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THE B612 MISSION DESIGN

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ABSTRACT

This paper describes a mission proposed by the B612 Foundation to demonstrate the feasibility of docking a spacecraft with a small asteroid and applying a controlled, steady thrust to it in order to measurably alter the asteroid's orbit and rotation pole by the year 2015. The target would be a rocky 200-meter asteroid with a mass of about 10 billion kilograms that does not pose any impact threat to the Earth. The technology goal of the mission is to demonstrate a measurable change in the orbital velocity of the asteroid, say 0.2 cm/sec, minimum. In addition, in situ science would also be performed to determine materials and structural properties of the surface. Secondary goals could include technology demonstrations for mining the natural resources found on the asteroid. The spacecraft would have liftoff mass of less than 20 metric tons, including fuel for the trip to the asteroid and fuel to push the asteroid once it has arrived, and it would be launched on a single heavy lift rocket such as the Proton, Ariane 5 or Titan 4. The spacecraft borrows heavily from NASA's Jupiter Icy Moons Orbiter (JIMO) concept vehicle in that it would rely on nuclear reactor power and ion-propulsion systems. A major departure, however, would be the use of a promising new propulsion engine known as the VASIMR (Variable Specific Impulse Magnetoplasma Rocket) which uses radio waves to excite fuel into a plasma and magnetic fields to direct the expanding stream of ions out of the engine at specific impulses between 10,000 and 30,000 seconds. With this configuration, the spacecraft would be able to apply a force of 2.5 Newtons to the asteroid over a period of about three months. The mission includes plans to reorient the spin axis of the asteroid to a preferred alignment with respect to its orbital velocity vector such that the spacecraft thrust is most effective in changing the orbital velocity. The continuous, controlled thrust will produce a change of about 0.2 cm/sec in the asteroid orbital velocity. This change in velocity can easily be verified by processing Earth-based, radio metric tracking (range and/or Doppler) from NASA's Deep Space Network.

INTRODUCTION

Near-Earth asteroids pose a threat due to potential impacts that could disrupt or even extinguish life on Earth. After recognizing such a threat and maybe even identifying a specific asteroid with a high probability of impacting the Earth, the question remains, 'what can be done to eliminate the threat?' There have been various proposals by researchers to deflect an asteroid that is heading toward Earth, such as nuclear explosions or high-impulse trajectory deviations, but these techniques are hard to control and their results are not easy to predict. However, a spacecraft sent to an asteroid to deliver a steady, controlled thrust of sufficient magnitude and duration could eventually divert the asteroid orbit sufficiently to avoid an Earth impact. Prior to the discovery of such an impacting asteroid, it would be prudent to test such a spacecraft system before it is urgently needed. This is the justification for the mission described in this paper that has been proposed by the B612 Foundation [1].

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The B612 Foundation was founded in 2002 by NASA astronauts Russell L. Schweickart and Edward T. Lu, and research scientists Piet Hut of the Institute for Advanced Study in Princeton, N.J., and Clark R. Chapman of the Southwest Research Institute in Boulder, CO. It is a non-profit group dedicated to defining, promoting and demonstrating the capability to deflect asteroids away from the Earth. B612 is the name of the asteroid in *The Little Prince,* a children's book by Antoine de St. Exupery, after which both the foundation and the proposed demonstration mission are named.

MISSION OVERVIEW

The B612 mission concept is to send an unmanned spacecraft to a suitable target asteroid, then land and attach to the asteroid surface so that the spacecraft thrusters can be used to apply a steady thrust to the asteroid in order to demonstrate the capability to change the asteroid orbit and also modify its spin axis orientation. This demonstration mission will build on previous mission experience at asteroids (i.e., the successful landing of the NEAR-Shoemaker spacecraft on the asteroid 433 Eros) and will apply new propulsion technology to reach the thrust levels and durations required to move the asteroid. Post-mission engineering and science analysis will show how it should be refined to react to a real impact threat.

To efficiently change the orbit, thrust should be applied along the direction of the orbital velocity vector, but since all asteroids have some spin, the thrust vector of a landed spacecraft will not, in general, be aligned in the desired direction. To keep the thrust vector aligned in a continuous direction through the center of mass of the asteroid, it is most advantageous to place the spacecraft (and its thrusters) on a spin pole of the asteroid. However, the spin pole of an asteroid will not be aligned for any length of time with its orbital velocity direction, so precession of the polar axis could be preformed to keep the thrust vector oriented in the desired direction. In the B612 mission, both the asteroid orbit and spin are changed to develop the technology and demonstrate the capability needed to deal with a real asteroid threat which might require re-orienting the spin axis so thrust can be applied in a controlled manner. The manner in which this could be done is detailed in [2].

The primary mission goals are to change the asteroid orbital velocity by 0.2 centimeters per second and torque the asteroid spin axis by five to ten degrees. In addition, invaluable scientific observations of the target asteroid are possible during the close orbit and post-landing operations. The mission should be accomplished by 2015.

The spacecraft design for the B612 mission borrows from the proposed development for NASA's Jupiter Icy Moons Orbiter (JIMO), a spacecraft that is expected to visit Jupiter and its moons, Ganymede, Callisto and Europa in the next decade. In order to launch the B612 spacecraft on a single heavy-lift launch vehicle such as a Proton, Ariane 5 or Titan 4, the total spacecraft lift-off mass will be limited to 20 metric tons. Of this mass, we believe about 2,000 kg will be fuel for the high ISP plasma engines, leaving a spacecraft dry mass of about 18,000 kg.

The technology development for JIMO will incorporate a nuclear reactor developed for NASA as part of the Prometheus Project. This power source will supply sufficient electrical energy to power the B612 spacecraft plasma thrusters for a long duration, continuous thrust cruise and asteroid push phase. The plasma thrusters are based on a new technology engine known as the VASIMR (Variable Specific Impulse Magnetoplasma Rocket)[3] which uses radio waves to ionize a gas and accelerate the resulting plasma to very high exhaust velocities. VASIMR uses magnetic fields to direct the output flow of plasma to produce specific impulses between 10,000 and 30,000 seconds. In order to reach the desired thrust level of 2.5 Newtons, the plasma engines will require about 250 kilowatts of electrical power (assuming an efficiency of about 50 percent). The nuclear reactor can be sized to produce this level of output while keeping the total spacecraft launch mass less than 20 tons.

After launch into low Earth orbit, the B612 spacecraft will perform a continuous thrust spiral to increase orbital energy until escaping from the Earth-Moon system into a continuous thrust trajectory to rendezvous with the target asteroid. The transfer trajectories will be similar to low-thrust designs, such as those for the DS-1 or Dawn missions, but for B612 the thrust levels will be about 25 times greater. It is expected that the transfer from LEO to asteroid rendezvous will take about two or three years. Allowing time for a six month operation at the asteroid (three months of orbit and landing operations plus three months of asteroid pushing) requires that the launch date be sometime early in 2013. Details of the mission trajectory will be the subject for further study.

In order to apply a controlled thrust to the asteroid, the B612 spacecraft will have to firmly attach itself to the asteroid since the gravitational attraction at the surface will by as much as 100,000 times weaker than the gravity on Earth. Since the knowledge of surface mechanical properties for asteroids is incomplete and uncertain, the mechanism for attaching to the surface will probably be designed based on results of upcoming missions to study small asteroids. The implications of surface conditions on mission design and several concepts for attaching to the surface are currently being considered by the B612 Foundation[2].

In order to provide navigation measurements in flight and to measure the small change in asteroid orbital velocity, NASA's Deep Space Network (DSN) tracking network will provide radio metric range and Doppler measurements to the B612 spacecraft. These will be the standard DSN tracking types used on other deep space missions, the difference being that the DSN will continue tracking the spacecraft once it is landed on the asteroid and throughout the asteroid pushing phase. By tracking the landed spacecraft, orbit determination can be performed on the combined spacecraft/asteroid to estimate the asteroid velocity change. Using conservative estimates on tracking precision for an X-band spacecraft transponder and adequate dynamical modeling, the asteroid velocity should be determined to an accuracy of about 0.1 mm/s (one sigma). Thus, the mission goal of total velocity change of 2 mm/s should be easily verified by processing the DSN tracking data.

SCIENCE OBJECTIVES

A fundamental outstanding issue both scientifically and technically regards the internal structure of 100-200 meter diameter and larger near-Earth asteroids (NEAs). If we are ever faced with the prospect of deflecting or destroying a threatening NEA, we will have to know how these objects respond to our attempts to physically interact with them. As a result, the B612 mission incorporates the following science objectives to add to the scientific understanding of these bodies.

The overarching science goals of the B612 mission are to characterize the physical and geological properties of the target asteroid and infer its elemental and mineralogical composition. We also want to determine its relationship to classes of meteorites. The detailed science requirements needed to meet these science goals are to:

1. Determine the size, shape, mass, bulk density, spin state, and composition of the asteroid.
2. Determine the asteroid surface properties:
    a. Determine elemental and mineralogical composition, geology, morphology, and texture.
    b. Characterize the physical, optical, chemical, etc. nature of the regolith (if any) or surficial particles, and the mechanism(s) whereby it adheres to the surface.
    c. Investigate the cratering record.
3. Clarify the relationship between taxonomic classes of asteroids and classes of meteorites. Provide a geologic context for the various classes of meteorites.
4. Determine the internal structure and hetero/homogeneity of a small NEA.

A preliminary instrument suite for science will include wide- and narrow-angle multi-spectral imagers (also used for optical navigation), a near Infrared (NIR) imaging spectrometer, APXS, RAMAN spectrometer, and a laser altimeter as an initial science payload.

TARGET BODY SELECTION

To size the B612 mission duration and be compatible with the thrusting capabilities envisioned for the 20 ton spacecraft, an appropriate target asteroid must be chosen. In addition, since B612 is a demonstration mission, the asteroid orbit, once perturbed, should not present a future impact hazard for the Earth. The B612 Foundation has chosen to size the mission for a 200 m diameter rocky asteroid with mass of about 10 billion kilograms. To meet the second requirement, the target asteroid will be chosen from the list of Near Earth Asteroids (NEAs) which are not also Potential Hazard Asteroids (PHAs).

One of the primary reasons for choosing a larger, 200-m diameter object rather than a smaller, easier to deflect asteroid is to prove mitigation techniques on a class of objects that really constitute a dire threat to Earth. Deflecting a smaller asteroid, say 30 meters in diameter, would not demonstrate the capability to save the Earth from a civilization-ending catastrophe since the smaller asteroid will break up and fragment in the atmosphere and do minimal, localized damage. However, an impact from a 200 meter diameter asteroid would indeed threaten life on Earth, so the B612 mission will demonstrate technology and engineering techniques necessary for deflecting the most ominous class of asteroid impactors.

Also, since current scientific thought is that the transition from a coherent monolith structure to a 'rubble-pile' is at about 100 to 200 meters diameter, it makes the B612 mission more relevant to dealing with the expected nature of the most devastating class of impactors. The poking and prodding and pushing on a 'rubble-pile' structured asteroid (if that is indeed what is encountered on the demonstration mission) will drive the B612 technology development to deal with the most complicated of mitigation scenarios (because a rubble pile has the potential to 'come apart' as a consequence of our very interaction with it). It is better to learn to deal with this more complicated possibility in the demonstration mission rather than when it is urgently needed for a real impact threat.

In order to reach the mission goal of changing the target asteroid's velocity by 0.2 cm/s, a continuous, controlled thrust of 2.5 Newtons should be applied to the target asteroid for about 93 days. Using the high specific impulse VASMIR engines, the total fuel mass required for asteroid pushing would be about 200 kg. A candidate set of potential target near-Earth asteroids for the B612 mission that have been radar observed, that are small (about 100 m to 200 m diameter), and that are not potential impact hazards are given in Table 1. The asteroid list in Table 1 is ordered by priority based on size and spin, with the most appealing target listed first. It remains to be determined which target is best based on mission timeline and spacecraft constraints, and this will be the subject of further study to determine optimal launch times, thrusting profiles and arrival times.

Table 1. Candidate Asteroid Targets for the B612 Mission.*

Asteroid ID	Diameter (m)	Spin Characteristics
2001 EC16	100 – 200	slow rotator
2001 XX4	130 – 250	?
2001 YP3	130 – 250	?
1999 FN19	95 – 190	<11 h period

The orbital properties of the primary candidate asteroid, 2001 EC16, include a semi-major axis of 1.345 AU, eccentricity of 0.3638, and inclination to the J2000 ecliptic plane of 4.71 deg. The orbital period is about 1.5599 years. A diagram of the orbit of 2001 EC16 (from JPL's Horizons website) is shown in Figure 1.

* chosen from a list provided by Dr. Steven J. Ostro, Jet Propulsion Laboratory, Calif. Inst. of Technology.

ORBIT AND LANDING

After the interplanetary cruise phase and rendezvous, a major challenge for the B612 mission will be close-in orbit operations, landing and attaching to the surface of the asteroid. If an initial orbit for a low-density asteroid proves too hard to control and maintain, the B612 mission can switch to an alternative active control scheme to maneuver in close proximity to the surface [4]. The problem of navigating a spacecraft about an asteroid is made difficult by the relative uncertainty in the asteroid physical properties that perturb the orbit. To help solve this problem, the navigation system for B612 will use a combination of tracking data types which proved successful on the NEAR mission. These include DSN radio metric Doppler and range tracking, along with optical landmark tracking and laser ranging to the asteroid surface [5].

The rapid progress of the orbit phase into the landing phase (through progressively lower orbits and targeted landing) depends on the ability of the navigation system to provide accurate orbit estimates. These estimates are adversely affected by imprecise knowledge about the asteroid physical parameters, including the uncertainty in the orientation of its rotation pole. For NEAR, pre-arrival estimates for orientation of the Eros rotation pole varied by more than 4 degrees. After obtaining the initial landmark tracking during the early orbit phase, the navigation team was able to estimate the pole orientation to within 0.05 degrees, one sigma. Before the NEAR-Shoemaker landing, these uncertainties were about tem times smaller allowing for very precise targeting[5, 6]. Knowledge of spin axis orientation is important not only to orient the gravity field model for subsequent orbit determination and prediction, but it also impacts mission design by precisely determining the inertial orientation of the B612 thrust vector.

Similarly, the plans for orbit altitude reduction (by a continuous thrust spiral) and eventual thrust sequences to landing will change in response to increased knowledge of the physical parameters and to improved navigation performance as the data acquisition and processing techniques are refined. The orbit radius and inclination relative to the asteroid equator may be varied during this phase to accommodate various science instrument observations at low altitude. During the descent, direct orbits below a certain critical altitude should be avoided since they are generally unstable[4]. For low orbits the asteroid shape will be an issue since close approaches of the spacecraft to the surface will not necessarily occur at periapsis. This will require some time in a medium-altitude mapping orbit to develop a suitable shape model for navigation.

A fundamental difficulty of this mission will be the navigation and design of the orbital trajectories, as they must account for the gravitational and solar radiation perturbations acting on the space vehicle. While an orbital mission is currently envisioned for the B612 project, it is not infeasible that a different approach to close proximity operations about the asteroid may be considered, one that relies on the spacecraft's thrusters to continually null out natural forces and fix its location relative to the asteroid. The balance between these issues are discussed in more detail in [4], where the relevant orbit dynamics and orbit control possibilities are covered.

Improving Physical Models

In order to improve estimates of the asteroid physical parameters, in situ measurements will be made by the spacecraft. Since the spacecraft is in an orbit being perturbed by the very physical characteristics being measured, estimation of the asteroid physical parameters is intimately tied to the spacecraft's orbit determination. As demonstrated on the NEAR mission, simultaneous estimation of spacecraft and asteroid parameters with DSN tracking and optical landmark tracking of craters results in rapid improvements in those parameters. For the B612 mission, it is expected this initial orbit modeling phase could be completed in about two weeks.

The placement of optical navigation pictures and trajectory correction maneuvers (TCMs) or thrusting segments will have to be iterated between the mission design, science, navigation, and spacecraft engineering teams to operate within constraints throughout the orbit phase. The overall shape and size of the asteroid will have to be determined early during the orbit phase to enable the close-in orbits required by science and landing reconnaissance instruments.

Navigation with Optical Landmark Tracking

Processing optical landmark tracking data proceeds in two phases. The first step is the initial identification and determination of a set of landmark craters (the landmark database), and the next step is finding and using those same landmarks in subsequent pictures as tracking data. These two functions overlap since the initial optical navigation task in orbit is to refine the location estimate of landmarks while also building up the landmark database. Hence, the picture planning process has to provide enough pictures to build a reasonable number and distribution of landmarks, and it has to provide designated optical tracking images of previously identified landmarks. The tracking information from optical landmark images is in measuring the apparent motion of a landmark in a series of pictures where viewing geometry is changing due to the relative motion of the asteroid spinning about its axis and the orbit of the spacecraft. Note that a single picture is thus useless as navigation tracking data.

The building and maintaining of the landmark database will be an ongoing process throughout the initial orbit phase, depending on current lighting conditions (i.e., the orientation of the spin axis relative to the Sun). Upon arrival, the sunlit portions of the asteroid may be quite different than those available three months later during the landing phase. Although this was a manual process on the NEAR mission, it is expected that this process could be automated and perhaps even placed on board the B612 spacecraft to improve response times and reliability.

The weak, non-spherical gravity field around the small target asteroid, combined with solar pressure accelerations on the large spacecraft radiator structure, will result in the low altitude orbits being highly perturbed, non-Keplerian, and difficult to predict. To estimate these orbits, the asteroid gravity field and its orientation in space will have to be estimated. Experience on NEAR suggests that these estimates are slow to converge when using only radio metric data types. The B612 mission will use the technique pioneered on the NEAR-Shoemaker spacecraft which processes optical landmark tracking in addition to the more traditional radio metric tracking from NASA's Deep Space Network to improve the gravity field estimate. The landmark tracking requires precise knowledge of spacecraft inertial pointing. To improve the spacecraft pointing knowledge for landmark image processing, occasionally the spacecraft can turn to point the imager at reference stars (as was done on NEAR).

Navigation Using the Laser Altimeter

The B612 mission includes a laser altimeter to aid in orbit and/or close proximity operations and landing.

During initial reconnaissance, the laser altimeter will be used to determine a preliminary shape model for the asteroid. The model can be developed quickly once the surface is over-flown regardless of lighting conditions (unlike optical images from the science imagers). The model will then be used for planning subsequent orbital operations and landing.

The laser altimeter will also provide tracking information useful for orbital estimation, as was demonstrated on the NEAR mission[6]. It will also provide excellent position and velocity feedback for active control techniques and landing. The altimeter measurement will be processed on board in autonomous control and landing sequences to avoid delayed control responses inherent in ground-based processing strategies that are limited by the round-trip light time.

SUMMARY

The B612 mission demonstrates that measurable deflection of an asteroid is possible, and it develops and validates technology necessary for this task. The mission brings together the latest developments in power and propulsion technology along with recently validated navigation techniques to accomplish its goals.

After arriving at the asteroid, knowledge of the mass, gravity distribution, and spin state of the asteroid will have to be quickly improved on final approach and during the orbit phase in order to predict the effect of trajectory correction maneuvers for capture, orbit and landing. The navigation challenge for the orbit phase will be to adapt the orbit plan while adjusting for improvements in knowledge of the asteroid physical parameters. Improvements in the estimates of the asteroid physical parameters during spacecraft approach and orbit will be crucial to mission success. Unlike a planetary orbiter, the very low gravity of the asteroid will mean that the spacecraft could easily escape or crash into the surface with small changes in velocity. This places additional demands on navigation accuracy while also imposing a generally shorter response time than that usual for planetary orbit missions.

Candidate near-Earth asteroid targets have been identified which meet the criteria for size (100 – 200 meter diameter) and slow spin rate. Based on the preliminary spacecraft design, the orbital velocity of these asteroids could be changed by about 0.2 cm/s after about three months of controlled thrusting.

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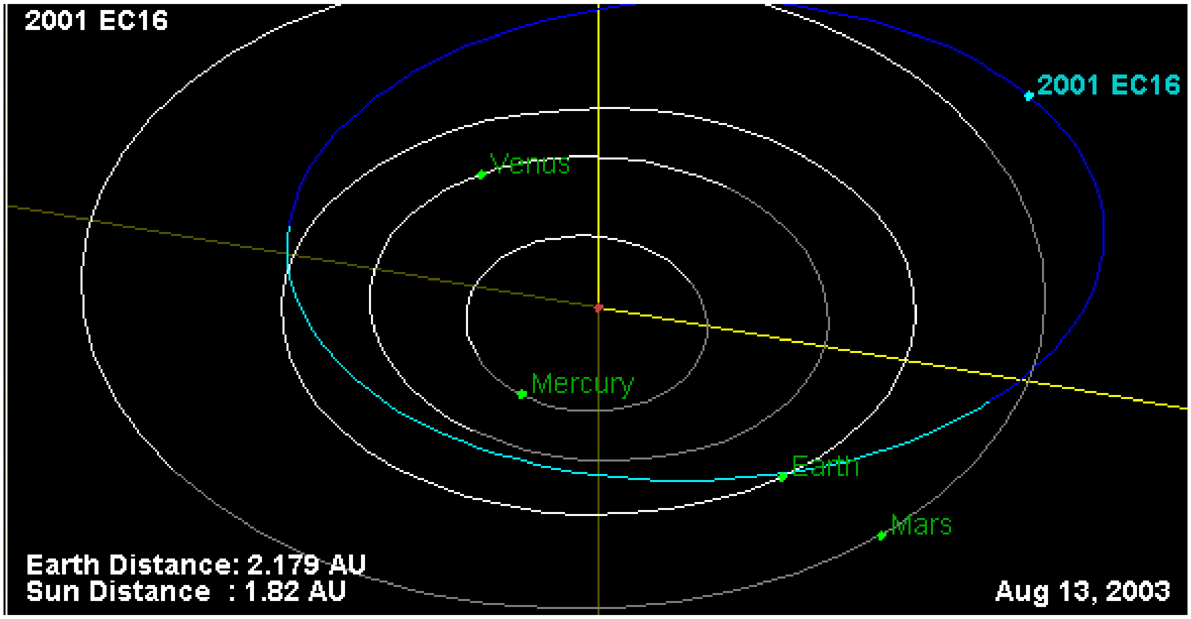

Figure 1. Orbit of candidate target asteroid '2001 EC16' shown at epoch August 13, 2003.