ANALYSIS OF COMMUNICATION INTERCONNECTEDNESS IN THE PROXIMITY OF NEAR-EARTH ASTEROIDS

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ABSTRACT

In this paper we analyze fundamental local-area communication issues related to proximity operations around near-earth asteroids. We are motivated by NASA's plan to send robotic spacecraft to numerous such asteroids in the coming years in preparation for an eventual manned mission. We consider here the case where multiple probes are deposited on the surface of an asteroid and must communicate the data they collect to each other and to earth by using the orbiting 'mothership' as a relay. With respect to this scenario, we statistically analyze the ability of surface probes in various locations to communicate with the mothership as well as their abilities to network with one another. For the purposes of this analysis, we assume the simplest possible communications scenario: a surface probe can communicate with the mothership only when it has an unobstructed line of sight. At the frequencies of interest here, line of sight is a necessary condition but it is obviously not sufficient—the end-to-end link margins of our communications system must be high enough to support the desired/required data rates. Nonetheless, this simplistic analysis represents the first step in characterizing the communication system requirements for the asteroid-local portion of the system.

Keywords: Space communications, space communication networks, NEA missions, asteroid surface to space networking.

1 INTRODUCTION

Recently, there has been a great deal of interest in sending robotic precursor missions to near-earth asteroids (NEAs) for scientific study and to prepare for a possible manned mission in the mid-2020s. In particular, increased understanding of these small irregularly-shaped bodies is essential to the development of an NEA deflection strategy which might someday be implemented for planetary protection. In the far future, NEAs might also serve as fueling stations, mining sites, or remote observatories, and recent interest in asteroid exploration has been demonstrated by past, present, and future missions such as NEAR Shoemaker, Hayabusa, DAWN, and OSIRIS REx.

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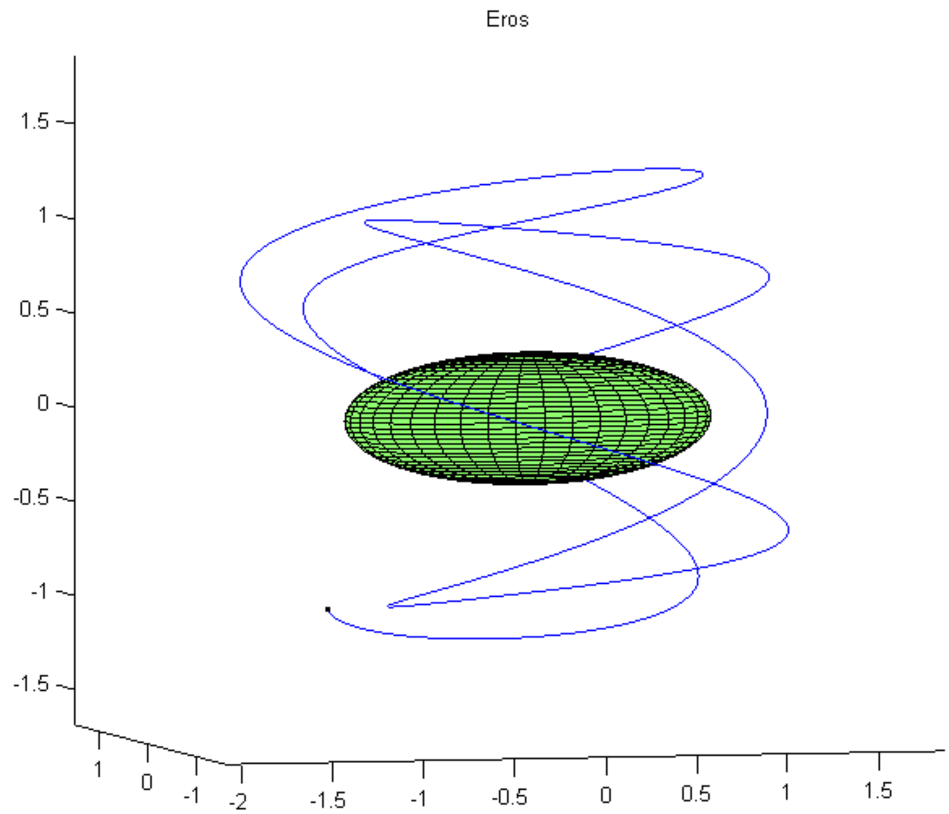


Figure 1: Simulated spacecraft orbit around asteroid Eros shown in the asteroid body-fixed frame.

The research presented here considers an issue that is likely to be critical to future NEA missions: communication and networking for supporting local operations in the vicinity of an asteroid. Our assumption here is that future missions to NEAs will deploy multiple sensing platforms once they arrive in the vicinity of the target asteroid: possibly additional autonomous spacecraft but certainly one or more surface platforms. While a great deal of research has been done in the area of space communications theory, low-cost transmitter/receiver designs, and even deep-space networking (e.g., [1, 2, 3, 4, 5, 6]), we have found no work that addresses the special challenges of establishing and maintaining local-area communications in the neighborhood of an NEA. The sensors on these various platforms must communicate their data to each other (in order to coordinate their actions) and ultimately back to earth, and this requires that an *ad hoc* local-area communication system be established. Furthermore, it seems likely that in most scenarios an orbiting spacecraft (i.e., the 'mothership') will be required to act as the relay for both surface-to-surface (between NEA-local sensor platforms) and surface-to-earth communication. This is the scenario we assume in the research presented here where a single orbiting spacecraft acts as the relay and six surface platforms communicate with each other and with earth through it.

Further narrowing our focus, we assume that if a surface platform has an unobstructed line-of-sight to the orbiting spacecraft, then it can communicate to and through that spacecraft. At the frequencies required for space operations due to antenna design constraints, line-of-sight is a necessary but not sufficient condition for establishing a communications link; thus, the results presented here can be viewed as the best-case scenario. An analysis of communication capacity or availability between surface platforms and a spacecraft orbiting a massive, roughly spherical body like the Earth is easily performed and therefore not of great interest. Many NEAs, however, are small, aspherical bodies having non-uniform mass distributions, and they not only allow for very irregular orbits but also often support a diversity of different orbits. Furthermore, the tumbling spin of many of these objects also causes significant variations in the communication connectivity for platforms at different locations on the surface. These factors combine to make the simulation results presented here non-trivial and of some importance as a first step in designing the local-area communication system for future missions to NEAs

This paper is organized as follows. Section 2 discusses the problem of orbital modeling and details the structure of the computer simulation that we have implemented while Section 3 details the precise orbital scenarios that we have considered here. The results of this analysis are presented and discussed in Section 4 with conclusions being made in Section 5.

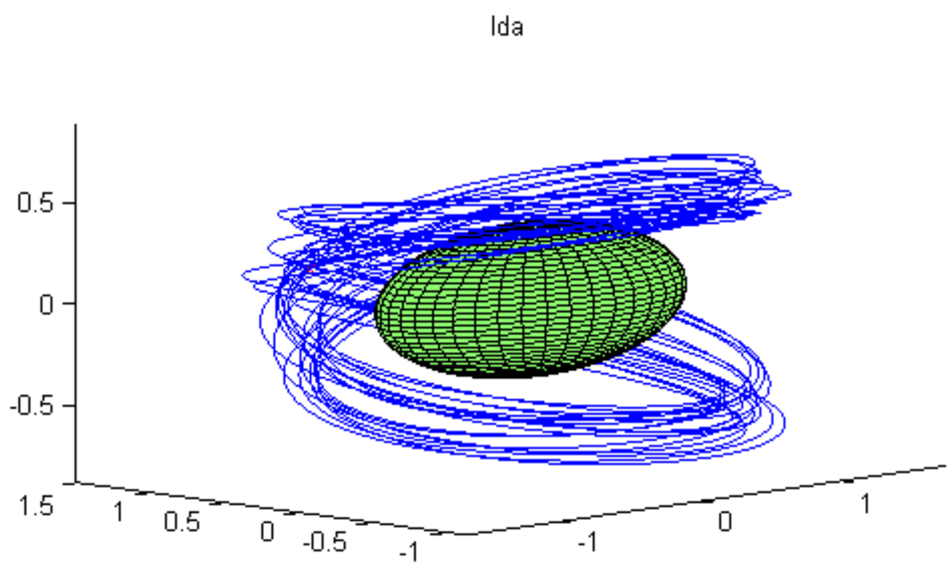


Figure 2: Simulated spacecraft orbit around asteroid Ida shown in the asteroid body-fixed frame.

2 ORBITAL MODELING

In most orbital models, both the celestial body and its satellite are treated as point masses with the assumption being that the satellite's mass is insufficient to affect the motion of the celestial body. This assumption holds in most applications, since the gravitational field produced by a constant-density sphere mimics that of a point mass, and the discrepancies between a celestial body's true shape and mass distribution relative to a constant-density sphere can often be modeled as perturbation functions with respect to the ideal orbit model. This simplification does not hold for a typical asteroid, however. The irregular shape of an asteroid creates a gravitational field that is much more complex than that of a sphere, resulting in a scenario where the gravity experienced by a satellite depends not just on distance but also on its position relative to the asteroid. Moreover, since the asteroid is rotating, its gravitational field in inertial space changes with time.

We model the motion of a satellite about an asteroid in this work using the restricted full two-body approach described by Scheeres [7], in which the asteroid is depicted as a scalene ellipsoid with constant density in uniform rotation about its largest moment of inertia. By using this simplification, the asteroid can be fully described with five parameters (three semi-major axis lengths, density, and spin rate), all of which can be approximated from ground-based observations. Furthermore, changing these body parameters allows one to model a wide variety of asteroids. Position in this model is described in a body-fixed Cartesian coordinate frame with the origin at the ellipsoids center of mass, and the x-, y-, and z-axes lie along the ellipsoids major, intermediate, and minor semi-major axes, respectively. For a scalene ellipsoid with semi-major axis lengths a, b, c (where $a \geq b \geq c$), and constant density ρ, the asteroids gravitational parameter μ is determined by

$$\mu = \frac{4\pi}{3} G\rho abc \tag{1}$$

where $G = 6.672 \times 10^{-8}\ cm^3 g^{-1} s^{-2}$ is the gravitational constant.

Another body parameter, δ, is analogous to the ratio between gravitational and centripetal accelerations acting at the longest end of the ellipsoid and is used to incorporate the effect that the asteroids spin rate, ω, has on the system. This parameter is defined as

$$\delta = \frac{\mu}{\omega^2 a^3}. \tag{2}$$

For ease of calculation, the system is normalized to have non-dimensional units of time and distance where the time scale is $1/\omega$ and distance is scaled to be multiples of the longest semi-major axis length, a. Thus the intermediate and minor semi-major axis lengths are redefined as $\beta = b/a$ and $\gamma = c/a$, respectively. Using these non-dimensional units, the equations of motion for the system are given by

$$\ddot{x} - 2\dot{y} = \frac{\partial U}{\partial x}, \tag{3}$$

$$\ddot{y} + 2\dot{x} = \frac{\partial U}{\partial y}, \tag{4}$$

$$\ddot{z} = \frac{\partial U}{\partial z}, \tag{5}$$

$$U = \frac{1}{2}\left(x^2 + y^2\right) - \delta V\left(x, y, z\right), \tag{6}$$

$$V\left(x, y, z\right) = \frac{3}{4}\int_{\lambda}^{\infty} \frac{\phi\left(x, y, z; u\right)}{\Delta\left(u\right)} du, \tag{7}$$

$$\phi\left(x, y, z; u\right) = \frac{x^2}{1 + u} + \frac{y^2}{\beta^2 + u} + \frac{z^2}{\gamma^2 + u} - 1, \tag{8}$$

$$\Delta\left(u\right) = \sqrt{\left(1 + u\right)\left(\beta^2 + u\right)\left(\gamma^2 + u\right)}. \tag{9}$$

The scalar value λ is the unique positive root of u for $\phi(x, y, z; u) = 0$ evaluated at any point outside the ellipsoid surface.

Orbital motion about the scalene ellipsoid is determined by the solution to Equations (1)-(9) with a given initial condition for the satellite's position and velocity. For this paper, the orbital motion was evaluated using a 7-8th order pair, variable step Runge-Kutta integrator. Since there is a tendency for numerical error to propagate over prolonged lengths of integration, the time interval used for the orbit simulation was kept to within twenty revolutions of the asteroid.

Table 1: Parameters for orbital design model.

Orbital Model	a (km)	b (km)	c (km)	$2\pi/\omega$ (hr)	ρ (g/cm^3)	Initial Conditions $[x, y, z, \dot{x}, \dot{y}, \dot{z}]$
Vesta (1)	265	250	220	5.3	3.5	[0, 1.5, 0, 3, 0, 1, 1.35]
Vesta (2)	265	250	220	5.3	3.5	[0, 1.8, 1.2, 3.5, 0, -0.85]
Eros	20	7	7	5.27	3.2	[0, 1.5, 0, 1.95, 0, 0.65]
Gaspra	9.5	6	5.5	7	3.5	[0, 1.25, 0, 2.95, 0, 1.65]
Tempel2	8	4.25	4.25	8.9	1.0	[1.25, 0, 0, 0, -3, 0.35]
Ida	28	12	10.5	4.63	3.5	[0,1.5, 0, 2.15, 0, 0.4]

As an example, Figure 2 shows an orbit about an ellipsoid model of the main belt asteroid 243-Ida in the body-fixed, rotating coordinate frame. Ida was approximated to have semi-major axis lengths of 28, 12, and 10 kilometers, a constant density of 3.5 g/cm^3, and a rotation period of 4.63 hours [7]. Model parameters for all of the asteroid scenarios considered here are given in Table 1.

Figure 3 shows the results of the orbit from Figure 2, assuming that the motion of the satellite is being tracked by a ground station located on Ida's surface. The satellite's position (left) and velocity (right) are portrayed in spherical coordinates based on the site's local coordinate frame, determined by the sites location on Idas surface (shown in the top-right corner of the figure). In order to show when the satellite cannot be tracked by the station, the elevation angle plot (lower-left) is highlighted in red whenever the satellite falls below the local horizon.

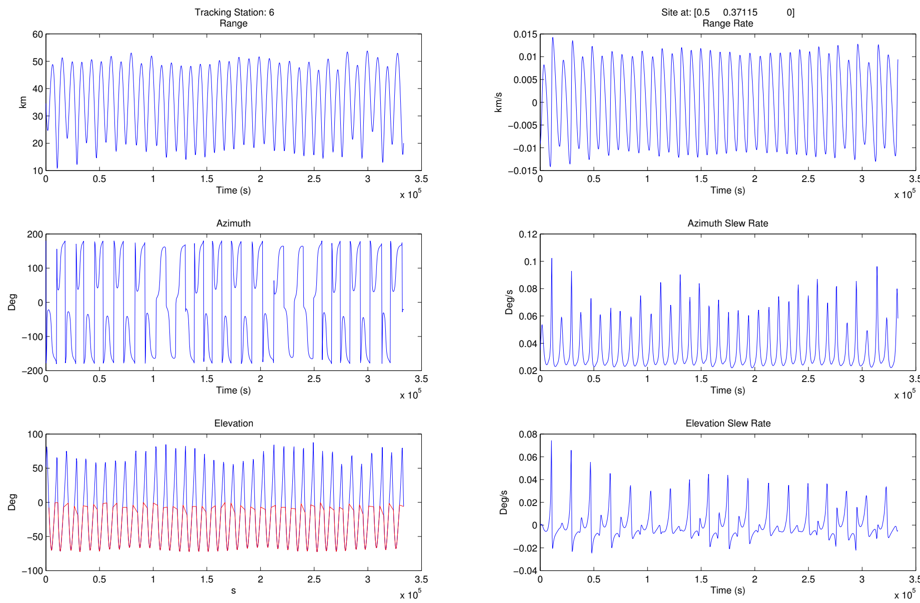


Figure 3: Satellite tracking data as seen from a location on the surface of Ida.

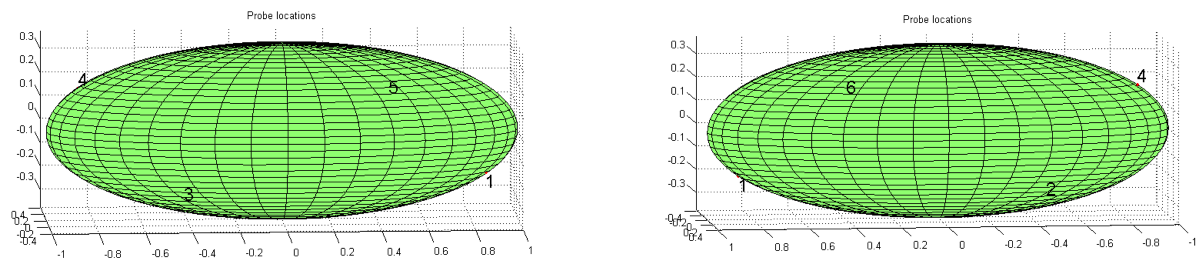
Table 2: Averaged comparisons for various asteroids.

Asteroid	Network Stability	Average Blackout Time	Average Net Access
Vesta (1)	8.7	82.2	15.1%
Vesta (2)	9.6	77.7	29.6%
Eros	12.4	95.6	32.0%
Gaspra	11.6	95.5	21.9%
Tempel2	20.5	131.1	45.5%
Ida	8.1	75.86	20.9%

3 ORBITAL SCENARIOS

It is clear from the discussion of Section 2 that the modeling of satellites in orbit around asteroids is far more complex than the modeling of similar satellites in orbit around planets like the Earth. In particular, the allowable range of stable orbits is often much greater and thus the exact choice of orbit can have a significant impact on the ability of a fixed set of surface probes to communicate information via the mothership relay. We analyze here a variety of scenarios which have been chosen at random simply to illustrate the range of the constraints that the different scenarios put on the communication system.

The ultimate goal of our project is to create a software simulator which can be used to design a given local-area NEA communication system and verify its effective operation for the planned mission. Thus, within the framework of our simulator, we wish to be able to model local-area communications for any asteroid (to an accuracy determined by the information known about it) for any orbital scenario or surface probe configuration. That said, we



(a) (b)

Figure 4: Probe locations on the two sides of Ida.

consider here five orbital scenarios whose resulting simulations vary widely. Specifically, our test cases are as follows: Vesta (Orbits 1 & 2), Eros, Gaspra, Tempel2, and Ida. All of these asteroids have highly irregular shapes, but only one of them (Eros) is technically an NEA and Tempel2 is considered to be a comet. In every example considered here, we place six sensor on the surface of the asteroid in the following manner: three latitudes are chosen arbitrarily and the positions of the probes along each latitude line distributed as longidunial pairs with reversed orientation in a semi-random fashion. What we mean by this is that if a single angle θ defines the longitudinal location of two sites at different latitudes, one site would be at $[\theta, \phi_1]$, then the other would be at $[\theta + \pi, \phi_2]$. Figure 4 illustrates the probe placement on asteroid Ida. The simulated orbital trajectories for Eros and Ida are shown in Figures 1 and 2, respectively. Just from these two plots, one can see how different the characters of these two orbits are.

Table 3: Results for Vesta orbit #1.

Surface Probe	Prob. of Comm Access	Avg. Blackout Time	Avg. Access Time
#1	0.1064	113.0	13.5
#2	0.1523	71.9	12.8
#3	0.1464	75.3	12.9
#4	0.1508	88.4	16.0
#5	0.1758	70.9	15.5
#6	0.1758	74.0	15.5

4 RESULTS

Table 2 provides an overview of our results. In the table, ‘network stability’ is the average length of time (in minutes) that a fixed set of surface probes can communicate with one another using the orbiting mothership as a relay while the ‘average blackout time’ is the

Table 4: Results for Vesta orbit #2.

Surface Probe	Prob. of Comm Access	Avg. Blackout Time	Avg. Access Time
#1	0.2363	83.8	26.7
#2	0.2517	79.4	26.5
#3	0.2552	75.3	26.2
#4	0.3322	84.3	42.3
#5	0.3536	69.3	38.8
#6	0.3501	73.9	39.3

time interval between communications windows with the mothership (averaged across all six surface platforms). The 'average net access' is the percentage of the time that surface probes have communications access via the mothership. From these averages, one can get some idea of how well each of the orbits accommodates various type of communications. For example, surface platforms have communications access 45.5% of the time for the Tempel2 scenario versus only 15.1% for the first Vesta scenario. On the other hand, communications blackout, when they occur, are 59.5% longer. The 'network stability' characterizes how long on the average a given set of surface probes can communicate with each other using the mothership spacecraft as a relay. This could be important if surface probes need to do collaborative processing on the measurement data that they are collecting. Studying Table 2, we note considerable variation in this quantity with Ida being least stable (8.1 minutes) and Tempel2 being the most stable (more than 20 minutes).

While the results summarized in Table 2 are useful, they do not allow us to characterize the communication constraints associated with the individual surface platforms. As it turns out, these constraints can vary widely depending on the orbital scenario. Tables 3 through 8 summarize these results for each sensor and each scenario. In these tables, we break out specifically the average probability that each surface platform (probe) has communications access (via line-of-sight to the relay mothership), the average time in minutes that each probe does not have communications access (labeled 'blackout time'), and the average time in minutes that it does have access. By combining the information generated by our simulations with surface probe sensor data generation rates, one could determine what the data buffering and throughput requirements are for the local-area communications network.

Table 5: Results for Eros.

Surface Probe	Prob. of Comm Access	Avg. Blackout Time	Avg. Access Time
#1	0.2647	122.4	46.5
#2	0.3377	81.3	41.1
#3	0.3262	84.4	41.3
#4	0.2887	125.1	51.9
#5	0.3556	78.4	42.8
#6	0.3501	82.3	44.3

Surveying the tables, one sees that there is a tremendous variability in the numbers. Just considering Tables 3 and 4 for the two Vesta orbits, we note that the average times

Table 6: Results for Gaspra.

Surface Probe	Prob. of Comm Access	Avg. Blackout Time	Avg. Access Time
#1	0.2273	108.5	32.9
#2	0.2902	88.9	35.9
#3	0.2862	88.3	36.1
#4	0.2218	112.8	32.8
#5	0.2897	87.8	35.8
#6	0.2887	87.0	34.6

during which surface platforms have communication access is almost twice as high for Orbit #2 than for Orbit #1. This implies that a communications network designed for Orbit #2 would require smaller surface-platform buffers and less communication channel capacity than one designed for Orbit #1. Examining Tables 3, 5, 6, and 8, we note that the blackout periods have significant variation for some surface platforms. The worst-case is illustrated in Table 8 where the average blackout time for Probe #1 is 2.5 times longer than it is for Probe #2. It is interesting to note that for the same orbital scenario and same two probes, the average access time is close to the same (9.7% longer for Probe #2). Taken together, these data imply that if both probes are collecting the same amount of sensor data, then the bandwidth of the communication channel connecting Probe #1 to the orbiting mothership has to be more than 2.5 times higher than that of the one connecting Probe #2. In addition, the data buffer on Probe #1 must also be approximately 2.5 times larger than that on Probe #2. Similar analysis can be performed for the other example scenarios simulated here.

Table 7: Results for Tempel2.

Surface Probe	Prob. of Comm Access	Avg. Blackout Time	Avg. Access Time
#1	0.4505	134.0	109.5
#2	0.4750	127.5	117.5
#3	0.4735	125.4	115.0
#4	0.4236	138.5	102.9
#5	0.4550	128.5	110.6
#6	0.4525	133.0	113.3

Table 8: Results for Ida.

Surface Probe	Prob. of Comm Access	Avg. Blackout Time	Avg. Access Time
#1	0.1593	126.4	24.6
#2	0.3591	49.2	27.0
#3	0.2842	54.2	21.9
#4	0.1638	122.9	25.3
#5	0.2862	53.5	22.1
#6	0.3671	48.9	27.6

5 CONCLUSIONS

In this paper, we have analyzed communications interconnectivity issues in the neighborhood of low-mass, irregularly-shaped celestial objects. While our major interest is studying local-area communications around near-earth asteroids, we have actually considered here a wider variety of objects. Our analysis here is based entirely on line-of-sight: i.e., if we have line-of-sight between two platforms, we assume that error-free communication is possible. Furthermore, this preliminary work only considers the timing of communication access—in future work, we will add communication link bandwidth estimation and surface platform buffer size estimation to our simulation. Going beyond this 'best case' line-of-sight analysis framework, we will also include channel capacity calculations based on ambient and self-generated noise models, antenna selection, modulation choice, and coding.

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