To appear in "Mitigation of Hazardous Comets and Asteroids," Edited by Michael Belton, Thomas H. Morgan, Nalin Samarasinha, Donald K. Yeomans, Cambridge University Press, 2004.

Close Proximity Operations at Small Bodies: Orbiting, Hovering, and Hopping

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Central to any characterization or mitigation mission to a small solar system body, such as an asteroid or comet, is a phase of close proximity operations on or about about that body for some length of time. This is an extremely challenging environment in which to operate a spacecraft or surface vehicle. Reasons for this include the *a priori* uncertainty of the physical characteristics of a small body prior to rendezvous, the large range of values that its physical parameters can have, and the strongly unstable and chaotic dynamics of vehicle motion in these force environments. To succesfully carry out close proximity operations about these bodies requires an understanding of the orbital dynamics close to them, a knowledge of the physical properties of the body and the spacecraft, and an appropriate level of technological sensing and control capability on-board the spacecraft. In this chapter we discuss the range of possible dynamical environments that can occur at small bodies, their implications for spacecraft control and design, and technological solutions and challenges to the problem of operating in close proximity to these small bodies.

1 Introduction

Mitigation and detailed characterization of asteroids and comets requires some period of close proximity operations about them. To support close proximity operations requires an understanding of dynamics of natural material on and about small bodies, and the dynamics, navigation, and control of artificial objects on and about small bodies. In this chapter we discuss some of the controlling issues that relate to close proximity operations, and draw connections between this issue and the design of spacecraft and mission concepts to carry out close proximity operations.

Since the field of astrodynamics and celestial mechanics is often considered to be a mature field, it is relevant to ask why the control of spacecraft about small solar system bodies is considered to be a difficult problem. There are a number of reasons for why this is the case, which we review here and explain in additional detail throughout this chapter. A clear rationale for why this is true can best be expressed through the following chain of facts.

Small bodies have large ranges in crucial physical parameters. This result arises by the nature and number of small bodies. By themselves, small bodies fall into multiple classes, such as comets, rubble-pile asteroids, monolithic asteroids, binary asteroids, and presumably other gross catagories that we have yet to discover. Within any of these classes there can be a diversity of different possible shapes, sizes, and densities, which immediately dictate the strength and distribution of the gravitational field of the body, which in turn has implications for the relevance of solar gravity and radiation pressure effects on trajectories near the body. Also, it is an established fact that small bodies can have a range of rotation states, from simple rotation about the maximum principal axis to complex rotation. Furthermore, the obliquity of their rotational angular momentum vectors are known to be distributed from 0 to 180 degrees, which can also have dynamical significance.

Each set of small body parameter values can have close proximity dynamics that are difficult in and of themselves. As a matter of fact, most of the dynamical environments found at small bodies can exhibit strongly unstable and chaotic motion for trajectories of practical interest. Significantly, as the force parameters of small bodies are changed, the range of orbit elements that lead to unstable motion can change drastically. For example, for one class of bodies it is known that orbits with an inclination of 180 degrees relative to their rotation pole can be very stable and safe. However, if the asteroid is relatively small these same orbits, due to solar radiation pressure effects, can be very unstable and lead to impact with the asteroid within a few orbits. Numerous other examples can also be found, indicating that small bodies, when taken together as a class, exhibit an extremely rich set of non-trivial dynamics.

Spacecraft designs and mission operation concepts can be driven in very different directions as a function of the close proximity dynamical environment. As a case in point, the asteroid mission phase for the NEAR mission at Eros looks very different than the asteroid mission phase of the Muses-C mission to 1998 SF36. For NEAR, there was no choice but to use an orbital approach, due to the large mass of Eros. However, due to its shape, rotation state, and rotation pole orientation, the orbital mission had to be designed carefully to avoid destabilizing interactions with the asteroid. For Muses-C, due to the possible low mass of its target asteroid and the large mass to area ratio of the spacecraft, it could not be guaranteed that an orbital mission would even be possible. Thus, the entire mission consists of forcing the spacecraft to "hover" on the sun-side of the asteroid (discussed later in this chapter), with an associated cost in terms of fuel and ability to measure the asteroid's gravity field. A crucial point to make is that the placement of instruments on the spacecraft bus are fundamentally different for each mission. The NEAR mission plan required instruments boresights to be placed orthogonal to the solar array normals, while the Muses-C mission plan requires the boresights to be anti-parallel to the solar array normals, a fundamentally different spacecraft design dictated by the type of dynamics about the small body, not dictated by an abstract "design philosophy".

Crucial small body parameters may not be known prior to rendezvous. In light of the previous point, it is clear that this can lead to increased design costs and impacts during the construction phase of the spacecraft. If relatively nothing is known about the target body, it will be necessary to design a spacecraft that covers a wider range of possible orbit and close proximity strategies – which will invariably lead to higher design and fabrication costs and to increased spacecraft mass. This places a strong driver on discovering as much as possible about the physical characteristics of potential target bodies prior to spacecraft and missin design.

It is likely that vehicle designs and operations concepts that fit one small body may not fit another. Again, it is instructive to compare the Muses-C and NEAR spacecraft designs. The Muses-C design is appropriate for very small bodies, and is designed to maximize scientific return from visiting such bodies. On the other hand, if the Muses-C spacecraft were sent to explore Eros, it is likely that the amount and quality of scientific measurements it could take would be significantly less than the NEAR spacecraft accomplished, and would require the spacecraft operations team to work much harder to accomplish them. The NEAR spacecraft design is appropriate for larger bodies such as Eros and was operated in that environment with a relatively small operations team. If, however, the NEAR spacecraft was used to explore a sub-kilometer asteroid it would have had profound difficulties in carrying out its mission and accumulating quality scientific measurements of that body, again at the expense of stressing the spacecraft operations team. Thus, spacecraft designs and mission scenarios that are optimized for one class of small body may not function well at all for a different class of small bodies. For missions that wish to visit multiple asteroids, this may force a difficult trade to be made between designing a spacecraft that can accomplish a mission to range of asteroid classes or designing a mission that only explores asteroids that fall within a restricted class of physical parameters.

Having sketched out our argument for why the issue of close proximity dynamics about small bodies is important, we will now explore some of these issues in more detail. First of all, it is important to note that a close coupling exists between the dynamics of natural material and artificial bodies about asteroids and comets. In recent years an appreciable body of literature has been built up in both of these areas, including a review chapter on the natural dynamics and modeling of natural material on and about asteroids

[Scheeres et al. 2002]. In the following we briefly review the main literature that has been published recently, and which is crucial for understanding the relevant details of close proximity dynamics at small solar system bodies.

One issue of importance is the modeling of the small body force environment. First consider the gravitational field of the body, the current state of the art is to describe these fields using spherical harmonic expansions [Miller et al. 2002]. These are useful for estimation and orbital computation, but fail when within the circumscribing sphere about the body. A partial remedy is the use of ellipsoidal harmonic expansions [Garmier and Barriot 2001], which decrease the radius of convergence to the circumscribing ellipsoid. There may still be problems for use at the body surface, an approach remedied by using closed form expressions of polygonal gravitational fields [Werner 1994, Werner and Scheeres 1997]. A draw-back with this approach is the requirement of constant density, although the evidence from Eros indicates that this is a good approximation for that body. The effect of solar radiation pressure and solar tides can be handled with standard approaches, applied to spacecraft in [Scheeres and Marzari 2002]. When considering the effect of cometary outgassing, models have not been developed to the same degree of fidelity. The basic model used for planetary science computations was first applied to spacecraft navigation in [Miller et al. 1990], further refined in [Weeks 1995], applied to spacecraft dynamical computations in [Scheeres et al. 1998b], and used as the basis for a more accurate formulation in [Scheeres et al. 2000a]. A newly recognized area of concern is the electrostatic environment on the surface of an asteroid. This issue has been considered by [Lee 1996], and has been suggested as a possible explanation for the dust ponds observed on the surface of Eros [Robinson et al. 2001].

The second issue of importance is natural and controlled dynamics of motion on and about small bodies, which includes studies of surface motion. The initial area of study concerned Phobos and Deimos [Thomas and Veverka 1980, Dobrovolskis and Burns 1980], and these asteroids are still a topic for research [Thomas 1998, Thomas et al. 2000]. Studies of motion about more generic asteroids began with studies of the orbital environment about asteroids in support of the Galileo flybys of Gaspra and Ida [Hamilton and Burns 1991a, Hamilton and Burns 1991b], closely followed by papers considering orbital dynamics close to asteroids [Chauvineau et al. 1993, Scheeres 1994] and studies of the orbital motion of Dactyl about Ida [Geissler et al. 1996, Petit et al. 1997]. Using radar-derived and observationally based models of asteroids, a number of papers were published studying the basic physics of orbital motion about real asteroid shapes, separately considering the case of a uniformly rotating asteroid [Scheeres et al. 1996] and an asteroid in a complex rotation state [Scheeres et al. 1998a]. A number of studies of orbital motion about 433 Eros were made, both before and after rendezvous [Scheeres 1995, Scheeres et al. 2000b, Thomas et al. 2001]. More recently, Hu has focused on understanding the motion about asteroids over a wider range of parameter space [Hu and Scheeres 2002, Hu 2002]. In terms of controlled motion about asteroids, recent work has broached the subject of directly controlled motion about asteroids [Scheeres 1999b, Sawai et al. 2002, Broschart and Scheeres 2003]. There still exist new areas that demand further exploration, especially motion in binary systems. Based on a preliminary review of the basic properties of binary asteroids, the orbital environment about them appears to be quite complex as well [Scheeres 2003].

2 Defining the Force Environment

Given the large range of possible situations, and the diverse types of motion that can ensue, it is crucial that the specific force environment of a small body be defined as early as possible, as it is much more difficult to design a mission and spacecraft to a body with unknown characteristics. This means that ground-based characterization must play an important role in target selection and initial mission and spacecraft design. In the following we discuss what important physical characteristics of a small body can be estimated using ground-based measurements. Following that we discuss the measurements that should be taken following rendezvous in order to facilitate robust implementation of close proximity dynamics.

2.1 Pre-Rendezvous Characterization

There are a number of important small body parameters that are accessible using ground-based observations. Some of these measurements are routinely taken, however a number of them require targeted observations that must be planned in advance and which require additional resources. It is fortunate to note that the majority of physical parameters needed to characterize the dynamical environment of a small body can at least be constrained by ground-based observations. The list of desired physical parameters needed to define the small body force environment is:

1. Number of co-orbitals.
2. Size.
3. Density.
4. Shape, gravity field, or density distribution.
5. Surface and interior morphology.
6. Spin rate and spin state.
7. Orientation of rotational angular momentum relative to orbital plane.
8. Heliocentric orbit.

The basic suite of ground-based measurements that are used to observe small bodies, and the physical parameters that they may be able to constrain, can be summarized as: astrometric measurements (items 1, 2, 8), intensity (lightcurve) measurements (items 1, 4–7), spectral measurements (items 2, 3), and range-Doppler radar imaging measurements (items 1–8). In the following we discuss each of these types of measurements and the physical parameters which they can determine, or at least constrain.

Astrometric Measurements: These observations are generally associated with discovery, recovery, and ephemeris improvement campaigns. They serve as the basic data type on small bodies and directly contribute to determining the heliocentric orbit. With assumptions on asteroid albedo they can also constrain the body size. If extremely high-accuracy astrometry is used (e.g., Hubble), it is also possible to directly determine if co-orbitals exist and to measure size.

Intensity (Lightcurve) Measurements: Lightcurve measurements can directly determine the spin period of a body, detect a complex spin state, place direct constraints on the body shape, and can detect the presence of a co-orbital by observing an eclipse. With additional processing it is also possible to invert lightcurve data to estimate body shape and rotational angular momentum directions and constrain some aspects of surface morphology.

Spectral Measurements: By measuring the spectra of a body it is possible to determine its “Type” classification, which in turn places constraints on its composition, grain density, and surface albedo. These, in turn, can provide bounds on its density and can improve size estimates.

Radar Measurements: Radar measurements can consist of detecting returns from the body, or if carried out at high enough signal strengths can provide resolution measurements in both Doppler and range. As has been demonstrated repeatedly, this data can be inverted to find the body shape and rotation state and can immediately detect the presence of co-orbitals. In addition to measuring the body shape, size, and spin state, radar measurements also provide the body's rotational angular momentum vector and significant improvements in its helio-centric orbit. In addition to these, characteristics of the return signal can be used to place constraints on the surface density of the body and on the roughness of the body at the scale of the radar wavelength.

While it is clear that radar observations of a body can provide the most comprehensive and detailed information, these are also the most restrictive measurements in terms of opportunities and are most effective when the body in question has been observed by all the other measurement types. It is also important to note that the ideal set of observations of a body would encompass all of the above types, as they each have unique measurement aspects and can often be combined together to complement each other in estimating physical properties.

2.2 Post-Rendezvous Characterization

Following rendezvous with the small body, it is necessary to develop precision models using navigation data, which generally consists of radio metric tracking data, optical observations, and altimetry. The specific physical parameters needed to support close proximity operations at the small body are its: mass, gravity field, spin state, surface topography and roughness, surface gravity field and density distribution.

The process of measuring these parameters using navigation data is rather involved, and ultimately relies heavily on combining the data to perform a joint solution for all of these parameters simultaneously. One of the main difficulties in performing these solutions is generating sufficiently accurate models to use as initial estimates. This is where the presence of existing models based on ground measurements can be crucial and can significantly cut the time required to estimate these models. Comprehensive discussions of these procedures for asteroids are documented in [Miller et al. 1995, Miller et al. 2002] and for comets in [Miller et al. 1990].

The only physical model that does not arise naturally out of the navigation measurement process is the surface gravity field and internal density distribution. While the estimated gravity field (usually parameterized as a spherical harmonic expansion) contains this information, the gravity field parameterization is generally not valid at the surface of the body and the density information cannot be uniquely extracted. One way to bypass the invalidity of spherical harmonic expansions at the surface of the body is to use ellipsoidal harmonics [Garmier and Barriot 2001], which are still formally divergent at the surface but which can be used much closer to the body surface. It is also possible to directly estimate ellipsoidal harmonic coefficients from existing spherical harmonic gravity field coefficients [Dechambre and Scheeres 2002]. In contrast, the polyhedron gravity field potentials are valid up to and even within the body, but rely on constant density assumptions. It is possible to mimic density distributions by placing mass concentrations of different density within the body [Werner and Scheeres 1997], but this requires that the density distribution be estimated. While this is a non-unique process, a least-squares estimation technique that uses the measured shape model and gravity field coefficients as data may allow for a rational approach to estimating these distributions [Scheeres et al. 2001]. It is important to note that the one small body for which we have an accurate gravity field and shape measurement, Eros, has only minimal density inhomogeneities [Yeomans et al. 2000]. This provides the hope that constant density surface gravity models may be sufficient for surface operations.

3 Close proximity dynamics and operations

In the introduction we gave a summary of past work on the question of close proximity dynamics of natural and artificial bodies, and we do not intend to review this material here. Rather, we will make a number of observations and discuss a number of scenarios where complications associated with close proximity dynamics can arise. In concert with these we will discuss various ways in which such complications can be mitigated, ultimately leading to the idea of controlled motions relative to a small body.

An important point to make is that the motion of particles in close proximity to a small body will usually deviate significantly from the familiar Keplerian motion due to perturbations from solar radiation pressure, solar gravity, small body shape/gravity, and small body rotation. Due to these perturbations it is very common to find trajectories that can escape, impact, or migrate substantially over only a few orbits about the body. Unlike most unstable and chaotic motion in the solar system, which has timescales on the order of thousands to millions of years, the time scale for these effects to act are very short, on the order of a few hours to days. Thus, these effects must be accounted for and understood in order to carry out close proximity spacecraft operations. It is important to stress that both orbital and surface motion must deal with these issues.

3.1 Complicating Scenarios and Possible Resolutions

Based on past analyses of close proximity motion, there are a number of items that can be identified as being of specific concern to the implementation of close proximity operations on or about a small body. In this chapter they have been divided into three broad classes: dynamics of disturbed regoliths, orbit mechanics issues, and surface motion dynamics. Many of the complicating scenarios discussed below can be dealt with by the appropriate choice of orbiting strategy or spacecraft design. Thus, where appropriate we mention some known strategies for mitigating some of these adverse dynamical effects. These strategies are by no means exhaustive, but are representative of the types of approaches that can be used. Each of these strategies have their own drawbacks, making the design of a close proximity mission a challenging exercise in system optimization.

3.1.1 Natural dynamics of disturbed regoliths

An interesting idea, posed in [Scheeres and Asphaug 1998] in the context of exploring small body surfaces, is that operations on the surface of a small body can excite the loose regolith, effectively creating a transient atmosphere. Since escape speeds on the surface of a small body are on the order of meters per second or less, it does not require much impulse to energize regolith. If the small body were a sphere, there would only be two outcomes for each particle, escape or re-impact. However, the small body will have an irregular shape, will be spinning, and is in the solar radiation pressure and gravitational field of the sun, thus it is probable that the trajectory of non-escaping disturbed material can transition into a non-impacting orbit about the body, or at least into an orbit that will not re-impact for an extended period of time. In [Scheeres and Marzari 2000] examples of this effect considering solar radiation pressure only are presented, while in [Scheeres et al. 1998a] examples of this considering the gravity field and rotation state of the small body only are presented. In both cases, re-impact of disturbed ejecta may not occur for many months! When the particles do re-impact, they will in general have speeds up to local escape speed (which is computed taking body rotation into account, see [Scheeres et al. 1996]).

While this would be an interesting effect to observe, it may not be a positive environment for a landed space vehicle or a vehicle in orbit about the small body. While the “density” of the transient atmosphere would likely be very low, there may be some increased risk associated with orbiting about a body surrounded by a dusty sphere. Similarly, a landed vehicle could be subject to re-impacting ejecta traveling at local escape speeds, with re-impact occuring long after the initial event. More serious issues could also involve the electrostatic potential on the asteroid surface in combination with an energized regolith and the introduction of a vehicle into that environment.

3.1.2 Orbit Mechanics

The peculiarities of orbital motion about asteroids is a subject that is more fully understood than surface motion, and for which much recent work has been performed. For these situations the "complicating scenarios" are known to be a strong function of the body's heliocentric orbit, shape, size, rotation and density as well as the spacecraft's mass and area. The main complications are due to gravity, rotation, and solar radiation pressure effects. Each of these complications can be analyzed in isolation, but for some bodies they can play an important role in combination. We also briefly consider binary asteroids, which adds a new dimension to this problem.

Gravity and Rotational Effects First consider the effect of gravity and rotation. The simplest unifying dynamical idea for a rotating asteroid is its synchronous orbit radius, specifically the size and stability of the circular orbit that has the same period as the body's rotation. For an asteroid of a given mass, represented by its mass parameter μ, and rotation period T, its ideal synchronous radius is computed as: $r_s = \left(\mu T^2/4\pi^2\right)^{1/3}$. Due to the distributed mass of the body, an asteroid will in general only have four specific locations close to r_s where truly synchronous motion exists [Scheeres 1994, Scheeres et al. 1996], analogous to the Earth's case [Kaula 1966], located along the longest and shortest body axis in the equatorial plane. For the majority of asteroids with known shapes, all four of these synchronous orbits are unstable, and trajectories started in their vicinity generally lead to impact or escape within a few orbits. This simple result lies behind most of the difficulties encountered in orbiting small bodies. In fact, for asteroids with all of their synchronous orbits unstable, motion within 2-3 synchronous radii of the asteriod mass center tends towards instability, with escaping and impacting orbits being the rule. There is a strong inclination dependence on this instability, it being the most pronounced when motion is in the plane of rotation and in the same sense (i.e., zero inclination). As motion is considered at higher inclinations, the minimum radius for stable motion tends to decrease. In Figure 1 we present a plot of stable and unstable regions as a function of radius and inclination, computed for the asteroid Eros [Lara and Scheeres *in press*]. As has been clearly established, when orbital motion is in the equatorial plane and opposite to the sense of rotation (i.e., retrograde), orbital motion is actually quite stable.

The basic complication from the gravity and rotation effect is that orbital motion close to the body with low relative speeds is in general not an option. Unfortunately, it is these orbits that are the most scientifically attractive for performing body-relative measurements and deploying measuring devices. The remedy is to fly in a retrograde orbit, which allows for very low altitudes relative to the long ends of the body. This, however, results in relatively high speeds with respect to the asteroid surface and places strict constraints on the geometry of close orbits.

Solar Effects While gravity and rotation work to destabilize motion close to the body, the effect of solar radiation pressure (in tandem with solar gravitational tides) is to destablize motion when relatively far from the body. The perturbative effect of solar radiation pressure combined with solar gravitational attraction is a strong function of the small body orbit, its overall mass, and of the spacecraft's mass to projected area ratio. Clearly, a spacecraft that strays far enough from the attracting asteroid will at some point fall under the influence of the sun. An appropriate rule of thumb for the distances at which these effects start to dominate can be approximated by the sphere of influence about the body, or more dynamically appropriately by the libration points of a particle between the asteroid and the sun. Considering only gravitational attractions, these will lie at a distance of $r_H \sim \pm (\mu/3\mu_S)^{1/3}\, d$ from the asteroid along the asteroid-sun line. Here, μ_S is the gravitational parameter of the Sun, and d is the distance of the asteroid from the sun. For example, an asteroid located at 1AU from the sun would have its libration orbits located at $r_H \sim \pm 133\rho^{1/3} R$ km, where ρ is the body density in g/cm^3, and R is the mean radius of the asteroid in km. Previous research has shown that circular orbits started with radii less than one-half of this distance are generally stable against escape from the body [Hamilton and Burns 1991a, Hamilton and Burns 1991b]. Furthermore, when relatively far from the body the orbital period can be very long, leading to relatively "slow" unstable dynamics that can be easily controlled. Thus, when viewed as a gravitational perturbation alone, we see that the Sun should not stress operations or spacecraft design except for the very smallest and least dense bodies.

The inclusion of solar radiation pressure can drastically alter the situation, however. Many spacecraft are moving towards the use of solar-electric propulsion technologies, which use the sun's light to generate propulsion power. These designs naturally lead to spacecraft with relatively large solar arrays, and hence large surface areas. In addition, spacecraft are generally designed to minimize their total mass. The combined effect leads to spacecraft with relatively small projected area densitites, defined as the spacecraft mass divided by its total sun-ward projected area. For example, the Rosetta and the Muses-C spacecraft have area densities on the order of 20-30 kg/m^2 [Scheeres and Marzari 2002].

The effect of the solar radiation pressure on spacecraft motion is complex, and different aspects of it are considered in [Scheeres 1999a, Scheeres and Marzari 2002], drawing on foundational work [Mignard and Hénon 1984, Richter and Keller 1995]. Again, it is simplest to think of the effect in terms of the radius of libration points. Solar radiation pressure introduces an asymmetry between the sun-side and anti-sun-side libration points, with the sun-side point being pushed further from the asteroid and the anti-sun-side point being pushed closer to the asteroid (Fig. 2). In [Scheeres and Marzari 2002] the relative effect of the solar radiation pressure is parameterized by a quantity $\tilde{\beta}$ which is a function of the solar radiation pressure strength, the spacecraft area density, the sun's gravitational parameter, and the asteroid's gravitational parameter. Leaving out the details of the derivation we find $\tilde{\beta} = 3.84/\left(B\mu^{1/3}\right)$, where B is the spacecraft area density in kg/m^2 and μ is the asteroid's gravitational parameter. When $\tilde{\beta} \leq \mathcal{O}(1)$ the sun's gravitational effects predominate, however when $\tilde{\beta} \gg 1$ the solar radiation pressure force dominates. As an example again, the Rosetta and Muses-C spacecraft will have estimated values on the order of $\tilde{\beta} \sim 30$. In this regime, the anti-sun-side equilibrium point is at a distance of $\sim (\mu/\mu_S)^{1/3}\, d/\sqrt{\tilde{\beta}}$. For a spacecraft and asteroid with $\tilde{\beta} \sim 30$ this radius shrinks to $\sim 35\rho^{1/3} R$ km, which is 25% of the gravitational only libration point distance. If $\tilde{\beta} \gg 1$ the escape dynamics of the problem also change and we find that the maximum semi-major axis that a spacecraft can have and remain captured at the asteroid is approximately one-fourth the radius of the anti-sun-ward libration point. These effects place a much more restrictive dynamical constraint on this system.

Furthermore, the dynamics themselves become much more complex, with orbital eccentricity experiencing large, periodic variations on the order of unity, which can lead to spacecraft impact after a few orbits. To avoid exciting such orbit eccentricity oscillations it is necessary for the spacecraft orbit plane to be perpendicular to the sun-line. Such a configuration, it turns out, yields a sun-synchronous orbit in that the solar radiation pressure will force the orbit plane to always lie perpendicular to the sun-line. When flying in this geometry, the spacecraft is in a terminator orbit and can have a constant eccentricity on average if its initial periapsis vector is chosen appropriately. Indeed, for small asteroids this may be the only orbital geometry that can yield feasible motion over long time spans as orbits that deviate significantly from the terminator plane may impact with the asteroid in only a few orbits. These limits and constraints can all be predicted using analytical results [Scheeres 1999a, Scheeres and Marzari 2000].

A more significant issue arises when the asteroid has a non-spherical mass distribution and rotation. At the least, such mass distributions can cause precession of the orbit plane (analyzed in [Morrow et al. 2002]) which in turn can excite the eccentricity oscillations which can lead to impact. If the maximum semi-major axis also happens to be within a few synchronous radii, the orbit may also be subject to destabilization from the gravity and rotation effects alone. The combination of all these effects will lead to difficult challenges for designing orbital missions to very small or under-dense bodies.

Binary Asteroids All asteroids will be subject, to some extent, to the force perturbations discussed above. Further complicating the issue, current estimates state that roughly 20% of the NEA population may be binary asteroids. While much is not known yet about the force environment of a binary asteroid, current indications are that it will be relatively difficult to find safe and navigable orbits close to either body. Approaching the problem from a conservative point of view, we can state that safe orbits will generally lie outside the secondary, so long as solar radiation pressure effects are not too severe, and will preferentially orbit retrograde to the binary system's orbital plane. Orbits close to or within the orbit of the secondary must contend with 3rd body forces in addition to the gravity and rotation perturbations discussed above.

One potentially attractive approach would be to place a spacecraft in one of the triangular synchronous orbits of the binary system (note, these will be synchronous with the secondary moving about the primary, but not synchronous with the rotation of the primary in general). A recent survey of known binary asteroid systems in the solar system [Scheeres 2003] shows that the majority of these systems have mass ratios small enough for the classical stability to exist. For many of these potentially stable environments, however, the gravitational disturbance of the solar tide is sufficient to destabilize their motion, such as occurs in the Earth-Moon system. If the mass ratio of the binary asteroid system is $\rho = M_2/(M_1 + M_2)$, then the classical constraint for the triangular points to be stable is: $27\rho(1 - \rho) \leq 1$. In [Scheeres 1998] a simple criteria for when an external perturbation (such as the sun) can destabilize such a three-body system is found. Define the sidereal period of the binary system to be T_b and the period of the binary system's orbit about the sun to be T_o. Then the condition for the triangular points to be stable when subject to the solar perturbation is: $T_b < 27/8T_o\rho(1 - \rho)$. The unstable motion associated with the solar perturbation will place a spacecraft on a potentially impacting trajectory within a few periods of the binary system. Thus, even though some NEA binaries may have stable triangular libration points, which may be a suitable place to park a spacecraft in, there will be many that have no stable solutions. Due to this, use of the triangular libration points cannot be relied upon as a generic strategy for exploring binary asteroids.

3.1.3 Surface motion

Finally, we can consider the motion of a vehicle (i.e., a rover) over the surface of a small body. Due to the weak gravitational attraction of the body and the uncertain properties of asteroid surfaces, the most feasible method of locomotion appears to be hopping. Several simple designs are possible, including the use of internal flywheels [Yoshimitsu et al. 2001]. When viewed as a means for controlled locomotion over an asteroid, however, some serious issues arise. First, let us consider some of the peculiarities of motion over the surface of an asteroid. The defining quantity for characterizing surface motion on an asteroid is the local escape speed. On the surface of a spherical, non-rotating asteroid with gravitational parameter μ and radius R this speed is just $V_{esc} = \sqrt{2\mu/R}$. Once we consider a rotating body, however, we see that the escape speed relative to the asteroid surface will now vary with latitude and with the direction of the surface relative velocity vector. At the equator, a particle at rest on the surface will have an inertial speed of ωR, where ω is the asteroid rotation rate. Surface motion in the direction of rotation at a speed of $\sqrt{2\mu/R} - \omega R$ will be escape speed, while motion in the opposite direction of rotation at a speed larger than $\sqrt{2\mu/R} + \omega R$ will lead to escape. A velocity in any other direction will have to be added (vectorially) to the velocity due to the asteroid rotation to find the total speed in inertial space, and to ascertain what this speed is relative to escape speed. Finally, if the asteroid has a non-spherical shape, we also see that the local gravitational attraction may be greater or lesser at different points on the surface of the asteroid as well as the surface speed due to rotation, leading to additional variations in escape speed. For definiteness, local escape speed is generally defined as the speed perpendicular to the surface necessary to achieve escape speed relative to the body (see

[Scheeres et al. 2002] for a more complete definition). Such local variations can be extreme, for the asteroid Eros the local escape speed varies between 5 and 15 m/s depending on surface location [Miller et al. 2002].

Local escape speed is a useful characterization as it provides an easily computable limit on surface speeds, however we must note that speeds less than local escape speed may also end up escaping the asteroid. In [Scheeres et al. 2002] a classification of surface ejecta is given in terms of their final state. It is useful to use periapsis passage relative to the asteroid to delimit between different classes of motion. At launch a particle starts from an initial radius $r_0 \geq q_0$, since in general the initial periapsis (q_0) lies beneath the body's surface. In the absence of perturbations the next periapsis passage q_1 will either equal q_0, and thus will be an impact, or will never occur, indicating escape. When perturbations are incorporated, or even if non-spherical shapes are allowed, it becomes possible for multiple periapsis passages to occur. We denote these as a series $q_i; i = 0, 1, 2, \ldots$. Associated with each periapsis passage is the periapsis vector, $\mathbf{q}_i$, representing the periapsis location in the asteroid-fixed space. If we denote the set of points that constitute the asteroid body as $\mathcal{B}$, then if $\mathbf{q}_i \in \mathcal{B}$ the sequence stops and an impact has occured. Conversely, given a periapsis passage q_i, if q_{i+1} does not ensue, then the ejecta has escaped. Finally, if the sequence never terminates ($i \rightarrow \infty$), then the ejecta is in a stable orbit about the asteroid. Figure 3 gives a graphical representation of these classes.

Based on this understanding, the following classifications can be defined [Scheeres et al. 2002]:

Class I Immediate reimpact: ejecta reimpacts with the surface prior to first periapsis passage.

Class II Eventual reimpact: ejecta does not reimpact at the first periapsis passage, but eventually reimpacts in the future.

Class III Stable motion: ejecta is placed into a long-term stable orbit about the asteroid.

Class IV Eventual escape: ejecta has at least one periapsis passage by the asteroid before it escapes.

Class V Immediate escape: ejecta escapes from the asteroid prior to its first periapsis passage.

Local escape speed really defines Class V ejecta. For motion relative to the surface, this is a sobering thought as an apparently "safe" trajectory that does not immediately escape may enter orbit and eventually escape. For controlled surface motion, the goal should be to place a rover trajectory firmly into Class I, which will immediately re-impact with the surface. Examples of all classes can be easily found, for example in [Scheeres et al. 1998a] a Class II trajectory that does not reimpact for almost a year is described. Such motion is clearly not suitable for controlled surface exploration using a rover.

These considerations force rover motion to be conservative, with only relatively small "hopping" speeds acceptable. This can lead to potential difficulties, however, depending on the topology of the asteroid surface. It is possible that a rover may be caught in a local potential well or gravitational basin, and that escape from this basin may require speeds large enough to place it into a Class II or higher trajectory. Being in such a situation would clearly be unacceptable, and implies that careful planning of surface motion trajectories are necessary prior to placing a rover on the surface of a small body. Specific strategies would probably involve the identification of paths that lead from regions of high potential to regions of low potential, avoiding large obstructions along the way.

A seperate issue is the coupling between the reimpacting rover and the surface. Due to the complex topography, gravity, and the small body's rotation the motion of a vehicle with rebound can become quite complex. Thus, it is desired to design rovers to have minimum recoil speeds (i.e., low coefficients of restitution). A complete understanding of this issue requires better knowledge of the properties of asteroid regoliths, as these asteroid soils may have features that will minimize recoil speeds. Still, the apparent presence of exposed bedrock on some asteroids [Hudson et al. 2001] implies that the mechanical design of the rover will still be an important element. Further complications can arise from coupling between the rover rotational and translational motion. The energy of a reimpacting body may be partially converted into rotational kinetic energy and stored until the next impact with the asteroid surface. Such energy storage can yield complex and unpredictable motions of a body across the surface of an asteroid, and is an aspect of dynamics that is poorly understood and modeled [Sawai et al. 2001].

Finally, the coupling of surface motion with the disturbance and electric potential of surface regolith mentioned previously could potentially create a poor environment for the mechanical and electrical operation of a sophisticated rover vehicle. Initial designs of rover vehicles may be biased towards self-contained designs with a minimal number of sensor portals, such as the proposed MINERVA rover for the Muses-C mission [Yoshimitsu et al. 2001].

3.2 Active Control Strategies for Close-Proximity Dynamics

An exciting possibility for close-proximity motion relative to small bodies is to take advantage of the relatively weak gravitational accelerations and actively control a spacecraft's motion relative to the body. Indeed, in the Muses-C mission such strategies have already been developed at a basic level and will be used to circumvent the problems associated with trying to follow an orbital approach for that mission [Hashimoto et al. 2001, Kubota et al. 2001]. It must be noted that active control techniques may not always be suitable for specific bodies and specific missions, still they can form a very important class of motions that will surely be applicable to the exploration of smaller asteroidal and cometary bodies.

There are two general approaches to controlled motion: near-inertial hovering and body-fixed hovering. In near-inertial hovering the spacecraft is stationed at a fixed location relative to the asteroid in the sun-asteroid frame, the asteroid rotating beneath the spacecraft. Such a situation is useful for the initial characterization and measurement of the body. In body-fixed hovering the spacecraft is stationed at a fixed location relative to the rotating asteroid, implying that the spacecraft is rotating with the asteroid in inertial space. This situation is useful for sampling a small-body surface. Both of these ideas, and their generalizations, are discussed in more detail below.

For the implementation of either approach, some minimal levels of sensing capability are needed onboard the spacecraft. First is the ability to directly sense altitude, either using a laser altimeter or by the efficient processing of stereoscopic optical measurements. This measurement type forms the backbone of an automatic control system to maintain altitude and position relative to an asteroid. In addition to this, it is ideal for the vehicle to have the ability to sense its location relative to the asteroid surface. This can be implemented by optical sensors or scanning lasers, both of these technologies are in different stages of development. These are not the only types of measurements available or useful, however they are the most essential. The efficient measurement of altitude allows for the implementation of automatic control algorithms that stabilize the spacecraft hovering position, while measurements of body-relative location allows for an expanded capability for the control and motion of the spacecraft. For the latter case, the spacecraft must be able to correlate measured features with a global topography map in order to locate its current location. For some specific applications it may only be necessary to measure and detect lateral motion in addition to vertical motion, however for the most general applications the ability to detemine its global location on the asteroid is necessary. This implies that a global map of the asteroid surface has been created at some point, probably using the same instruments to be used for the relative navigation, although hopefully also using higher resolution scientific instruments. The develpment and implementation of such sensor systems is a technology that is currently being developed, and should be available for use in the future.

In addition to the above sensing and estimation capability, the spacecraft will also require precise 6-DOF control capability. This implies a full set of thrusters for executing arbitrary control moves, perhaps augmented by momentum wheels for fine attitude control. It may be feasible to use more restrictive thruster configurations for the control of the spacecraft, although these would have to be carefully designed for specific implementation approaches. Finally, some, but not all, of these active control approaches imply that the vehicle may be out of sun-light for considerable periods of time. Thus, such power considerations should be factored into the development and design of space vehicles for these advanced approaches.

3.2.1 Near-Inertial Hovering

In this approach the spacecraft fixes its location relative to the body in the rotating body-sun frame, creating an artificial libration point in this frame. A useful way to think about this approach is to first consider the sun-asteroid libration point. A spacecraft placed in this location will, ideally, remain fixed in its position. If, however, the spacecraft adds a constant thrust acceleration away from the asteroid, it would have to move its location closer to the asteroid in order for the forces to balance again. If a sufficiently large acceleration is added, it could conceivably hold its position relatively close to the asteroid. If it is close to the asteroid, it would have to supply an acceleration of $\sim \mu/r^2$ to "hover" at a radius of r from the attracting asteroid. Considering the more general case, it is possible to specify the necessary control thrust to maintain position at an arbitrary location in the asteroid-sun rotating frame. Due to the relatively slow motion of the body about the sun (on the order of degrees per day at fastest), this position can be considered to be nearly inertial over relatively short periods of time.

One complication with this approach to hovering is that these artificial equilibrium points are unstable, meaning that a small error in the open-loop thrust acceleration (or a small error in positioning the spacecraft) will cause the spacecraft to depart from its desired hovering point at an exponentially increasing rate. For example, assume a spacecraft is hovering above a spherical asteroid with a constant, open-loop thrust acceleration $a = \mu/R^2$, but is positioned at a distance of $R \pm \delta R$ from the asteroid. If the spacecraft is at a slightly higher distance, $R + \delta R$, it's thrust is greater than the gravitational attraction and it will start accelerating away from the asteroid. Conversely, if it is at a slightly lower distance, $R - \delta R$, it's thrust is less than the gravitational attraction and it will start to accelerate towards the asteroid. Thus, practical implementation requires the addition of a closed-loop feedback control that senses the altitude or distance deviation of the spacecraft from its ideal hovering point. The necessary control loop to stabilize this motion is actually quite simple, and can be implemented in an automatic way using minimal spacecraft resources [Broschart and Scheeres 2003]. There are limits to this approach, however. A spacecraft cannot inertially hover within the maximum radius of the asteroid at its hovering latitude, due to obvious physical constraints. Additionally, as the radius of hovering becomes closer to the body, the automatic control approach described here can become unstable, potentially leading to difficulties in implementation.

It is not necessary, however, to force the spacecraft to be fixed precisely at one location. A generalization of this idea places the spacecraft in an elliptic or hyperbolic orbit relative to the asteroid, but has its velocity vector "reflected" whenever it gets within a certain distance to the asteroid (for an ellptic orbit) or gets a certain distance away from the asteroid (for a hyperbolic orbit), forcing the spacecraft to travel back on, or close to, its original path but in the opposite direction. This approach can be thought of as hovering with a relatively large dead-band control about the nominal hovering point, and requires essentially the same control and sensing capability on-board the spacecraft. This is essentially the approach to be used by the Muses-C spacecraft when it arrives at its target asteroid [Kubota et al. 2001]. In this approach the time between control maneuvers can be made arbitrarily long by increasing the size of the dead-band box.

Inertial hovering has several attractive attributes which may make it a mainstay approach of future exploration. There are also a number of drawbacks and limitations, however. On the positive side, this approach can be applied to any small body, and the cost of inertial hovering can theoretically always be driven to zero (not accounting for the statistical control to stabilize the hovering point). However, the position where hovering is feasible may be far from the body, and may not afford the optimal viewing geometry. For example, if the NEAR spacecraft had taken a hovering approach to its mission to Eros and implemented inertial hovering at a distance of 50 km from the asteroid (which was the nominal orbit radius for most of the mission), it would have required over 15 m/s per day to maintain this position, or for its prime 9 month mission would have required a total ΔV on the order of 4 km/s. Contrasted with the actual fuel usage (on the order of a few tens of m/s), hovering was clearly not a reasonable approach for that body. Thus, to gain high resolution scientific measurements this approach is largely limited to smaller bodies with their associated smaller hovering cost. A related drawback pertains to the ability of the spacecraft to accurately measure the mass and gravity field of the asteroid, and hence to compile an accurate global topographic map. When using such a controlled hovering mode, errors in the spacecraft thrusters and solar radiation pressure parameters will dominate over the signature of the asteroid gravity field acting on the spacecraft. While it might be possible to extract some averaged results on the total mass of the asteroid, these results would be corrupted by many different uncertainties that will not be uniquely separated from the gravity signature. Additionally, higher order gravity fields will be nearly impossible to extract. This is a serious limitation, as it deprives the mission of essential scientific data and may make it difficult to subsequently transition to a body-fixed hovering exploration of the asteroid. It is possible to enact a few ballistic flybys of the asteroid to gain an improved estimate of its mass, but this estimate will not be as accurate as a mass estimate obtained by tracking the spacecraft while in orbit about the body.

3.2.2 Body-fixed Hovering

In this approach the spacecraft now fixes its position relative to the rotating body. A natural way to visualize this approach is to imagine using a “jet-pack” to levitate off of the surface of a rotating body, such as the Earth or an asteroid. Since the gravitational attraction is relatively weak at asteroids, it is possible to implement such hovering trajectories for extended periods of time (hours) with total costs on the order of tens of meters per second. This approach to controlling motion in close proximity to small bodies has been analyzed in detail [Scheeres 1999b, Sawai et al. 2002] and a detailed simulation of this approach has been developed for analysis of hovering over arbitrary models of asteroids [Broschart and Scheeres 2003]. Resulting from this work, body-fixed hovering has been shown to be feasible from a dynamics and control perspective. The approach is essentially identical to inertial hovering, except everything is now done relative to the asteroid-fixed frame, which generally has a rotation period on the order of hours to days at most. Thus, the spacecraft acceleration must accomodate both the gravitational and centrifugal accelerations, although there are locations where the hovering cost is zero (at the synchronous orbits). This body-fixed hovering approach also suffers from the same basic instability noted for the inertial hovering case, although there are regions where this approach yields completely stabilized motion [Scheeres 1999b]. A similar control strategy, using altimetry to maintain a fixed altitude, can stabilize a hovering point so long as it is located within the synchronous radius of the body. This result holds approximately true over the entire body and places an altitude “ceiling” on hovering for a simple control law to be able to stabilize its location. Some important points relative to this approach can be noted. First is that this technology can be seen as a precursor to a controlled landing on an asteroid surface, and is probably necessary for sample return missions. Second, the Muses-C spacecraft is, in essence, using this approach when it performs its surface sampling runs [Hashimoto et al. 2001].

The implementation of body-fixed hovering can also be accomplished using a simple dead-band controller acting on the altitude of the spacecraft, in conjunction with a single thrust direction properly aligned relative to the asteroid gravity field. Thus, the technology to implement this is clearly available now. If, in addition to maintaining a single altitude at a specific location, it is desired for the spacecraft to translate in the asteroid-fixed frame, moving from one site to another, and to descend and ascend from the surface, additional sensing and control technology will have to be used. First, the spacecraft must maintain its attitude in the body-fixed frame – we should note that it will not do so naturally, as its attitude will remain fixed in inertial space and will want to spin in the asteroid-fixed space. Second, for it to perform translational motions will require that the spacecraft have the capability to locate itself relative to the surface and perform some higher-level control to null out transverse oscillations about the hovering point.

The development of this surface relative motion capability is perhaps the most advanced concept tendered here. This idea also solves the problem of rover locomotion over an asteroid surface, as instead of relying on natural trajectories induced by mechanical "jumpers", we have controlled motion from one location to another. There are a number of interesting peculiarities associated with such surface relative motion, such as the fact that there is a preferred direction of motion about an asteroid in this mode [Sawai et al. 2002]. Motion in the same direction as asteroid rotation can actually destabilize the dynamics of the spacecraft control, while translational motion in the opposite direction will tend to stabilize the control system. Other than this observation, which can be easily proven, there is little known about the stability and control of surface relative motion at small bodies, making it an essential topic for future research.

There are a number of drawbacks related to body-fixed hovering as well. First, it is essential that a fairly accurate model of the asteroid spin, topography and gravity field be available. The gravity field must be defined down to the surface of the body as well, something which is not always easy to do (as described previously). Thus, body-fixed hovering should be preceeded by a period of characterization at a relatively high level of accuracy. In the future, it may be possible to dispense with this requirement, but that would only be after the basic technology and approach has been proven. Next, there is an altitude limit at which the conventional (and simple) stabilizing control becomes unstable, which could conceivably limit its application, although this does not seem to be that strong of a drawback. Most importantly, however, is that a body-fixed hovering vehicle will undoubtably experience periods of solar occultation, making the presence of batteries or non-solar power generation essential for long-term operations at the surface of a body. Additional operations issues also exist, such as communications, attitude determination, and mechanical interfaces with the surface.

4 Conclusions

Ultimately, close proximity missions are driven by the small body environment that they will encounter. This is an important point that leads to a strong emphasis on pre-launch and pre-design observation campaigns for target bodies. Once the small body environment has been constrained, there are a number of approaches that can lead to a successful mission. None of these approaches is without drawbacks, but the wealth of options ensures that there exists a rational and reasonable strategy for exploring and characterizing any small solar system body. This being said, it must also be realized that there is a real diversity among these approaches, and a spacecraft designed to optimize one specific mission may not be suitable for a different mission. This is a serious issue and should be understood by spacecraft and mission designers alike. This fact leads to two different approaches to the problem:

The target bodies are sufficiently characterized prior to mission and spacecraft design, allowing for a clearly delineated set of mission operations approaches.

The spacecraft and mission is designed to handle a range of possible situations, out of which most asteroids of the class being visited would fall.

The latter approach is clearly more risky as it relies on unknown properties falling within a certain range, and in general will lead to a more expensive mission as this fundamental parameter and mission uncertainty must be accounted for at every step in the design. On the plus side, it opens up the number of target bodies for a single mission.

Within the realm of possible mission concepts, some are better understood than others. The issues that currently demand further study are the basics of dynamics about binary asteroids, the dynamics of rovers on the surfaces of asteroids, and the dynamics of transient atmospheres and re-impacting ejecta. In terms of controlled motions, there is still much work to be done on all aspects of hovering, with a special emphasis on surface relative translations, as this is the most demanding application of this approach.

Finally, as has been pointed out repeatedly, missions to asteroids with known physical properties are simpler and allows the mission and spacecraft design to be optimized for the more precisely known parameters. While there are a large range of possible physical parameters which could be measured from the ground, there is a smaller set that yield the most important physical characteristics needed to decide which close proximity approach should be used. These are: number of co-orbitals, body size and type, body spin rate and spin state, body shape.

Acknowledgements

The research reported here was supported in part by the IPN Technology Program by a grant from the Jet Propulsion Laboratory, California Institute of Technology which is under contract with the National Aeronautics and Space Administration, and by the Planetary Geology and Geophysics Program by a grant from the National Aeronautics and Space Administration.

References

[Broschart and Scheeres 2003] Broschart, S. and Scheeres D.J., (2003). Numerical Solutions to the Small-Body Hovering Problem. Paper presented at the 13th AAS/AIAA Space Flight Mechanics Meeting, Ponce, Puerto Rico, February 2003. Paper AAS 03-157.

[Chauvineau et al. 1993] Chauvineau, B., Farinella, P., and Mignard, F., (1993). Planar Orbits about a Triaxial Body: Application to Asteroidal Satellites, *Icarus*, Vol 105, pp. 370 - 384.

[Dechambre and Scheeres 2002] Dechambre, D. and Scheeres, D.J., (2002). Transformation of spherical harmonic coefficients to ellipsoidal harmonic coefficients, *Astronomy and Astrophysics* 387: 1114-1122.

[Dobrovolskis and Burns 1980] Dobrovolskis A.R. and Burns J.A., (1980). Life near the Roche Limit: Behavior of ejecta from satellites close to planets. *Icarus* 42, 422-441.

[Garmier and Barriot 2001] Garmier, R., Barriot, J.-P., (2001). Ellipsoidal harmonic expansion of the gravitational potential: Theory and Application. *Celestial Mechanics and Dynamical Astronomy* 79, 235-275.

[Geissler et al. 1996] Geissler P., Petit J.-M., Durda D. D., Greenberg R., Bottke W., Nolan M., and Moore J., (1996). Erosion and ejecta reaccretion on 243 Ida and its moon. *Icarus* 120, 140-157.

[Hamilton and Burns 1991a] Hamilton D.P. and Burns J.A. 1991a. Orbital Stability zones about asteroids. *Icarus* 92, 118-131.

[Hamilton and Burns 1991b] Hamilton D.P. and Burns J.A. 1991b. Orbital Stability zones about asteroids. II. The destabilizing effects of eccentric orbits and of solar radiation. *Icarus* 96, 43-64.

[Hashimoto et al. 2001] Hashimoto, T., Kubota, T., Kawaguchi, J., Uo, M., Baba, K. and Yamashita, T., (2001). Autonomous Descent and Touch-Down Via Optical Sensors, in *Advances in the Astronautical Sciences* Vol. 108, 469–480.

[Hu and Scheeres 2002] Hu, W. and Scheeres, D.J., (2002). Spacecraft Motion about Slowly Rotating Asteroids, *Journal of Guidance, Control, and Dynamics* 25(4): 765-775.

[Hu 2002] Hu, W., (2002). Orbital Motion in Uniformly Rotating Second Degree and Order Gravity Fields, Ph.D. Thesis, The University of Michigan.

[Hudson et al. 2001] Hudson, R.S., Ostro, S.J., Jurgens, R.F., Rosema, K.D., Giorgini, J.D., Winkler, R., Rose, R., Choate, D., Cormier, R.A., Franck, C.R., Frye, R., Howard, D., Kelley, D., Littlefair, R., Slade, M.A., Benner, L.A.M., Thomas, M.L., Mitchell, D.L., Chodas, P.W., Yeomans, D.K., Scheeres, D.J., Palmer, P., Zaitsev, A., Koyama, Y., Nakamura, A., Harris, A. W. and Meshkov, M. N., (2000). Radar Observations and Physical Modeling of Asteroid 6489 Golevka, Icarus 148: 37-51.

[Kaula 1966] Kaula, W.M. 1966. *Theory of Satellite Geodesy*, Blaisdell.

[Kubota et al. 2001] Kubota, T., Hashimoto, T., Uo, M., Maruya, M. and Baba, K., (2001). Maneuver Strategy for Station Keeping and Global Mapping Around an Asteroid, in *Advances in the Astronautical Sciences* Vol. 108, 769–780.

[Lara and Scheeres *in press*] Lara, M. and Scheeres, D.J. Stability bounds for three-dimensional motion close to asteroids, *Journal of the Astronautical Sciences* in press.

[Lee 1996] Lee P., (1996). Dust levitation on asteroids. *Icarus* 124, 181-194.

[Mignard and Hénon 1984] Mignard, F. and Hénon, M., (1984). About an unsuspected integrable problem. *Celestial Mechanics* 33, 239-250.

[Miller et al. 1990] Miller J.K., Weeks, C. and Wood, L.J., (1990). *Journal of Guidance, Control, and Dynamics* 13(5) 775-784.

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

[Miller et al. 2002] Miller, J.K., Konopliv, A. S., Antreasian, P. G., Bordi, J. J., Chesley, S., Helfrich, C. E., Owen, W. M., Scheeres, D. J., Wang, T. C., Williams, B. G. and Yeomans, D. K., (2002). Determination of shape, gravity, and rotational state of Asteroid 433 Eros *Icarus* 155:3-17.

[Morrow et al. 2002] Morrow, E., Scheeres, D.J. and Lubin, D., (2002). Solar Sail Orbital Operations at Asteroids, Part 2: Exploringthe Coupled Effect of an Imperfectly Reflecting Sail and a Non-Spherical Asteroid, paper presented at the 2002 Astrodynamics Specialist Meeting, Monterrey, California, August 2002. Paper AIAA 2002-4991.

[Petit et al. 1997] Petit, J.-M., Durda, D.D., Greenberg, R., Hurford, T. A. and Geissler, P. E., (1997). The long-term dynamics of Dactyl’s orbit. *Icarus* 130, 177-197.

[Richter and Keller 1995] Richter, K. and Keller, H.U., (1995). On the stability of dust particle orbits around cometary nuclei. *Icarus* 114, 355-371.

[Robinson et al. 2001] Robinson, M. S., Thomas, P. C., Veverka, J., Murchie, S., Carcich, B. (2001) The nature of ponded deposits on Eros. *Nature* 413, 396-400.

[Sawai et al. 2001] Sawai, S., Kawaguchi, J., Scheeres, D.J., Yoshizawa, N., Ogawara, M., (2001). Development of a target marker for landing on asteroids. *Journal of Spacecraft and Rockets* 38(4), 601-608.

[Sawai et al. 2002] Sawai, S., Scheeres, D.J. and Broschart, S., (2002). Control of Hovering Spacecraft using Altimetry, *Journal of Guidance, Control, and Dynamics* 25(4): 786-795.

[Scheeres 1994] Scheeres, D.J., Dynamics about Uniformly Rotating TriAxial Ellipsoids: Applications to Asteroids, *Icarus*, Vol 110, 1994, pp. 225 - 238.

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

[Scheeres 1998] Scheeres, D.J., (1998). The Restricted Hill Four-Body Problem with Applications to the Earth- Moon-Sun System, Celestial Mechanics and Dynamical Astronomy 70:75-98.

[Scheeres 1999a] Scheeres, D.J. 1999a. Satellite Dynamics about small bodies: Averaged Solar Radiation Pressure Effects, *Journal of the Astronautical Sciences* 47:25-46.

[Scheeres 1999b] Scheeres, D.J., (1999b). Stability of Hovering Orbits around Small Bodies, presented at the 1999 AAS/AIAA Spaceflight Mechanics Meeting, Breckenridge, CO, February 1999. AAS Paper 99-159.

[Scheeres 2003] Scheeres, D.J., (2003). The Dynamical Environment of Binary Asteroids. Abstract presented at the 34th Meeting of the AAS Division on Dynamical Astronomy, May 2003.

[Scheeres et al. 1996] Scheeres, D.J., Ostro, S.J., Hudson, R.S., and Werner, R.A., Orbits Close to Asteroid 4769 Castalia, *Icarus*, Vol 121, 1996, pp. 67-87.

[Scheeres and Asphaug 1998] Scheeres D.J. and Asphaug E.I., (1998). Debris and Sample Transport About Asteroids. In *Space 1998* 340-346 (R.G. Galloway and S. Lokaj eds.), American Society of Civil Engineering, Reston, Virginia.

[Scheeres et al. 1998a] Scheeres, D.J., Ostro, S.J. Hudson, R.S., DeJong, E.M. and Suzuki, S. 1998a. Dynamics of orbits close to asteroid 4179 Toutatis. *Icarus* 132, 53-79.

[Scheeres et al. 1998b] Scheeres, D.J., Marzari, F., Tomasella, L., and Vanzani, V. 1998b. ROSETTA mission: satellite orbits around a cometary nucleus, *Planetary and Space Science*, Vol 46, pp. 649–671.

[Scheeres and Marzari 2000] Scheeres, D.J. and Marzari, F. 2000 Temporary orbital capture of ejecta from comets and asteroids. *Astronomy and Astrophysics* 356, 747-756.

[Scheeres et al. 2000a] Scheeres, D.J., Bhargava, S. and Enzian, A. 2000a. A Navigation Model of the Continuous Outgassing Field Around a Comet, *Telecommunications and Data Acquisition Progress Report* 42-142.

[Scheeres et al. 2000b] Scheeres, D.J., Williams, B.G., Miller, J.K. 2000b. Evaluation of the Dynamic Environment of an Asteroid: Applications to 433 Eros, *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 3, 2000, pp. 466–475.

[Scheeres et al. 2001] Scheeres, D.J., Khushalani, B. and Werner, R.A., (2000). Estimating Asteroid Density Distributions from Shape and Gravity Information, *Planetary and Space Science* 48: 965-971.

[Scheeres and Marzari 2002] Scheeres, D.J. and Marzari, F., (2002). Spacecraft dynamics far from a comet *Journal of the Astronautical Sciences* Vol. 50.

[Scheeres et al. 2002] Scheeres, D.J., Durda, D.D. and Geissler, P.E. (2002). The Fate of Asteroid Ejecta, in *Asteroids III*, W.M. Bottke, A. Cellino, P. Paolicchi, and R. P. Binzel, eds., University of Arizona Press, Tucson.

[Thomas and Veverka 1980] Thomas, P. and Veverka, J., (1980). Downslope movement of material on Deimos. *Icarus* 42, 234-250.

[Thomas 1998] Thomas, P. C., (1998). Ejecta Emplacement on the Martian Satellites. *Icarus* 131, 78-106.

[Thomas et al. 2000] Thomas, P. C., Veverka, J., Sullivan, R., Simonelli, D. P., Malin, M. C., Caplinger, M., Hartmann, W. K., and James, P. B., (2000). Phobos: Regolith and ejecta blocks investigated with Mars Orbiter Camera images. *Journal of Geophysical Research* 105, 15091-15106

[Thomas et al. 2001] Thomas, P. C., Veverka, J.,. Robinson, M. S., and Murchie, S., (2001). Shoemaker crater as the source of most ejecta blocks on the asteroid 433 Eros. *Nature* 413, 394-396.

[Weeks 1995] Weeks, C.J., (1995). The effect of comet outgassing and dust emission on the navigation of an orbiting spacecraft. *Journal of the Astronautical Sciences* **43**(3), 327–343.

[Werner 1994] Werner, R.A., The Gravitational Potential of a Homogeneous Polyhedron, *Celestial Mechanics and Dynamical Astronomy*, Vol. 59, 1994, pp. 253-278.

[Werner and Scheeres 1997] Werner, R.A. and Scheeres, D.J., Exterior gravitation of a polyhedron derived and compared with harmonic and mascon gravitation representations of asteroid 4769 Castalia, *Celestial Mechanics and Dynamical Astronomy*, Vol. 65, 1997, pp. 313 – 344.

[Yeomans et al. 2000] Yeomans, D.K., Antreasian, P.G., Barriot, J.-P., Chesley, S.R., Dunham, D.W., Farquhar, R.W., Giorgini, J.D., Helfrich, C.L., Konopliv, A.S., McAdams, J.V., Miller, J.K., Owen Jr., W.M., Scheeres, D.J., Thomas, P.C., Veverka, J., and Williams, B.G.,(2000). Radio Science Results During the NEAR-Shoemaker Spacecraft Rendezvous with Eros, *Science* 289:2085–2088.

[Yoshimitsu et al. 2001] Yoshimitsu, T., Kubota, T., Nakatani, I. and Kawaguchi, J., (2001). Robotic Lander Minerva, Its Mobility and Surface Exploration, in *Advances in the Astronautical Sciences* Vol. 108, 491–502.

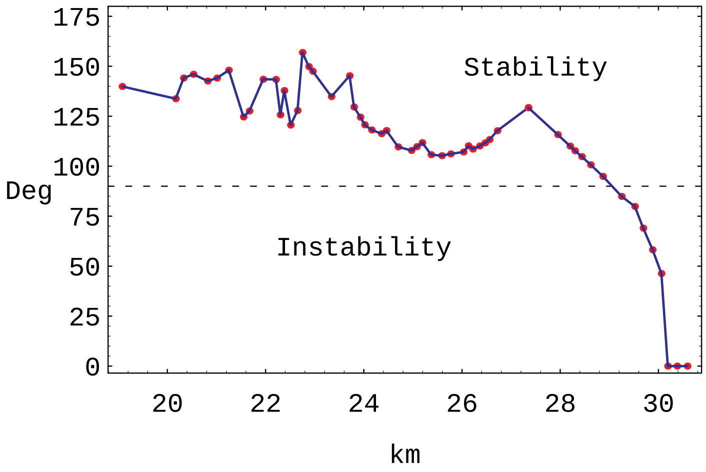

Figure 1: Stability regions for three-dimensional motion around the asteroid Eros [Lara and Scheeres *in press*].

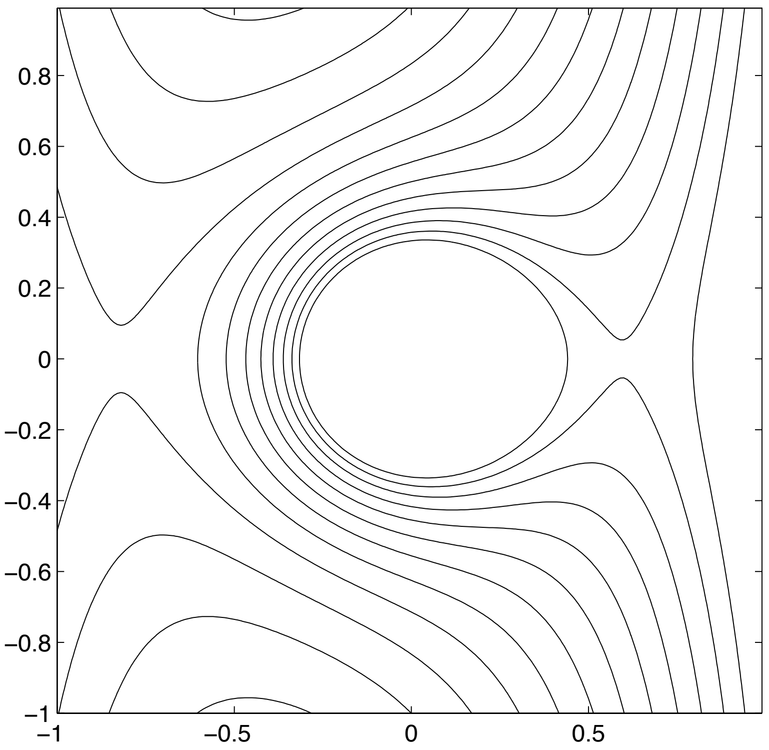

Figure 2: Generic Zero-Velocity Curve for $\tilde{\beta} > 1$ [Scheeres and Marzari 2002].

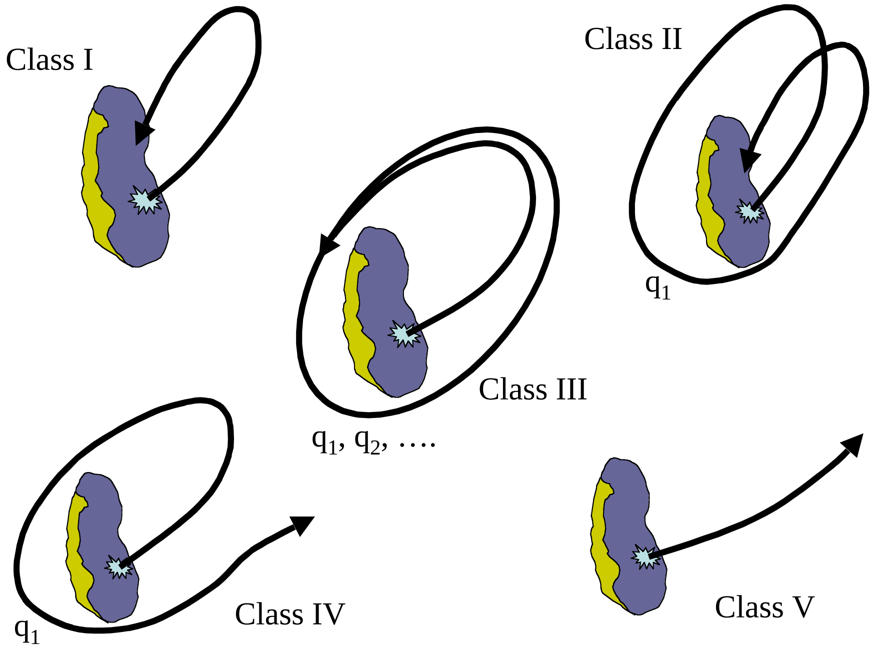

Figure 3: The five classes of ejecta fate [Scheeres et al. 2002].