targeted flyovers of selected sites on the surface. Here the spacecraft performs one low-altitude flyover of the surface and takes its measurements during closest approach. Due to the strong perturbations that the orbit will receive, such flyovers cannot be made in rapid succession, however, and must begin and end with a period of orbiting at a higher, safe altitude above the small body. Also, only certain regions on the small-body surface can be safely targeted, following rules outlined in [1,2]. In general, flyovers of certain portions of the body surface will result in the spacecraft orbit being drawn immediately into an unsafe orbit environment, while passage over other areas will result in the orbit being transitioned into a safer post-flyby orbit. Despite these restrictions, it is possible to target a much larger region of the body surface and achieve significantly lower altitude flyovers, enabling very detailed measurements to be taken during the closest approach.

To effect such a flyover, the initial orbit should be at a benign altitude with the proper inclination and phasing to allow the flyover. Then the flyover can be initiated with one maneuver, targeting the closest-approach altitude in conjunction with an accurate gravity field and rotation state of the body. Note that the lowest altitude of the flyover will not, in general, occur at periapsis, due to the nonspherical shape of the small body. Following the flyover, the spacecraft orbit will be significantly perturbed and, if left uncorrected, may come much too close to the body during its next periapsis passage. Thus, once the spacecraft reaches a safe altitude, a second maneuver should be performed to recircularize or transition the orbit to one with a safe periapsis altitude. Before another low-altitude pass can be undertaken, the orbit must be redetermined to sufficient accuracy and maneuvered into the proper plane with the proper phasing to set up the next flyover.

It is possible to achieve close approaches on the order of hundreds of meters with this approach. This approach also can be categorized into the same class as a sampling approach that would shoot a projectile to raise ejecta from the surface and then measure the ejecta at close range. Altitudes of a few hundered meters or less can be designed using this approach.

C. Precision Landing

If in situ measurements of the surface are desired or if high-resolution imagery of the surface is desired over a longer time span, then the spacecraft may land on the surface of the body. For reasons of scientific merit and spacecraft safety, it usually is desirable to control the landing area on the body surface to some degree of accuracy—hence the name precision landing. Here we assume that the spacecraft makes contact with the surface for an extended period of time, essentially coming to rest. In this class of close-proximity operations, we assume that the spacecraft may lift off again, achieve orbit, and then land on another portion of the surface.

To achieve such a landing, the spacecraft must perform at least two deterministic maneuvers and follow a period of closed-loop trajectory control as it approaches and lands on the surface [8–10]. The first maneuver takes the spacecraft from a safe orbit and drops its periapsis to a lower altitude, similar to the targeted, low-altitude flyby. Then, at the low altitude, it performs another maneuver to align its velocity vector with the rotating body, allowing it to fall towards the surface. Then, in the final phase, the drop rate of the spacecraft must be controlled so that it intersects with the surface with its velocity vector within some design envelope that will constrain both its magnitude (impact speed) and direction (flight-path angle). The size of this envelope is a function of the specific spacecraft design.

D. Low-Altitude Hovering

The final option considered combines elements of the targeted low-altitude flyover and precision landing. In this approach, the spacecraft implements a hovering control at a given altitude over a given location on the body, nulling out the gravitational and centripetal accelerations to sustain a given altitude over a given location [6,9]. To implement such a control requires a closed-loop control that can operate over extended periods of time. This approach also includes the possibility for the spacecraft to move over the surface in a controlled fashion (at some altitude above the surface) and to briefly touch down on the surface before raising its altitude again.

To implement such a trajectory requires the same capability as precision landing, the ability to supply a nominal hovering thrust, and a closed-loop control about that hovering position. To achieve repeated soft touchdowns will require a significantly tighter control envelope than precision landing because the craft's trajectory will not be able to tolerate large, random perturbations from a jarring landing and still continue its hovering trajectory.

This approach obviously yields the greatest scientific return as the hovering location on the surface is fairly unconstrained, although the stability characteristics of hovering over a small body will change as a function of location [6].

III. Navigation Measurement Suites

To enact any of the above schemes will require a certain level of navigation capability, which implicitly means that certain types of measurements will be required to carry out each of the above scenarios. Here we define four different levels of navigation measurement capability, each building on the previous capability. Obviously, as the navigation capability increases, so do the hardware design and fabrication costs as well as the software design and implementation costs, but we do not consider such costs here. A summary of the different measurement suites is given in Table 1.

Table 1. Navigation measurement suite summary.

Suite	Measurements/data[a]				Capability
	Radio metric	Optical	Altimetry	Scanning laser	
NM1	Y, G	Y, G	Y, G	N	Position and velocity knowledge on ground
NM2	Y, G	Y, G	Y, O	N	NM1 plus altitude and descent-rate knowledge onboard
NM3	Y, G	Y, O	Y, O	N	NM1 plus position knowledge and filtered velocity knowledge onboard
NM4	Y, G	Y, O	Y, O	Y, O	NM3 plus surface characterization and measured surface-relative velocity

[a] Y = yes, available; N = no, not available; G = ground processing; and O = onboard processing.

A. Navigation Measurement Suite 1: Basic Capability

The base capability relies on both radiometric and optical data (and possibly altimetry data), all of which are processed on the ground. This corresponds to the basic level of navigation control that any small-body orbiter would require. This level of capability is similar to the level of capability of the NEAR spacecraft without some proposed end-of-mission upgrades [3]. It is an essential level of capability for the initial estimation of the small-body gravity field and rotational dynamics.

It assumes that regular radio contact with the spacecraft is made and that frequent optical images are shuttered and transferred to the ground for processing. It does not preclude that processing of the images may occur onboard, but does assume that the information from the images is used in joint solutions with the Doppler data. This case is denoted as NM1 in the following discussions.

B. Navigation Measurement Suite 2: NM1 Plus Altimetry

The first upgrade to the basic capability assumes that the spacecraft has an altimeter that can be used to measure altitude to the body and can be incorporated into a closed-loop control scheme on the spacecraft. Implicit in this capability is the ability of the spacecraft to track and control its attitude autonomously, a capability that is within reach of almost all spacecraft flown today. This suite corresponds to the anticipated upgrades to the NEAR navigation measurement suite and allows the spacecraft altitude to be controlled [1]. This case is denoted as NM2.

C. Navigation Measurement Suite 3: NM2 Plus Onboard Position Measurements

The next upgrade assumes all previous capabilities plus the ability for the spacecraft to process and extract information from an onboard sensor such as an optical navigation imager [11]. For this capability, it is assumed that the onboard processor is given a landmark map of sufficient accuracy to carry out the desired mission, but that this map is constructed earlier in the mission using the basic capability (NM1). We do not consider the construction of the map "on the fly" as this approach is at odds with using the spacecraft for close-proximity observations and is better suited for an extended mission at higher altitudes, where the unstable orbital regions are not encountered. This gives the spacecraft the ability to autonomously determine its location in the body-fixed frame but does not give it a rapid measurement of the surface conditions at an arbitrary location. Neither does it give the spacecraft the ability to rapidly, or accurately, estimate its body-relative velocity. This case is denoted as NM3.

D. Navigation Measurement Suite 4: NM3 Plus Accurate Surface-Relative-Position Measurements

The final upgrade incorporates all the above capabilities plus the ability of the spacecraft to measure the local terrain of the body and extract information about the spacecraft's motion relative to the local terrain. This instrument would correspond to the scanning laser developed for the ST4 mission.[2] Note that this measurement alone does not suffice for accurate navigation of the spacecraft, as such relative measurements do not contain much information about the absolute position and velocity of the spacecraft—items that are essential for the true navigation of the spacecraft about the body. It does not preclude, however, the scanning laser (or similar instrument) performing the functions of altimetry and global positioning. This case is denoted as NM4.

IV. Measuring the Performance and Tracking Costs

To give a relative measure of the different close-proximity operations and the navigation measurement suites, we use three basic criteria. Due to the number of parameters and the general approach taken in this article, we do not give detailed cost evaluations, as these are extremely dependent on the specific missions at hand. Rather, we use criteria that reflect the relative costs of the approaches as compared with each other. Although the absolute "scale" of the costs will vary from mission to mission, the "ratio" of the costs should remain somewhat constant.

The first measure is an indication of the feasibility of the operation given the navigation sensor suite. The second measure is an indication of the fixed tracking costs associated with the combination and covers the estimation of the force model and initialization of the spacecraft trajectory. The third measure is an indication of the recurring costs that arise each time the operation is undertaken. The fourth measure evaluates the cost of planning and implementing scientific measurements during the operation.

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[2] M. San Martin, personal communication, Autonomy and Control Section, Jet Propulsion Laboratory, Pasadena, California, 1998.

A. Feasibility of Operation

The most fundamental consideration, given a close-proximity operation and navigation measurement suite, is whether or not the operation is feasible to perform with the suite. As we shall see, some combinations are not feasible at all, while others are only marginally feasible, and some should be completely feasible. To indicate these three levels, we define the operation as either infeasible, marginally feasible, or feasible.

An infeasible operation indicates that the measurement suite is insufficient to support the given operation and should not be attempted. A feasible operation indicates that the measurement suite theoretically is able to support the operation. This does not mean it is easy or inexpensive to do so, only that sufficient information content is available to carry out the task. Marginally feasible operations fall between these two and indicate that the operation may be possible, although there may be significant restrictions on carrying it out or a significant increase in risk should the operation be attempted.

B. Model Development

For any close-proximity operation, there will be a series of fixed costs that apply to any of the measurement suites. These include the estimation of the body's gravity field, shape, and spin state, as well as the determination of the initial spacecraft orbit about the body. Here again there are three levels of possible costs—no initial information needed, low-precision information, and high-precision information.

No initial information needed indicates that the spacecraft could fly in and perform the operation without spending any time accumulating small-body information. We see that none of the combinations gives this result, but it is included to allow for future advances or alternative operations not considered here.

Low-precision indicates that only the body mass, low-order gravity field, and relatively low-order shape and rotation state need to be estimated prior to the operation. Although it is difficult to give general numbers on tracking times needed for this level, it is possible to sketch out the mission scenario leading to this level of model accuracy. For a low-precision model, it should be sufficient for the body model of shape, rotation, and mass to be estimated during the initial periods of rendezvous, including a slow flyby of the body or a slow transfer into a stable, higher-altitude orbit. For all the approaches, at least a fourth-degree and -order gravity field should be attempted, but it may rely on the measured mass, shape, and constant density assumptions for the body. Tracking the spacecraft in a relatively low orbit (at several radii) should give information on the first- and second-degree and -order gravity fields and give an initial indication of the density distribution within the body. Barring any odd distributions (i.e., assuming the density is relatively constant across the body), this information can be used for the low-precision result. This level of characterization may be possible in as short a time as 1 or 2 weeks after initial rendezvous.

High-precision indicates that a detailed surface map of the body would be needed as well as a direct estimation of the gravity field to sufficiently high degree and order. The degree and order needed will be a function of the body size and mass, but it should at least be made up to the eighth degree and order. To obtain such an accurate field usually will require the spacecraft to spend at least a few weeks in an orbit that would allow for a global gravity field to be measured. With this level of gravity-field measurement, it then is possible to estimate the internal density distribution of the body [4] to use in the gravity-field modeling when close to the body surface. As detailed in [13], the use of gravity harmonics for a spacecraft trajectory that comes close to the body surface is unacceptable and results in extremely large gravity-field errors (on the order of hundreds of percent when at the surface), forcing the use of alternative gravity-field models. To implement these models, a density distribution is a necessary element [13]. An improved, high-accuracy rotational model of the body results from these measurements. This level of characterization may take up to 1 or 2 months to perform.

C. Monitoring Costs

Given the measures of feasibility and fixed costs, there also will be recurring costs for each operation that the spacecraft undertakes. These consist of the estimation of the initial and final conditions for the spacecraft and also include the monitoring of the spacecraft during the operation itself. Given an adequate initial model, an accurate spacecraft trajectory usually can be estimated with a few days of tracking, a week at most. Each operation will require that an accurate initial trajectory of the spacecraft be found (up to the accuracy of the model), and, thus, this is not included in the recurring costs. After the operation, an accurate trajectory again will be required, and so too is not included. The variable here will be the amount and intensity of tracking needed during the operation itself, which will be used to either estimate crucial quantities or to monitor the progress of the operation.

We do not consider it feasible for the spacecraft ever to be placed into an autonomous mode and "forgotten," as this would be a reckless approach to space exploration and not a good investment. Although autonomous operations are needed for some of these operations, this does not mean that the spacecraft can be considered to be fully responsive to all possible scenarios. As the spacecraft is exercised through several operations, it may, however, be feasible to decrease the amount of monitoring as experience is gained. This is not reflected here as it is an intangible result.

To measure this cost, we combine two quantities—one a measure of the frequency of contact that is needed, the other a measure of the duration of the operation. For frequency of contact, we use infrequent, frequent, and continuous monitoring. For the duration of the operation, we use indefinite, extended, and definite. Indefinite indicates that the operation can be carried on for an arbitrary length of time. Extended indicates that the operation can be carried out for a finite, but arbitrary, length of time (such as a few hours or a day). Definite indicates that the operation has a fixed time span (usually on the order of hours).

D. Science Planning Costs

A final cost that can be defined is the amount of support that is needed to plan and take scientific observations and measurements during a period of close-proximity operations. Depending on the capability of the spacecraft to determine its current location relative to the body (or desired observation site), either more or less stringent predictions of the trajectory are required during the close-proximity operation. This factors into the necessary initial accuracy to which the spacecraft state should be estimated and into the amount of tracking that will be needed during the operation to support the prediction requirements.

We define three levels of this cost depending on the specific implementation of which the spacecraft is capable. The traditional approach, called time specific, has the observation sequences built around an explicit prediction of where the spacecraft will be relative to the target as a function of time. Thus, implementation of this approach requires the delivery of an accurate spacecraft ephemeris prior to observation selection and sequencing. It also can require intensive ground operations to perform the planning. A less strenuous approach, called event specific, uses the onboard measurement capability of the spacecraft to detect a one-dimensional event to which the observation can be tied. This generally allows the timing of an observation to "float," although the direction in which the observation must be made still must be specified open loop. This implementation usually will result in less stringent prediction accuracy of the spacecraft trajectory during the close-proximity operation. The least strenuous approach, called geometry specific, uses the measurement capability of the spacecraft to estimate the actual location of the spacecraft relative to the target observation and uses multidimensional constraints to control when and where the observation is taken. This requires the least stringent trajectory-prediction accuracy, although it still does require some degree of accuracy and control as the ground still must prepare the spacecraft to look for specific observation sites. In none of these approaches do we assume that the spacecraft determines what measurements are "scientifically relevant," as this is best left to the mission scientists.

V. Cost Matrices

Using the above definitions and costs, we combine the results into four matrices, one matrix for each of the measures defined above. Each matrix entry is located by the close-proximity operation and the navigation measurement suite. The measurement costs are footnoted where appropriate. This gives us a simple and flexible way to survey the different close-proximity operations and navigation measurement suite options and will, we hope, allow mission designers to more easily set the basic parameters of the mission. In its ideal use, these matrices will free mission designers from pondering the basics of these different options and allow the specialists to come up with novel combinations or solutions to the design problem, having the basic connections mapped out for them.

A. Feasibility Matrix

Table 2 shows the feasibility matrix for the 16 different combinations of operations and measurement suites. For notational brevity, we indicate the feasibility of each combination as "I" for infeasible, "MF" for marginally feasible, and "F" for feasible. For the MF cases, we indicate what restrictions will exist.

Table 2. Feasibility of operations.

Navigation suite	Close-proximity operations[a]			
	Close orbits	Flyover	Landing	Hovering
NM1	F	F	I	I
NM2	F	F	MF[b]	MF[c]
NM3	F	F	F	MF[d]
NM4	F	F	F	F

[a] F = feasible; MF = marginally feasible; and I = infeasible.

[b] Requires tight trajectory control to ensure lateral spacecraft trajectory is adequately constrained.

[c] Only possible at relatively high altitudes over certain regions.

[d] Cannot support hovering very close to the surface or repeated touchdowns.

B. Model Development Matrix

Table 3 shows the model development matrix for the different combinations. For notational brevity, we indicate the fixed cost of each combination as "NI" for no information needed, "LP" for a low-precision model, and "HP" for a high-precision model. In this and the following tables, "X" is for not applicable.

C. Monitoring Matrix

Table 4 shows the monitoring matrix for each of the combinations. For notational brevity, we indicate the monitoring cost of each combination as "IM" for infrequent monitoring, "FM" for frequent monitoring, and "CM" for continuous monitoring. For the duration of each operation, we use "I" for indefinite, "E" for extended, and "D" for definite.

D. Science Planning Matrix

Table 5 shows the science planning matrix for the different combinations. For notational brevity, we indicate the science planning approach of each combination as "T" for time specific, "E" for event specific, and "G" for geometry specific.

Table 3. Model development costs.

Navigation suite	Close-proximity operations[a]			
	Close orbits	Flyover	Landing	Hovering
NM1	LP	HP	X	X
NM2	LP	HP	HP	HP
NM3	LP	HP	HP	HP
NM4	LP	HP	LP	HP

[a] NI = no information needed; LP = low-precision model; HP = high-precision model; and X = not applicable.

Table 4. Monitoring costs.

Navigation suite	Close-proximity operations[a]			
	Close orbits	Flyover	Landing	Hovering
NM1	IM, I	CM, D	X	X
NM2	IM, I	CM, D	CM, D	CM, E
NM3	IM, I	FM, D	FM, D	FM, E
NM4	IM, I	FM, D	IM, D	IM, E

[a] IM = infrequent monitoring; FM = frequent monitoring; CM = continuous monitoring; I = indefinite duration; E = extended duration; D = definite duration; and X = not applicable.

Table 5. Science planning requirements.

Navigation suite	Close-proximity operations[a]			
	Close orbits	Flyover	Landing	Hovering
NM1	T	T	X	X
NM2	E	T (E)	E	T
NM3	G	G	G	G
NM4	G	G	G	G

[a] T = time specific; E = event specific; G = geometry specific; and X = not applicable.

VI. Discussion

To focus the discussion and give some overall conclusions from the cost matrices in Tables 2 through 5, we discuss each of the close-proximity options in turn, giving relevant supporting information and justifications.

A. Close Orbits

This approach is clearly the lowest-cost approach to close-proximity operations as it requires only a low-precision model to initiate and does not require extensive monitoring. This is so due to the inherent stability of this class of orbits (although some characterization is required). This also, of course, yields the lowest potential scientific return of all the operation types. It can always be flown, however, and, due to its less stringent demands, can serve as one of the platforms from which the high-precision model of the body can be generated early on in a rendezvous mission. The only real benefit that an enhanced navigation measurement suite can provide is a decrease in the science planning costs as more sophisticated approaches to observation planning can be used.

B. Flyover

This approach can be used to gain high-resolution measurements of select regions of the body surface. Due to its inherent design, it can be implemented without requiring the spacecraft to spend an extended period of time close to the body. For this approach, an expanded suite of navigation measurements does not add any significant capability beyond science planning, since a single operation must be carefully targeted initially to ensure a safe passage over the body. Having an expanded navigation suite does, however, aid in science planning as some of the prediction constraints can be relaxed and reliance can be given to the autonomous functions for the actual timing and direction of the images. The high-precision model is required since the surface geometry should be well understood and since the trajectory will receive an appreciable perturbation from the flyover itself. The expanded navigation suites may allow for noncontinuous monitoring as simple recovery sequences can be designed based on the measurements that these sensors take after the closest approach. The basic and altimetry suites require recontact with the ground for an assessment of the post-flyover state before the orbit safing maneuver should be implemented. As mentioned earlier, the potential flyover areas of the body surface are constrained by the natural dynamics of such a flyover.

C. Landing

The basic capability is deemed inadequate for this approach due to the lack of real-time measurements of the spacecraft distance from the surface. The altimeter option is deemed marginally feasible since considerable effort is required to ensure that the impact state's lateral motion and footprint—unsensed by the altimeter—fall within acceptable bounds. Since the NM4 suite can make measurements of the surface during descent, it can use internal guidance logic to steer its final touchdown site, allowing for a lower-precision model for this approach. The NM3 suite must rely on an accurate terrain map to design its final approach, something it cannot sense on the fly as it approaches the body. Science observation planning considerations are valid only during the approach to landing and, in general, will not be a priority with this particular operation.

D. Hovering

Altimetry-only hovering has been shown, in principle, to be feasible [2], but it is quite restrictive and subject to a host of failure modes. Due to this, it requires continual monitoring. Hovering with the NM3 suite should be quite feasible, although at extremely low altitudes there is a loss of lateral information and a lack of surface terrain sensing, which will restrict the possible operations to be implemented. As with all the extremely close proximity operations, frequent monitoring always should be implemented. This can be relaxed to infrequent monitoring for the NM4 suite due to its ability to enact a tight closed-loop control. For all the hovering approaches, a high-precision model should exist because the spacecraft will be controlling its trajectory over a wide region of the surface and will require such models for choosing the proper thrust law and for planning or implementing the desired flight paths over the surface. The science observation planning criteria become much more important here as the path of the spacecraft over the surface may vary. Thus, if observations of specific sites are required, only the NM3 and NM4 suites will allow for them to be identified and the appropriate measurements taken. If a specific site is to be observed with the NM2 suite, then an accurate predicted trajectory (incorporating the expected control) must be delivered. For these approaches, it is much simpler, and still scientifically relevant, to take observations without strict control of what is being observed.

VII. Conclusion

A series of close-proximity operations options for a spacecraft at a small body were discussed in terms of the navigation measurement suites needed to adequately control the trajectories. We developed a set of simple matrices that compared the different options and combinations and, thus, identified the basic capabilities and tracking profiles needed to enact the different approaches. We saw that the most consistent benefits of increased autonomy are increased capability (i.e., science return) and decreased science planning costs. The reductions in tracking time given increased autonomy were seen to be marginal as relates to close-proximity operations. These results are intended to be of use to mission designers contemplating how best to make scientific measurements of a small body.

References

[1] P.G. Antreasian, C. L. Helfrich, J. K. Miller, W. M. Owen, B. G. Williams, D. K. Yeomans, J. D. Giorgini, D. W. Dunham, R. W. Farquhar, J. V. McAdams, and D. J. Scheeres, “Preliminary Considerations for NEAR’s Low-Altitude Passes and Landing Operations at 433 Eros,” AIAA Paper 98-4397, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Boston, Massachusetts, 1998.

[2] P.G. Antreasian, C. L. Helfrich, J. K. Miller, W. M. Owen, B. G. Williams, D. K. Yeomans, J. D. Giorgini, D. W. Dunham, R. W. Farquhar, J. V. McAdams, A. G. Heyler, G. L. Heyler, and D. J. Scheeres, “Preliminary Planning for NEAR’s Low-Altitude Operations at 433 Eros,” AAS Paper 99-465, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, 1999.

[3] J. K. Miller, W. E. Bollman, R. P. Davis, C. E. Helfrich, D. J. Scheeres, S. P. Synnott, T. C. Wang, B. Williams, and D. K. Yeomans, “Navigation Analysis for Eros Rendezvous and Orbital Phases,” *Journal of the Astronautical Sciences*, vol. 43, pp. 453–476, 1995.

[4] D. J. Scheeres, B. Khushalani, and R. A. Werner, “Estimating Asteroid Density Distributions from Shape and Gravity Information,” Poster 24-18P, 1999 Asteroids, Comets, Meteors Conference, Cornell University, Ithaca, New York, July 1999.

[5] D. J. Scheeres, B. G. Williams, and J. K. Miller, “Evaluation of the Dynamic Environment of an Asteroid: Applications to 433 Eros,” AAS Paper 99-158, 1999 AAS/AIAA Spaceflight Mechanics Meeting, Breckenridge, Colorado, February 1999.

[6] D. J. Scheeres, “Stability of Hovering Orbits Around Small Bodies,” AAS Paper 99-159, 1999 AAS/AIAA Spaceflight Mechanics Meeting, Breckenridge, Colorado, February 1999.

[7] D. J. Scheeres, F. Marzari, L. Tomasella, and V. Vanzani, "ROSETTA Mission: Satellite Orbits Around a Cometary Nucleus," *Planetary and Space Science*, vol. 46, pp. 649–671, 1998.

[8] D. J. Scheeres, "Interactions Between Ground-Based and Autonomous Navigation for Precision Landing at Small Solar-System Bodies," *The Telecommunications and Data Acquisition Progress Report 42-132, October–December 1997*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–12, February 15, 1998. http://tmo.jpl.nasa.gov/tmo/progress_report/42-132/132D.pdf

[9] D. J. Scheeres, "Close Proximity and Landing Operations at Small Bodies," AIAA Paper 96-3580, AIAA/AAS Astrodynamics Specialist Conference, San Diego, California, July 1996.

[10] D. J. Scheeres, S. J. Ostro, and R. S. Hudson, "Issues of Landing on Near Earth Asteroids," Space 96 Conference, Albuquerque, New Mexico, June 1996.

[11] D. J. Scheeres, B. G. Williams, W. E. Bollman, R. P. DAVIS, C. E. Helfrich, S. P. Synnott, and D. K. Yeomans, "Navigation for Low-Cost Missions to Small Solar System Bodies," *Acta Astronautica*, vol. 35 supplement, pp. 211–220, 1995.

[12] D. J. Scheeres, "Analysis of Orbital Motion Around 433 Eros," *Journal of the Astronautical Sciences*, vol. 43, pp. 427–452, 1995.

[13] R. A. Werner and D. J. Scheeres, "Exterior Gravitation of a Polyhedron Derived and Compared with Harmonic and Mascon Gravitation Representations of Asteroid 4769 Castalia," *Celestial Mechanics*, vol. 65, pp. 313–344, 1997.