POLITECNICO DI MILANO

Facoltà di Ingegneria Industriale

Dipartimento di Ingegneria Aerospaziale

Mission Analysis for radio science measure on asteroid

Phase A Study for NEO DQ Mission on 2002AT4 and 1989ML asteroids

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Summary

Ciò che generalmente chiamiamo asteroidi sono una popolazione eterogenea di corpi minori in orbita attorno al Sole a distanze che vanno da dentro l'orbita della Terra al di là di Saturno. Gli asteroidi sono tradizionalmente distinti rispetto ad altre classi di corpi minori. Oggi, più di 250.000 asteroidi hanno un'orbita ben conosciuta e la maggior parte di essi si trovano nella cosiddetta Fascia degli Asteroidi, tra le orbite di Marte e Giove. Inoltre, vi è una popolazione importante di piccoli corpi in orbita attorno al Sole in prossimità della Terra che attraversano la regione dei pianeti interni. Questi sono i cosiddetti Near-Earth Objects o NEO. I NEO comprendono sia oggetti che hanno una origine probabilmente astereoidale sia comete estinte originariamente nate nel sistema solare esterno. Lo studio dei NEO è estremamente importante per una serie di motivi: poiché tali corpi hanno un approccio ravvicinato alla Terra, e perche rappresentano la popolazione dei più piccoli corpi del sistema solare che può essere accessibile a modalità di investigazione fisica. Nonostante gli importanti miglioramenti che sono stati fatti negli ultimi anni nella comprensione sull'origine e la natura dei NEO, una serie di problemi critici sono ancora aperti e meritano ulteriori indagini. Prima di tutto, un grande sforzo è stato ed è attualmente dedicato alla scoperta dei NEO nuovi e alla modellazione della loro probabile evoluzione dinamica. Uno dei problemi principali, tuttavia, rimane l'impegno attualmente insufficiente dedicato alla caratterizzazione fisica dei NEO che è necessario per sviluppare una strategia credibile di mitigazione del rischio d'impatto NEO. I NEO sono conosciuti dalla comunità scientifica come un pericolo per il pianeta. Le probabilità di un impatto catastrofico sono veramente piccole, ma per la prima volta nella storia dell'umanità abbiamo gli strumenti per evitare un evento catastrofico e preciso che probabilmente ha causato l'estinzione dei dinosauri. E' essenziale che l'umanità migliori la propria conoscenza in materia di asteroidi. Dobbiamo sapere in dettaglio la struttura interna degli asteroidi come risposta le ripercussioni per capire come progettare in modo efficiente i metodi per ridurre il rischio di effetti indesiderati. La missione dovrebbe contenere i seguenti elementi:

- due satelliti distinti lanciati in traiettorie interplanetarie;
- uno veicolo spaziale, che sarà denominato Hidalgo, avrà un impatto con un asteroide di circa 500 metri di diametro ad una velocità relativa di almeno 10 km / s;
- la sonda, chiamata Sancho, arriverà prima al medesimo asteroide lungo un viaggio molto diverso; effettuerà un rendez-vous e rimarrà in orbita attorno all'asteroide per diversi mesi prima e dopo l'impatto di Hidalgo;
- Sancho rilascerà inoltre 4 penetratori, per formare una rete sismometrica sull'asteroide. Prima e dopo l'impatto di Hidalgo verrà effettuato un esperimento sismico (tomografia sismometrica) per studiare la struttura dell'asteroide.
- Al momento dell'impatto, Sancho si terrà a distanza di sicurezza per osservare l'impatto senza prendere rischi inutili. Esso tornerà successivamente su un'orbita più vicina, per osservare i cambiamenti nell'orbita e nella rotazione, e (opzionalmente) per raccogliere campioni delle polveri sollevate dalla formazione del cratere.

Scopo della NEO DQ

La missione ha un altissimo valore scientifico, ma aiuterà anche nella sperimentazione di tecnologie necessarie per le future missioni di deviazione e suscitare interesse nelle persone per l'esplorazione dello spazio. La missione in particolare avrà i seguenti scopi:

1. determinare la struttura interna degli asteroidi,
2. conoscere le proprietà meccaniche del materiale dell'asteroide.
3. misurare le deformazioni orbitali dell'asteroide a causa dell'impatto di Hidalgo.
4. misurare la massa di un asteroide, il rapporto tra i momenti di inerzia e le armoniche di ordine inferiore del suo campo di gravità.
5. modellare la forma dell'asteroide prima e dopo l'impatto.
6. misurare lo stato di rotazione dell'asteroide prima e subito dopo l'impatto.

7. rilevare la dissipazione dell'asse non principale di rotazione dopo l'impatto.
8. determinare la precisa composizione mineralogica e la struttura dell'asteroide.
9. fornire un modello per le forze non gravitazionali.

SCELTA DELL'ASTEROIDE

I Near-Earth Asteroids in orbita, vale a dire quelli le cui orbite sono potenzialmente in grado di portarli vicino alla Terra, sono suddivisi in quattro gruppi distinti: - AMOR: hanno un periodo di oltre 1 anno e perielio con distanza superiore a 1,07 UA (afelio Terra) e inferiore 1,3 UA, le loro orbite non intersecano quella della Terra. L'osservatorio Lowell ha attualmente nel suo databse 1362 corpi presenti per il gruppo Amor. - APOLLO: hanno un periodo di oltre 1 anno e perielio inferiore a 1,07 UA. Le loro orbite possono intersecarsi con quella della Terra. Ci sono attualmente 1.801 istanze del gruppo di Apollo nella banca dati dell'osservatorio Lowell. - ATENS: hanno una durata di meno di 1 anno e un afelio di più di 0,983 UA. Le loro orbite possono intersecarsi quella della Terra. Il Lowell database elenca 285 membri di questo gruppo. - Vi è un quarto gruppo, con un periodo orbitale di meno di 1 anno e un afelio inferiore a 0,983 UA. Le orbite di questi asteroidi non si intersecano con quella della Terra. Ci sono solo 4 membri conosciuti di questo gruppo, ma si deve notare che essi sono difficili da osservare dalla Terra e che pertanto una popolazione significativa potrebbe esistere ed è ancora sconosciuta.

La scelta è avvenuta su due asteroidi molto simili tra loro ma con orbite differenti, 1989ML e 2002AT4.

Successivamente è stato necessario creare le Efemeridi e modellare tutte le possibili perturbazioni che potrebbere influenzare l'esperimento. Sono stati modellati i seguenti tipi di perturbazioni:

- perturbazioni di terzo corpo
- effetto Yarkovsky
- radiazione solare

- pressione solare

E' stata modellata un'orbita Terminator eliosincrona. Su un'orbita eliosincrona terminator (nota anche come orbita dal tramonto all'alba), il sole è in direzione normale al piano dell'orbita. Le forze indotte da SRP e la gravità solare sono anche loro normali al piano dell'orbita. Quindi, teoricamente, un'orbita di tipo terminator è il modo più stabile di orbitare attorno a un piccolo corpo in presenza di perturbazioni. Il problema è come mantenere una configurazione terminator per un periodo prolungato di tempo. La direzione del sole si modifica in quanto l'asteroide si muove lungo la sua orbita. e' possibile creare orbite Terminator auto-stabilizzatrici ma il loro diametro orbitale non scenderebbe al di sotto di 2.1 km, è per effettuare gli esperimenti di topografia sismometrica il satellite Sancho deve essere molto più vicino.

Dalle considerazioni precedenti, un'orbita naturale attorno ad un piccolo asteroide rimane naturalmente ad altitudine di confine. Questo, naturalmente,richiede una configurazione speciale orbitale. In altri casi, le orbite devono essere attivamente controllate con manovre propulsive da escludere l'impatto o la fuga.

Per questo motivo sarà necessario definire ulteriormente il modello creato da questa tesi per verificare la possibilità di riuscire a creare un controllo attivo che permetta al satellite di avere una sua orbita per le misurazioni scientifiche.

Introduction

0.1 Near Earth Objects

We generally call asteroids are a heterogeneous population of minor bodies orbiting the Sun at distances ranging from inside the orbit of the Earth to beyond Saturn's. Asteroids are traditionally distinguished with respect to other classes of minor bodies orbiting the Sun at large heliocentric distances, including Comets and, more recently, the Trans-Neptunian objects (TNOs). Classical asteroids are characterized by the lack of cometary activity (sublimation of volatiles) and by a likely origin at moderate heliocentric distances. Dynamical mechanisms may perturb the orbits of minor bodies; then transitions of objects from asteroids to Comets or TNOs, or viceversa, are possible in principle. Some ambiguities therefore may exist for what concerns the classification of minor bodies located, mostly, either at very small or at large heliocentric distances. For instance, some objects previously classified as asteroids have been subsequently found to exhibit a cometary activity. Nowadays, more than 250,000 asteroids have well-determined orbits, and the vast majority of them are located in the so-called Main Belt, between the orbits of Mars and Jupiter. Another important subset of the population consists of objects having orbits around the stable L4 and L5 Lagrangean points of Jupiter. These bodies are called Jupiter Trojans. In addition, there is an important population of small bodies orbiting the Sun in the near Earth Space,crossing the region of the inner planets. These are the so-called Near-Earth Objects or NEOs. NEOs include both objects having a likely asteroidal origin, and extinct comets originally accreted in the outer Solar System. NEOs having an asteroidal origin are called near-Earth asteroids (NEAs).

0.2 The Importance of Studying NEOs: Theoretical Aspects

The study of NEOs is extremely important for a number of reasons: since these bodies experience close approaches to the Earth, they represent the population of the smallest Solar System bodies that can be accessible to detailed physical investigations. As a consequence, NEOs offer a unique opportunities to study small bodies accreted originally at very different heliocentric distances, and evolved under the effects of different processes. Asteroids are strictly related to the building blocks (planetesimals) from which the terrestrial planets accreted some 4.6 G.y. ago. Therefore, they preserve a record of the physical properties of the primordial material in the protoplanetary disk at moderate heliocentric distances at the time of planetary accretion. The nature, size and orbital distribution, as well as the evolution of asteroids are crucial for understanding the formation and evolution of the planets and the entire solar system.

0.3 The Impact Hazard

NEOs are a heterogeneous population consisting today of almost 3500 catalogued objects coming from almost every region of the solar system. NEOs are subject to strong planetary perturbations, and have consequently chaotic orbits and quite short dynamical lifetimes, up to a few tens of million years. Most NEOs are subject to a fast increase in orbit eccentricity, leading eventually to crash into the Sun, or to ejection from the solar system. Another possible end-state is an impact with one of the terrestrial planets. NEOs therefore must be steadily supplied by some sources. According to current models, most NEOs come from the asteroid Main Belt, after a complex evolution involving collisions and a dynamical drift in semi-major axis. The latter one is mainly due to the so-called Yarkovsky effect (Bottke et al. 2002), consisting of a gradual orbital drift of a relatively small body (up to 20-30 km in size) produced by the momentum carried off by its own asymmetrically emitted thermal radiation. The fact that NEOs may collide with terrestrial planets, including the Earth, makes them potentially dangerous (impact hazard). The study of NEAs, is therefore ultimately related to the history and evolution of the Earth's biosphere and to the past and future existence of life on our planet. The reason is that an energetic impact of a NEO with our planet, although extremely rare, can have extremely severe effects. It is estimated that the odds of an impact of an NEO with a diameter equal or larger than 1 km, causing a global catastrophe, are of about 1 every 600000 years. Those of an impact of a 200m body, being able to produce regionally destructive devastation, are of 1 every 56000 years (see e.g. Stuart and Binzel, 2004). For this reason, different countries, mainly the US and the European community, are funding studies aimed at discovering potentially dangerous NEOs and to develop credible strategies of mitigation of the impact hazard. The human kind is the first living species in the Earth that has developed (or is developing) the necessary know-how to defend itself against catastrophic impacts with celestial bodies. An accurate assessment of the impact hazard for NEOs requires knowledge not only of the overall inventory of population of potential Impactors, but also of the size and orbital distribution of NEOs, corrected for observational biases.

0.4 Sizes and Orbits

We know that the largest majority of the NEAs discovered so far have diameters smaller than 0.5 km. There are about 700 known NEOs smaller than one kilometer, while about 500 bodies are larger than this size. However, models of the total bias-corrected NEO population (e.g., Stuart and Binzel, 2004) predict that the number of NEOs with size larger or equal than 1 km is about 1100. Their size frequency distribution turns out to be a power law of the form: $N(> D) = kD^{-1.95}$. With respect to their orbital parameters, traditionally NEOs are defined as the small bodies having perihelion distances $q \leq 1.3AU$ and aphelion distances $Q \geq 0.983AU$. Traditionally, NEOs have been further subdivided into three major subclasses, including the Apollos with $a \geq 1.0AU$ and $q \leq 1.0167AU$, where a is the orbital semajor axis; the Atens with $a < 1.0AU$ and aphelion distance $Q \geq 0.983AU$; the Amors with $1.0167AU < q \leq 1.3AU$; and the inner-Earth Object or IEOs, having $Q < 0.983AU$. Atens and Apollos are on orbits that can sooner or later intersect the Earth's orbit. IEOs are currently entirely inside the Earth's orbit, while Amors are completely external. However, the above classes are based on osculating orbital elements and it is possible for any NEA, during its chaotic orbital evolution, to move from one class to another. The typical NEO orbits are chaotic over relatively short times scales of some hundred years. Accurate predictions of the future positions and motion of individual bodies over long time scales cannot therefore be computed. Only statistical estimates of the impact probability based on current dynamical properties of the whole population are therefore meaningful. All NEOs can be therefore dangerous over the time scales of some million years due to their chaotic orbital evolution. However, individual objects having currently orbits very close to that of the Earth may be discovered, and are called potentially hazardous asteroids (PHA). They have a minimum orbit intersection distance (MOID) with the Earth of less than 0.05 AU and an absolute magnitude H = 22 or brighter (i.e. a diameter greater than 150m).

0.5 The Torino Scale

To asses the risk posed by NEOs an impact hazard scale similar to the Richter scale used for earthquakes, was introduced in June 1999 and revised this year (*neo.jpl.nasa.gov/torinoscale.html.*). It is named the Torino Impact Hazard Scale, from the Italian city in which it was adopted for the first time at a workshop of the International Astronomical Union (IAU). On this scale, zero means virtually no chance of collision, while 10 means certain global catastrophe. The classification of a given object depends both on the probability of an impact with the Earth, and on the likely consequences of the impact, essentially related to the object's size. The overall goal is to provide easy-to-understand information to assuage concerns about a potential doomsday collision with our planet. The highest Torino level ever given an asteroid was a 4 last December for the asteroid 2004 MN4 now renamed 99942 Apophis, with a 2 percent chance of hitting Earth in 2029. After extended tracking of the asteroid's orbit, it was later reclassified to level 1, effectively removing any chance of collision. This example shows that any given object can change its classification according to the Torino scale, when new observations become available. In the particular case of Apophis, the close encounter with the Earth (30000 km!) that will occur in 2029, will alter the orbit in an unpredictable way, and could lead to an actual collision with the Earth in 2036. Very poor knowledge of the physical properties of this object (size, thermal inertia, etc.) makes it very difficult to make an accurate prediction of the orbital evolution of this body,which is expected to be significantly affected by the Yarkovsky effect.

0.6 Open Problems

Despite the important improvements that have been made in recent years in understanding the origin and nature of NEOs, a number of critical problems are still open and deserve further investigations. First of all, a large effort has been and is currently devoted to the discovery of new NEOs and to modeling their likely dynamical evolution. One major problem, however, remains the currently insufficient effort devoted to the physical characterization of NEOs (see e.g. Cellino et al., 2002) which is a necessary requisite to develop any credible strategy of mitigation of the NEO impact hazard. The current knowledge of the NEO size distribution, for instance, is still unsatisfactory, mainly at small sizes (below 1 km). Also in the case of the surface reflectance (albedo), that is a very important parameter to characterize the overall mineralogy of NEO surfaces and to identify NEOs having a likely cometary origin, the current data are still strongly insufficient. Albedo, spin state, mineralogical composition and thermal inertia are the major parameters determining the effectiveness of the Yarkovsky effect, currently the major dynamical mechanism that is currently not modeled. Even more important from the point of view of choosing the optimal technique for orbital deflection is our poor understanding of the internal structure of NEOs. We basically do not know whether they are they monolithic, or loose aggregates of chunks of rock held together by gravity. The macroscopic porosity, that is the presence of large empty spaces in the internal structure, is also essentially unknown. This issue is obviously of crucial importance for the development of effective techniques of orbital deflection and impact mitigation. Due to the above reasons, it is now generally recognized that an actual experiment of the kind already successfully carried out in the case of a comet by the Deep Impact space probe, is now urgent. The proposed Don Quijote mission is aimed at being the first practical realization of this idea. An artificial impact seems in principle the most direct way to assess the response of a NEO to a deflection attempt. It is true, however, that an in situ exploration of a NEO might offer a wealth of additional opportunities for the physical studies of NEOs. In addition to an impact experiment, in fact, a large variety of possible techniques can be used to extract further information. The most trivial options include extensive spectrophotometric investigations of the surface, at visible and IR wavelengths. From these data, a reliable assessment of the surface composition and thermal inertia can be derived. At a higher degree of complexity, a better technique of investigation of the internal structure would be radio tomography. In the case the NEO target is a small object not larger than 1 km, as expected in principle, radio tomography can provide detailed information on the structure of the internal layers. A radio tomography experiment is currently under development having as a target the satellite of Mars Phobos, which has a size larger than 10 km. The main problem of this planned Phobos, experiment is the limited penetration capability of the radio tomography equipment. In the case of a much smaller body like a small NEO, this problem would be greatly reduced.

Capitolo 1

Introduction to NEO DQ mission

To understand fully the aim of this thesis, it is a benefit what is the environment of the mission.

NEO (Near Earth Objects) are all these natural bodies that pass near the Earth's orbit and they are known from the scientific community as a danger for the planet. Probability of a largest impact are so really small, but for the first time in the humanity story we have the tools to avoid an event definite Catastrophic and that probably caused the extinction of the dinosaurs. It is essential that the humanity improve its knowledge about the asteroids. We have to know in detail the internal structure of the asteroids and ho they answer at the impacts to understand how to design efficiently methods to reduce risk of unwanted impacts. Seismic Tomography is one of the tool to study the internal structure of the celestial bodies or of the small bodies like asteroids.

(Seismic waves are the results both of the Hidalgo impact and small detonation of small explosives and collected by the seismometer).

Seismology is an efficient method already used by the Apollo's astronauts to study the internal structure of the Moon more as 30 years ago. It is nowadays used on the Earth to search mineral, natural gas, oil. The exchange of technology between the life in space and the life on earth improves the research and reduces the cost.

The NEO DQ Mission object is an asteroid investigation, geophysical characterization and deflection technological experiment of the orbitation around the Sun.

1.1 NEO DQ mission

The mission would contain the following elements:

- two spacecraft are to launch in separate interplanetary trajectories;
- one spacecraft, which will be referred to as Hidalgo, will impact an asteroid of approximately 500 meters diameters at a relative speed of at least 10 km/s;
- the other spacecraft, called Sancho, will arrive earlier at the same asteroid along a very different route; perform a rendez-vous and remaining in orbit around the asteroid for several months before and after the Hidalgo impact;
- Sancho will also deliver at least 4 penetrators, to form a seismometer network on the asteroid.Before and after Hidalgo impact an active seismic experiment (seismic tomography) to study internal structure will be carried out, by means of seismic activators (small explosives) that will be launched from Sancho.
- At the impact time, Sancho will retreat to a safe distance to observe the impact without taking unnecessary risk (with an attitude appropriate to its name). It will later return to a close orbit, to observe the changes in the orbit and rotation state of the asteroid, and (optionally) to collect samples from the dust ejected by the crater formation.

1.2 NEO DQ purposes

The mission has a very high scientific value, but it will also help in testing technologies required for future deflection missions and raise interest in people for space exploration. The mission will in particular:

1. To determine the **asteroid internal structure**, especially the size of the main solid pieces, the average particle size and thickness of regolith and of the debris layers in the space left between the main pieces. This requires seismology, although very useful constraints can also be obtained from the shape changes and rotation dissipation.

2. To constrain the **mechanical properties of the asteroid material**. This is measured by the seismic propagation speeds, but also by the penetrators (with an accelerometer).

3. To measure the **orbital deflection of the asteroid** as a result of the impact of Hidalgo, with an accuracy of about 10 percent. This can be achieved with range-rate and/or with range, and also requires that the orbit determinations of the asteroid-centric orbit of Sancho before and after the impact are accurate as necessary: this implies the requirements on the accelerometers performance or alternative options.

4. To measure the **mass of the asteroid**, the **ratio of the moments of inertia** and the **low order harmonics of its gravity field**. This is needed also to achieve 3., but is a goal in itself. 3. and 4. together measure the transfer of linear momentum achieved with Hidalgo impact.

5. To model the **asteroid shape** before and after the impact, to detect changes (if any). The main problem is that it is very difficult to estimate a priori the size of such changes, thus they may not be detected, apart from the impact crater (delayed changes are possible, and would be very interesting).

6. To measure the **asteroid rotation state** before and immediately after the impact; the accuracy must be such that the difference is measured with an accuracy of 10 percent. This allows determining the absolute value of the moments of inertia.

7. To detect the **dissipation of the non-principal axis rotation after the impact**, if possible.the problem is that the dissipation factor Q is very hard to predict, thus we do not know the time-scale of the dissipative changes in the rotation state. Note that the dissipative changes in the rotation state could be associated with delayed shape changes.
8. To determine the asteroid **large scale mineralogical composition**. Since such a small asteroid is likely to be rather homogeneous, this suggest low spatial resolution/high spectral resolution IP spectrometry.
9. To determine the detailed **mineralogical composition and texture**. Mass spectrometry could be interesting, but may not be top priority. This requires capture and in situ analysis of some particles, e.g., the ones released in orbit around by Hidalgo impact.
10. To provide a **model for non-gravitational forces**, such as Yarkovsky effect, acting on the asteroid orbit rotation. This requires a thermal model.

1.3 NEO DQ Mission's phases

1.3.1 The Launch

The critical phase of launch will be carry out with two separated launch.

First launch will be effected when the asteroid will be in a favorite conjunction,i.e. when the earth and the asteroid are both in perihelion zone.

Second launch will be made in order to impact the asteroid after six month of study from Sancho. Its relative speed velocity at arrival will must be so necessary to give to the asteroid a minimum of momentum of inertia.

1.3.2 The trajectory

As shown before the satellites have two different trajectory:

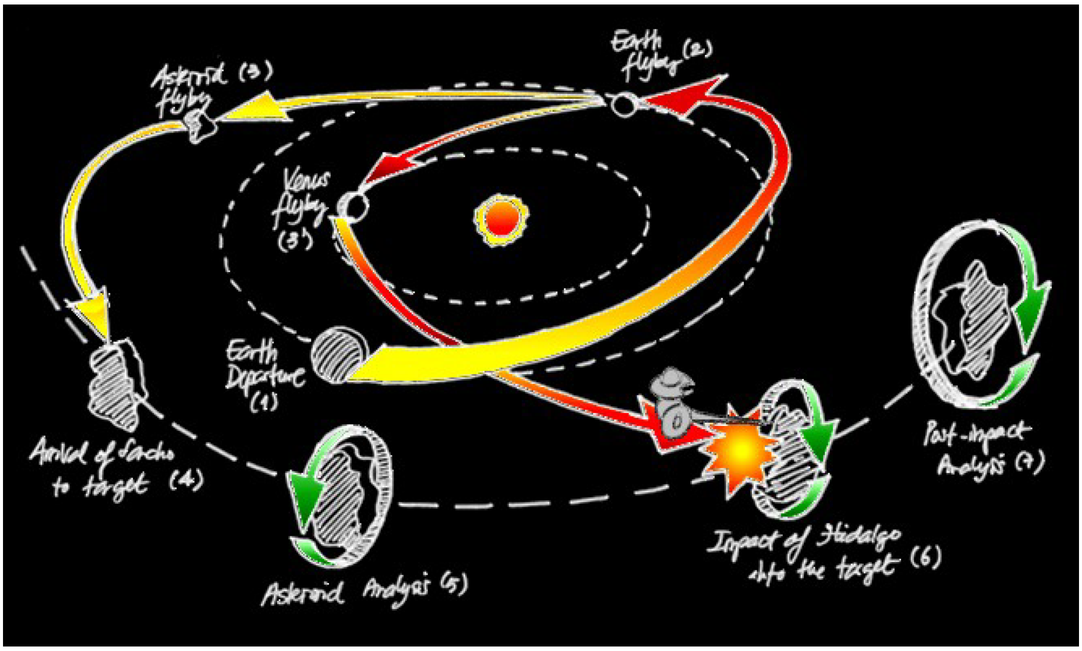


Figura 1.1: Don Quijote Baseline Trajectory Design.

- the observational satellite, Sancho, will be launch as first and its purpose is to enter in close orbit around the asteroid; the satellite will must increase the semi-major axis of its orbit with propulsion ignition to arrive at the asteroid's orbit, in contrast with an Homann trajectory that is more expensive;
- the impact satellite, Hidalgo, will be launch successively and it will follow a trajectory to made a fly-by with the earth to increase its velocity and deflect the orbit to met and impact the asteroid.

1.3.3 The Rendez-Vous

The Sancho satellite is the only one that effect a rendez-vous with the asteroid, this manoeuver it will be useful to insert the asteroid in a close orbit. The rendez-vous will be made about six month before the Hidalgo impact, because the asteroid must be

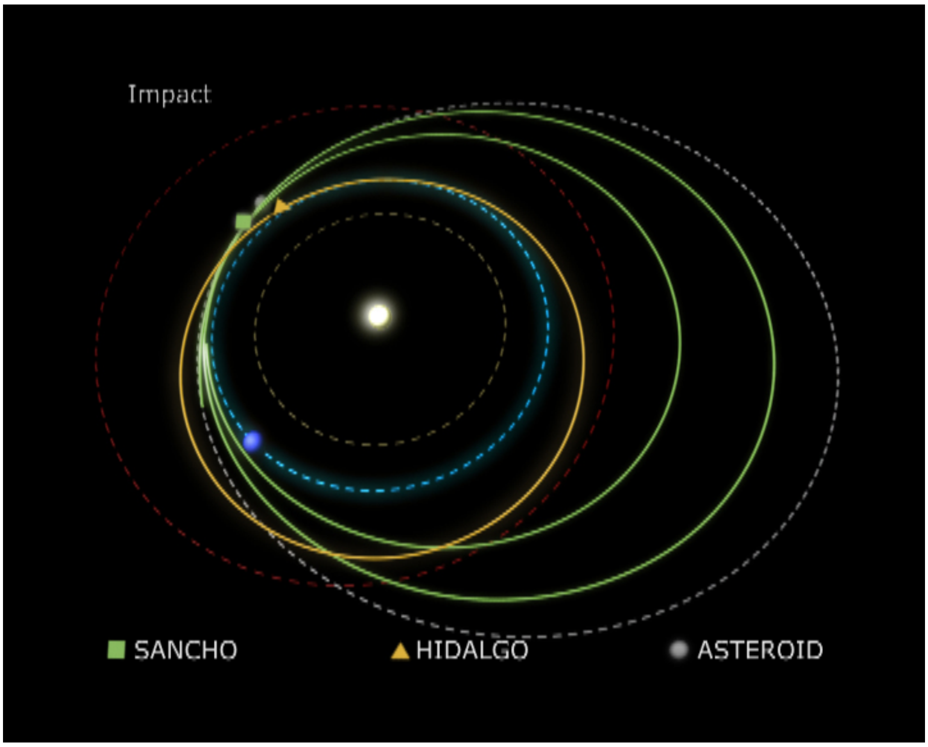


Figura 1.2: Don Quijote Final Trajectory Design.

	INSTRUMENT	Mass [Kg]	Power [W]	Pointing Direction
1.	Narrow Angle Camera	1.75	1.0	Nadir(and impact event)
2.	Micro Laser Altimeter	5.0	16.5	Nadir
3.	Orbiter Ka Transponder	- - -	- - -	- - -
4.	DPU	2.0	4.52	N/A
5.	Near Infrared Mapping Spectrometer	1.0	8.5	Nadir
6.	Thermal Radiometer	2.24	3.7	Nadir + deep space
7.	X-Ray Spectrometer	4.6	17.0	Nadir
8.	Solar Monitor	1.53	1.81	Sun and deep space
9.	Autonomous Surface Package	8.0	Auto	All around

studied and analyzed. The knowledge of physical and orbital parameters is one of the mission objective.

The rendez-vous phase is very important, because it will give to the spacecraft the possibility to choose the better orbit around the asteroid analyzing the arrival condition. The arrival phase will must made with a low relative velocity, because the sphere of influence is small and an high velocity during the rendez-vous phase maybe produce a fly-by effect.

1.3.4 Observation before impact

From its arrival even to the Hidalgo's impact, the Sancho satellite have to map the asteroid surface and to analyze the orbital parameters in order to increase our knowledge of the asteroid orbital parameters or to discover the rotational mode of the asteroid. To achieve this small objectives the satellite is equipped with:

1.3.5 Hidalgo's impact

After a long voyage Hidalgo will must arrive with a relative velocity of 10 kilometers per second. This value of velocity must be necessary to give at the asteroid a change in its orbital parameters and create a crater for the installation of the ASP.

Figura 1.3: Sancho Observation Asteroid before impact.

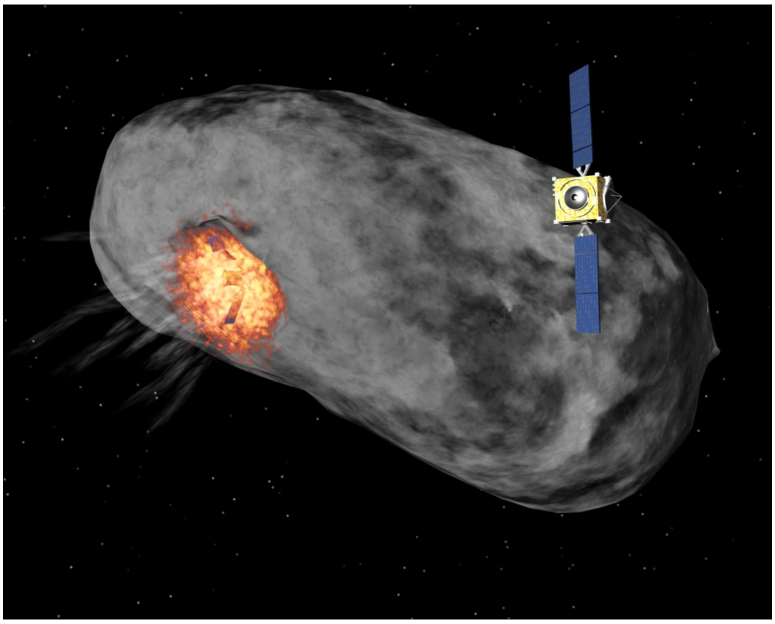


Figura 1.4: Hidalgo impact with Sancho observation.

1.3.6 Observation after impact

One moment after the impact the Sancho satellite will come back near the asteroid to release the ASP and continue its purpose of measure the orbit deflection. During the satellite measure the ASP will go inside the crater of the Hidalgo impact to detect the residual.

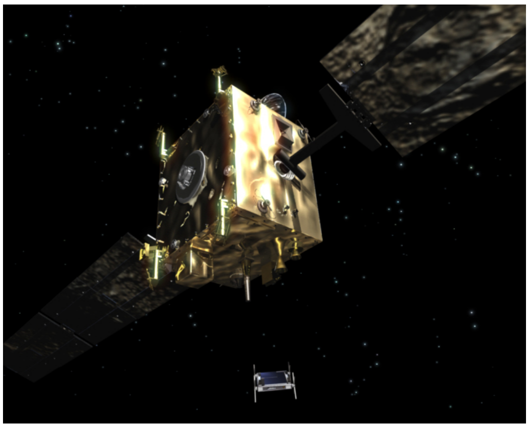


Figura 1.5: ASP free-fall.

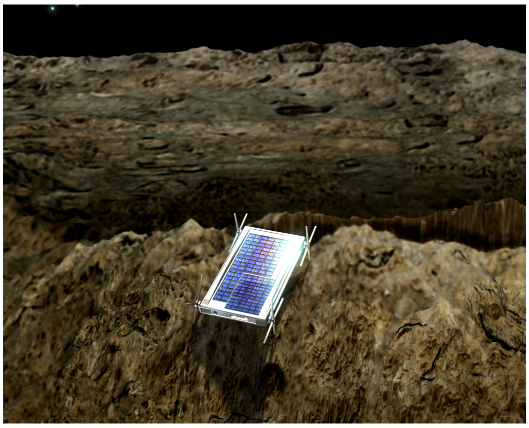


Figura 1.6: ASP on asteroid.

1.3.7 End Mission

1.4 Choice of the asteroid

Near-Earth-orbiting asteroids, i.e., those whose orbits can potentially take them close to the Earth, are subdivided into four distinct groups:

- Amors (named after 1221 / Amor) have a period of over 1 year and a perihelion radius of over 1.07 AU (Earth aphelion) and below 1.3 AU, their orbits do not intersect that of the Earth. The Lowell observatory asteroid database currently lists 1362 bodies of the Amor group.

- Apollos (named after 1862 / Apollo) have a period of over 1 year and a perihelion of less than 1.07 AU. Their orbits can intersect that of the Earth. There are currently 1801 bodies of the Apollo group in the Lowell observatory database.
- Atens (named after 2062 / Aten) have a period of less than 1 year and an aphelion of more than 0.983 AU. Their orbits can intersect that of the Earth. The Lowell database lists 285 members of this group.
- There is a fourth group with an orbital period of less than 1 year and an aphelion of less than 0.983 AU. These asteroids orbits do not intersect that of the Earth. As yet, there are only 4 known members of this group, but it must be note that they are difficult to observe from the Earth and that therefore a significant population may exist that is as yet unknown.

1.4.1 1989 ML

The orbit of 10302/1989 ML, an Amor-type asteroid, is completely enclosed within the Mars orbit. The cost of an orbiter mission is therefore fairly low, but a high velocity impact requires some effort.

The relative proximity of the asteroid and Earth orbits and the fairly large ecliptic inclination of the asteroid orbit limit the launch opportunities, as shown in Figure.

1.4.2 1989 UQ

This Aten-type asteroid was briefly regarded as target for a spacecraft mission. No detailed mission analysis was performed. Figure 3 shows that the asteroid approaches the Earth to within 0.15 AU every 7 years.

1.4.3 2002 AT4

2002 AT4 imposes a very demanding requirement because the asteroid's orbit takes it far beyond the Mars orbit into the main asteroid belt at aphelion, while the perihelion

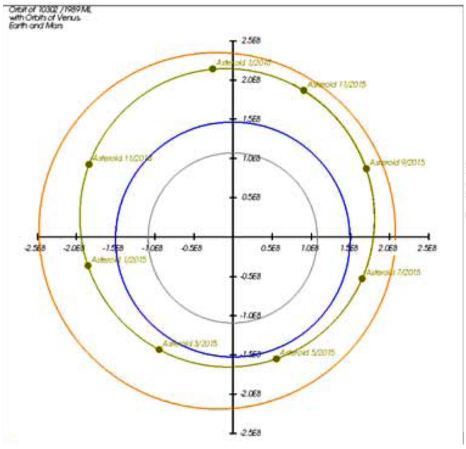


Figura 1.7: 1989 ML Orbit.

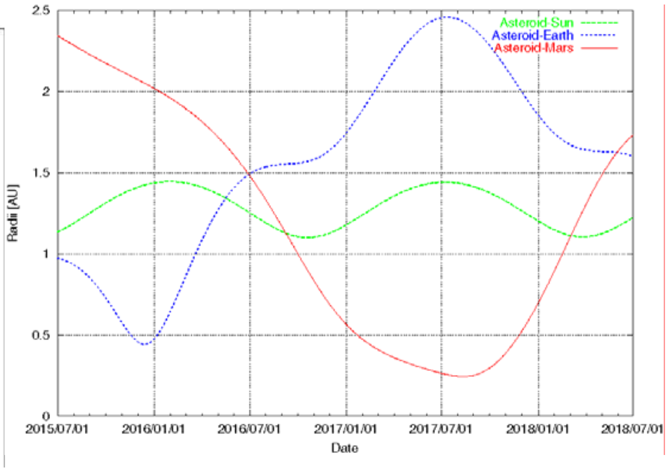


Figura 1.8: Earth,Sun and Mars ranges.

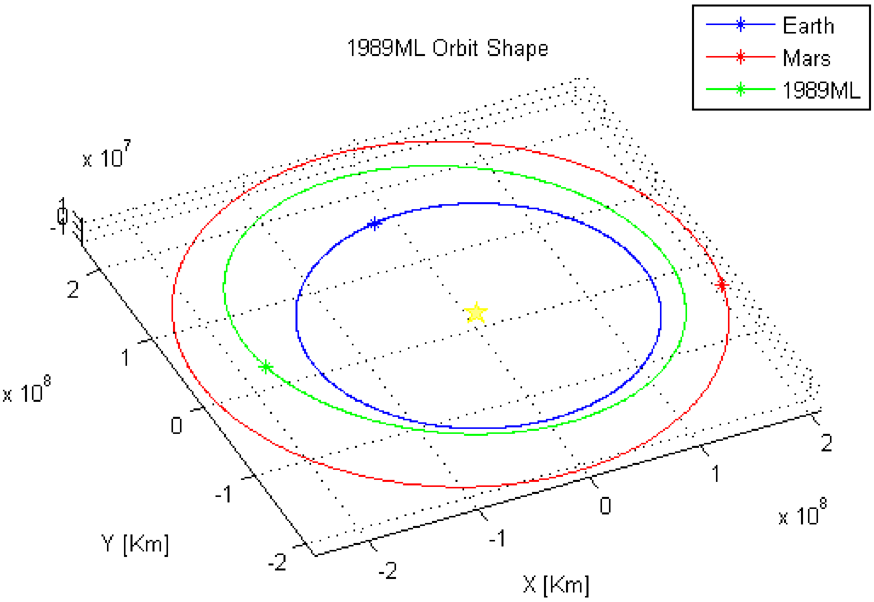


Figura 1.9: 1989 ML 3D orbit Shape.

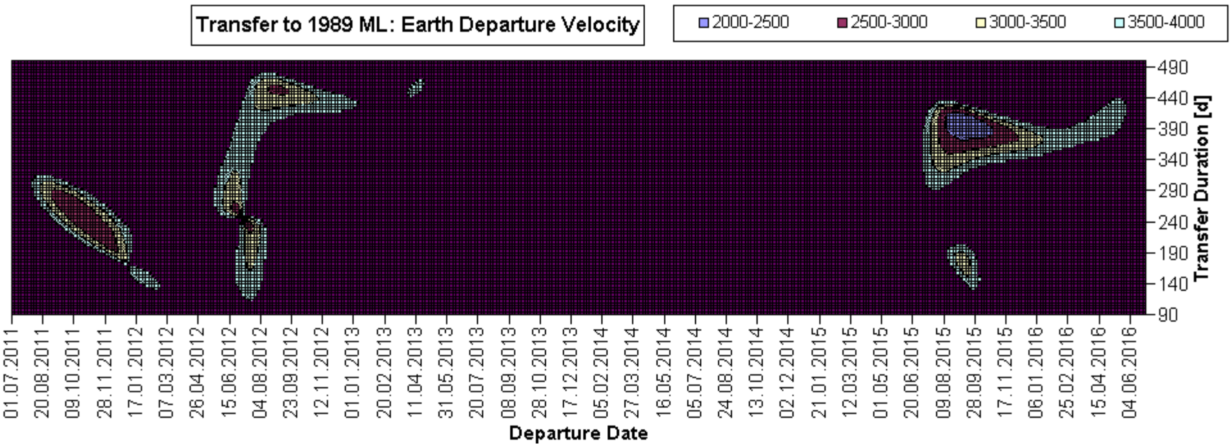


Figura 1.10: Earth departure velocity.

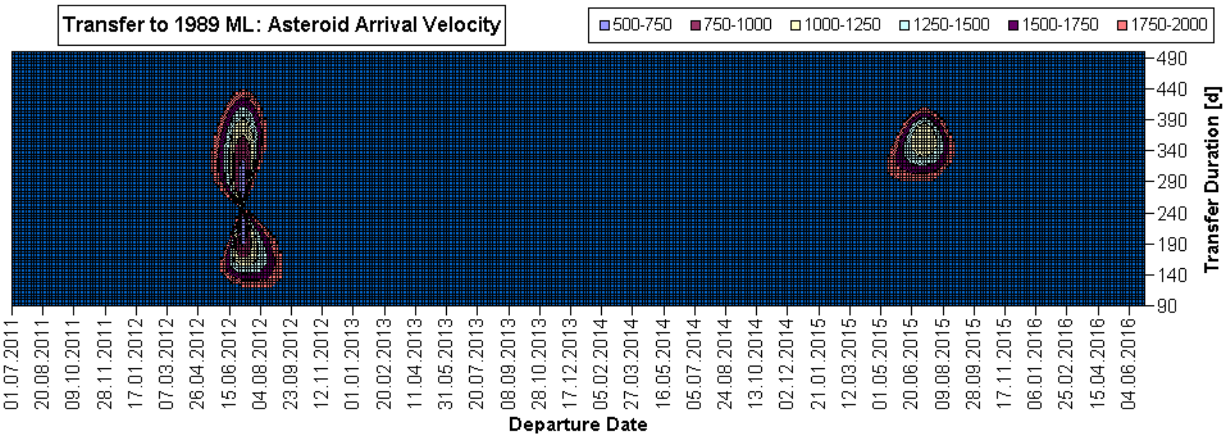


Figura 1.11: 1989 asteroid arrival velocity.

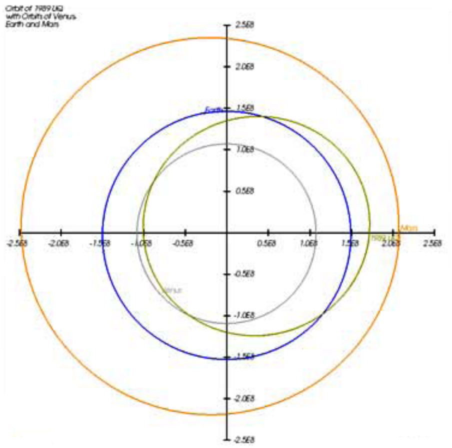


Figura 1.12: 1989 UQ Orbit.

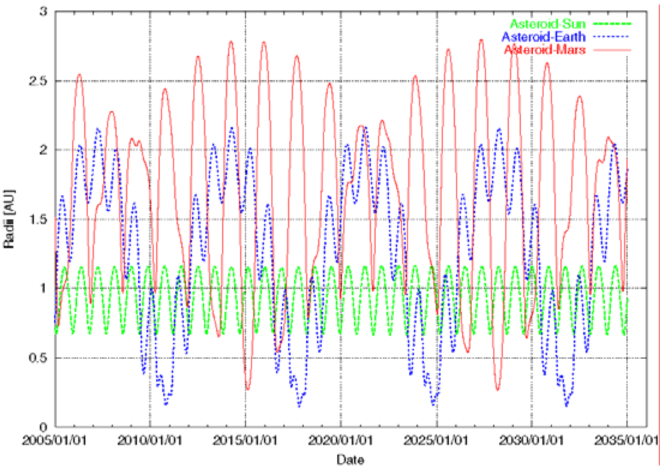


Figura 1.13: Earth,Sun and Mars ranges.

almost grazes the Earth orbit. As Figure 4 shows, this not only leads to a maximum solar distance of over 2.6 AU, but also induces large Earth range variations.

The launch windows from the Earth to asteroid 2002 AT4 are shown in Figure 4. There is always a large departure velocity from the Earth and a sizeable arrival velocity. The departure velocity is imparted by the launch vehicle or escape stage, which limits the available payload mass. The arrival relative velocity must be reduced to 0 by the onboard propulsion system. In total, departure and arrival velocity add up to a minimum of over 6 km/s, making this a very demanding mission and immediately ruling out a purely chemical propulsion system. Here, use of a chemical propulsion stage with a moderate escape velocity was envisaged. The orbiter spacecraft must then use SEP to impart the remaining large velocity increment to rendezvous with the asteroid.

1.4.4 Apophis

Apophis, formerly known as 2004 MN4, gained worldwide notoriety because of initial concern that it might hit the Earth in April 2029. Subsequent orbit determination shows the probability of this happening in 2029 to be small. However, the Earth flyby

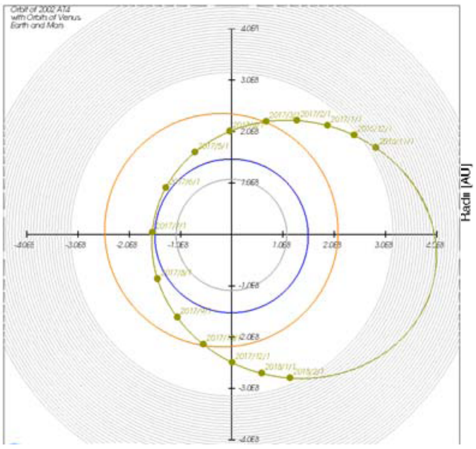


Figura 1.14: 2002 AT4 Orbit.

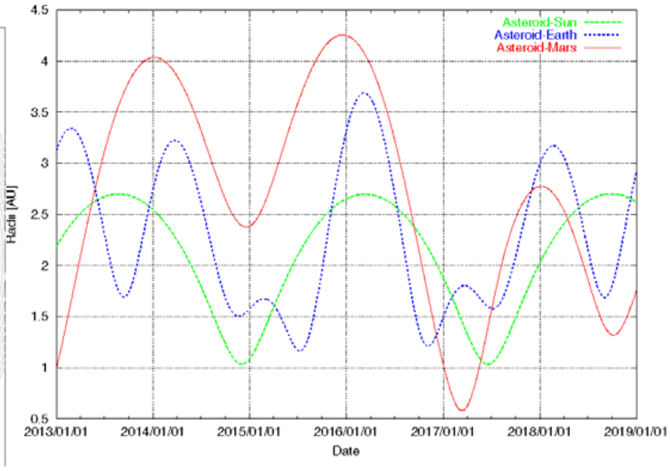


Figura 1.15: Earth,Sun and Mars ranges.

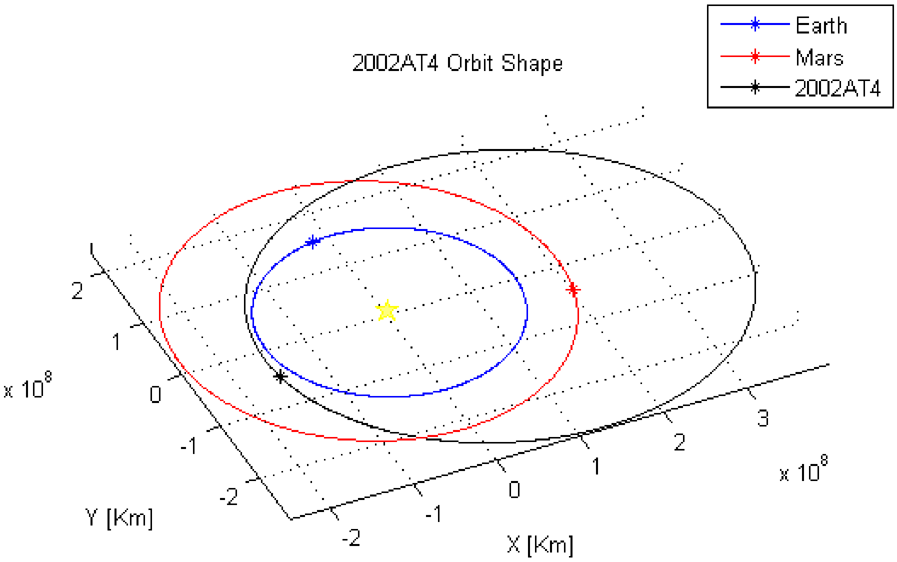


Figura 1.16: 2002 AT4 3D orbit shape.

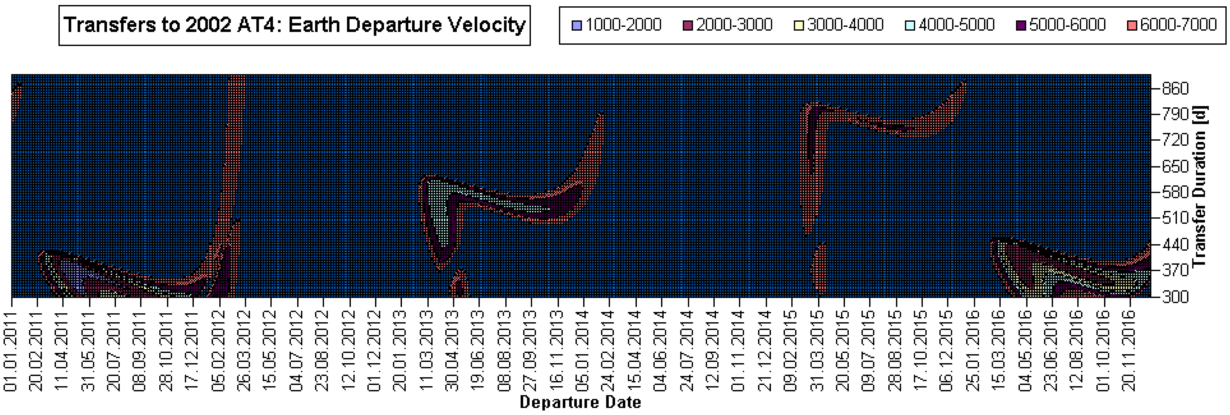


Figura 1.17: Earth departure velocity.

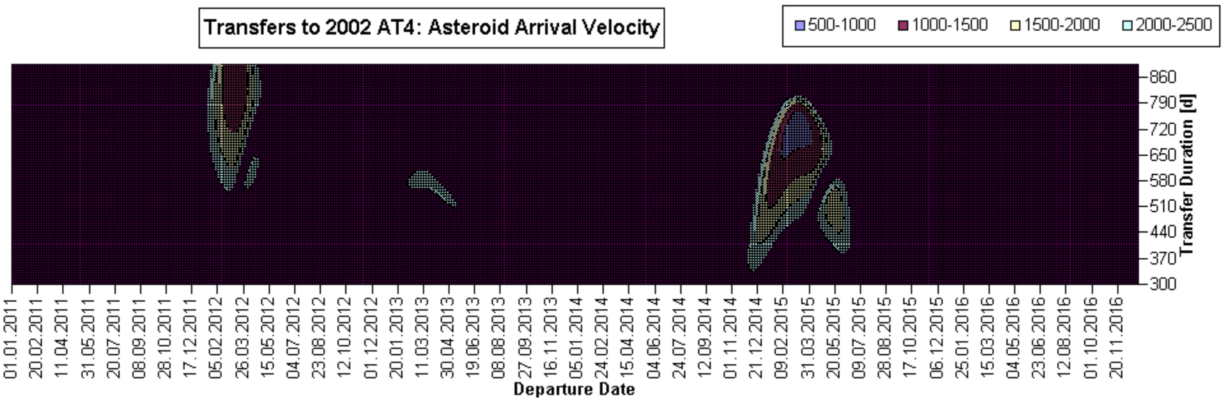


Figura 1.18: 2002 AT4 asteroid arrival velocity.

on April 13, 2029 will be at a distance of around 30000 km, so the asteroid's orbit will be strongly perturbed by the Earth's gravity. Its current orbital parameters make it an Aten-type asteroid, but the flyby is likely to turn it into an Apollo.

Uncertainties in the knowledge of the orbital parameters currently lead to a large dispersion in the assumptions for the post-2029 orbit, rendering prediction for the Earth miss distance in the following years difficult. An orbiter mission to Apophis, placing a transponder on its surface, would allow it to be tracked from the Earth at much higher precision, greatly reducing all current uncertainties.

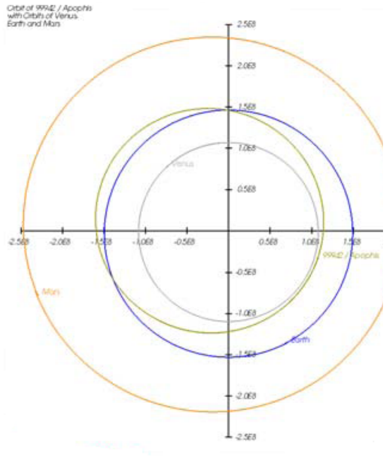


Figura 1.19: Apophis Orbit.

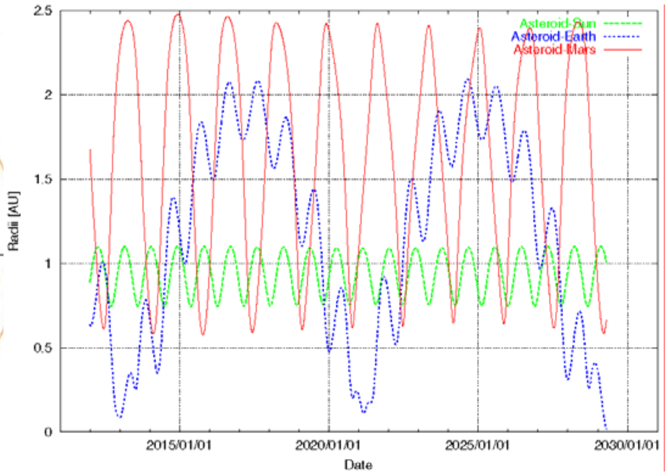


Figura 1.20: Earth,Sun and Mars ranges.

Previous Figure shows the Aten-type current orbit of the asteroid and the distances from Sun, Earth and Mars up to April 2029, again illustrating the very close encounter. The launch opportunities are illustrated in next Figure.

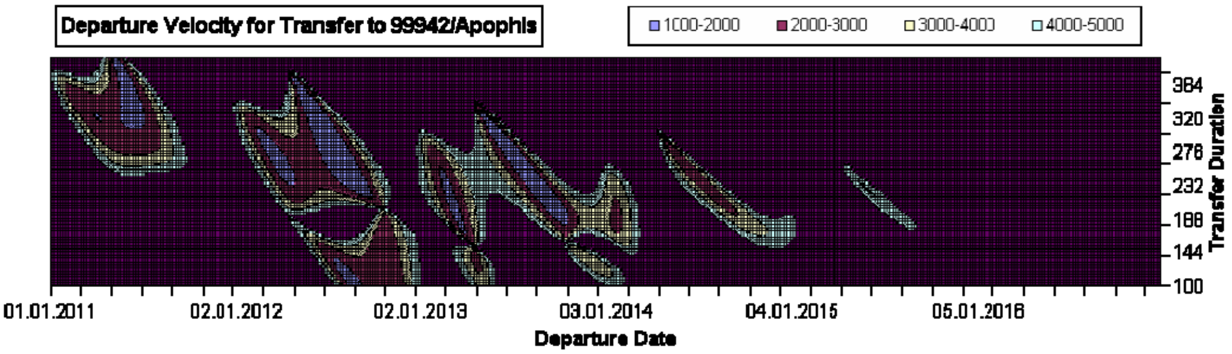


Figura 1.21: Earth departure velocity.

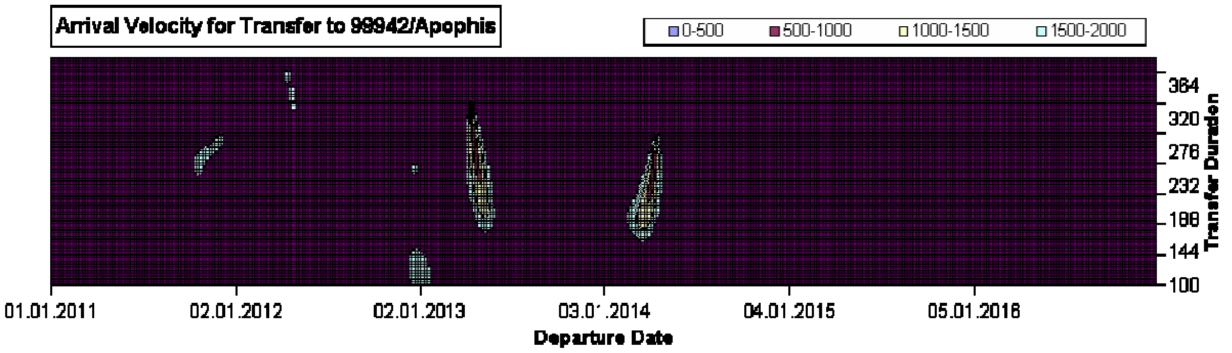


Figura 1.22: Apophis asteroid arrival velocity.

Capitolo 2

Radio Science Problem

2.1 Don Quijote Mission Objectives

The Radio Science experiment is to perform a dual Objective:

- Primary Experiment : determine the transfer of momentum resulting from the impact of Hidalgo with the asteroid, measuring the physical properties, the orbital parameters and the relative rotation before and after impact;
- Secondary Experiment: mapping autonomous and engineered (Autonomous Surface Deployment Package Engineering Experiment (ASP-DEX)) and make a path of multispectral data and a description of the asteroid thermal and mechanical properties of the surface of the asteroid.

Two system options, DQ+ and DQ light have been considered, depending on whether they address only the primary goal or both the primary and secondary objectives. In both system options, the Orbiter spacecraft is the vehicle performing a low relative velocity rendezvous with the target asteroid and being inserted into an orbit about it in order to characterize the geophysical parameters of the asteroid before the impact of a second spacecraft, the Impactor, takes place. It should carry out measurements (as a minimum) of the mass, size, gravity field and shape of the asteroid. In addition, the orbiter shall operate as a backup data relay for the impactor and image the impact from a safe parking position. It shall be inserted into an asteroid orbit again after the impact has taken place to characterize the geophysical parameters for a second time and determine any changes. The DQ+ mission includes in addition an Autonomous Surface Package Deployment Engineering eXperiment (ASP-DEX). The experiment would consist of a demonstration of the simplest possible spacecraft operations required for the release and de-orbit of a small device while the spacecraft is placed in an orbit about the asteroid. For the experiment to have a successful outcome, the device, called Autonomous Surface Package or ASP, would passively free-fall towards the asteroid surface after its release, and should touchdown within a certain distance of a target landmark. The ASP should also be able to communicate with the orbiter for a TBD period while laying on the asteroid's surface. This experiment shall be carried out after the Orbiter has completed its primary mission.

The experiment would consist of a demonstration of the simplest operations possible by the spacecraft for the issue and the stage of de-orbiting of small devices while the Orbiter (Sancho) is positioned orbit defined around the asteroid. In order the experiment has a positive feedback, the device, called Autonomous Surface Package (ASP), must be able to make a free fall towards the surface of the asteroid after his release, and must landing at a distance from eligible target landing. The ASP must be magnified to communicate with the orbiter for a time defined as being on the surface of the asteroid. This experiment will be made after the Orbiter will complete the primary mission.

2.2 Radio Science Experiment concept description

Initially conceived as an exploratory tool, radio science techniques have provided considerable knowledge of the atmospheres and gravity of the planets-many of them originally unanticipated. Previous experiments at Mars have demonstrated accuracies in measurements of Martian atmospheric surface pressure and temperature that surpassed those of in situ measurements made with the Viking Landers (Hinson et al., 2001). This performance can be duplicated or possibly improved for occultation immersion measurements with Mars Express and Venus Express. Radio Science techniques are applied to the study of planetary and cometary atmospheres, planetary rings and surfaces, and gravity, as well as the solar corona. Much of our current knowledge of these subjects has been based on radio science observations. Early missions incorporating radio science investigations included the Mariners, Pioneers, and Viking, as well as Soviet projects. Examples of recent and current experiments include those conducted with Voyager (Eshleman et al. 1977; Tyler 1987), Ulysses (Bird et al., 1994; Pätzold et al., 1995), Giotto (Pätzold et al., 1991a; 1991b; 1993), Galileo (Howard et al. 1992), Magellan (Tyler et al., 1991), Mars Global Surveyor (Tyler et al. 2001), Cassini (Kliore et al., 2002), Cassini-Huygens (Bird et al., 1995), Rosetta (Pätzold et al., 2000), Mars Express (Pätzold et al., 2004), Pluto-Kuiper Belt, and Venus Express (Häusler et al., 2005). Radio science investigations fall into three broad categories of observation: the study of planetary atmospheres, ionospheres and other plasma regions, the study of the gravity fields, and the bistatic radar measurements. We shall address here only the latter two, which are relevant for the DQ mission. When the radio path is well-clear of occulting material, the spacecraft can be treated as a classical test particle falling in the gravity field of the planetary system. This type of experiment is optimized when the component of its velocity is along the line-of-sight to the tracking station, thus allowing a measurement of the Doppler effect of the radio carrier signal(s). The spacecraft motion causing the Doppler shift is in response to the variations in mass distribution within a planet or its satellites. This is a classical physics laboratory experiment carried out on planetary scales. Our global knowledgeof Earth's gravity field comes from such studies. The only information on the gravity field of Mercury is based on the two flybys of Mariner 10 (Anderson et al., 1987). Similarly, observational inferences as to the internal structures of the Galilean satellites, for example that there is an ocean on Europa, are based on the perturbations of the trajectory of Galileo spacecraft during close flybys (Anderson et al., 1992; e.g. Anderson et al., 1997). A precise determination of the total mass of Uranus and Neptune from the Voyager 2 flybys (Tyler et al., 1986) has led to the conclusion that there is no need for a 'Planet X' to explain the orbits of these bodies (Standish, 1993). The method has been extended to small bodies as well, for example in the mass determination of asteroid Mathilde (Yeomans et al., 1997) and gravity field of asteroid Eros (Yeomans et al., 2000; Konopliv et al., 2002) and is planned for the Rosetta flyby at asteroid Lutetia in 2010 (Pätzold et al., 2001; paper is treating the Siwa asteroid of the old Rosetta- Wirtanen mission). At Mars, techniques similar to those used for asteroids can be applied to a precise determination of the masses of Phobos and Deimos and are planned for Mars Express during close encounters (Pätzold et al., 2004). Oblique incidence scattering investigations using propagation paths between a spacecraft, a planetary surface, and an Earth station, can be used to explore the surface properties through study of the microwave scattering function and were first described by Fjeldbo (1964). Such investigations are referred to as bistatic radar since the transmitter and receiver are separated by significant angular distances or ranges. The first such experiment in space was conducted with Luna-11 in August 1966 to study the surface of the moon (Yakaovlev and Efimov, 1966). The oblique scattering geometry afforded by the Lunar Orbiter-1 spacecraft, which orbited the moon in October 1966, provided the signal source for the first US experiment (Tyler et al., 1967). Recording of signals transmitted to Earth by Explorer 35 also contained echoes of the transmissions from the lunar surface (Tyler, 1968). As it happened, the plane of the spacecraft spin axis and the antenna polarization made it possible to measure the Brewster angle of the lunar crust, leading to an unambiguous value for the relative dielectric constant of lunar soil between 2.9 and 3.1, and thereby confirming that a future landing spaceship would be on firm ground on the surface.

Capitolo 3

Model Created for RSE

3.1 Ephemeris creation

Before to start the Mission Analysis one of the biggest problem it is to create the ephemeris of the near asteroids.

3.2 Perturbation Analysis

3.2.1 Third Body Perturbation

This study should detect the semi-major axis perturbation by other bodies (i.e. Planets or Asteroids) upon the 2002AT4 asteroid. A restricted three body (Sun, perturbing body and 2002AT4) analysis should be implemented. The 'restriction' hypothesis means that the mass of the restricted (m) body is negligible w.r.t. each other two bodies' masses (M):

$$M \approx M + m$$

Concerning with this hypothesis the considered perturbing bodies are chosen in function of their mass and distance w.r.t. the considered asteroid. The bodies selected are:

- Sun,
- Earth,
- Mars,
- Jupiter,
- Ceres,
- Pallas,
- Vesta.

Assuming these bodies it is not obvious that the hypothesis of restriction taking on is always valid. As a reference case the Apollo service module orbiting around Moon is used. Therefore the mass ratio has been analyzed.

Reference case	Sun	Earth	Mars	Jupiter	Ceres	Pallas	Vesta
10^{-19}	10^{-20}	10^{-15}	10^{-14}	10^{-17}	10^{-11}	10^{-11}	10^{-11}

From Table 1 the 'restriction' hypothesis could not be applied except for the Sun. For planets and asteroids it must be moreover considered the huge distance from the 2002AT4. This means that the perturbing force of 2002AT4 on another body should be however negligible. To evaluate the gravitational force, the relative acceleration between the considered asteroid and the different body it has computed. Appling Newton's laws w.r.t. an inertial frame it can be obtain the acceleration acting on a satellite or a reference body.

$$\ddot{r}_{SAT} = -\frac{G \cdot M_{moon}}{r^2} = -\frac{6.6726 \cdot 10^{-20} \cdot 7.3483 \cdot 10^{22}}{(1373.1 + 86)^2} \frac{Km}{s^2} = 2.3031 \cdot 10^{-3} \frac{Km}{s^2}$$

For other perturbing bodies the relative acceleration was computed between 01/01/2013 and 01/01/2050. This analysed epoch it has been chose to cover a synodic period at least.

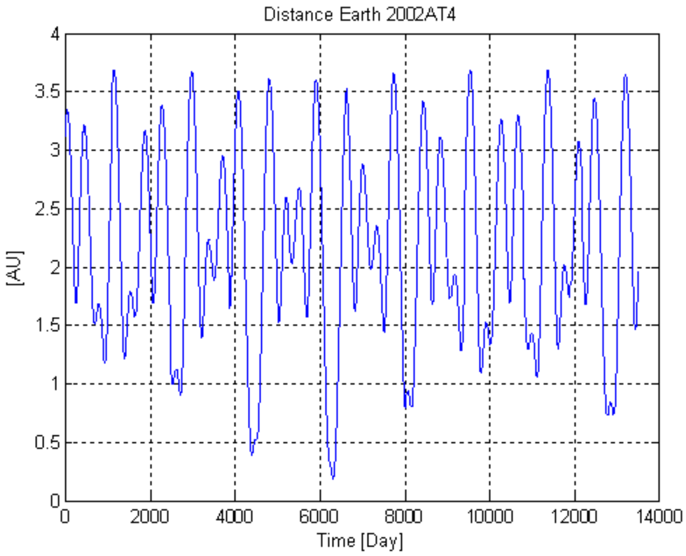


Figura 3.1: Distance between Earth and 2002AT4.

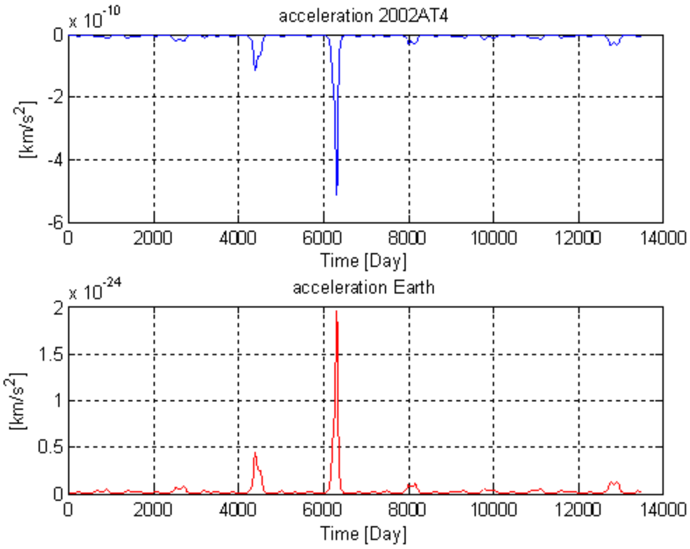


Figura 3.2: Acceleration between Earth and 2002AT4.

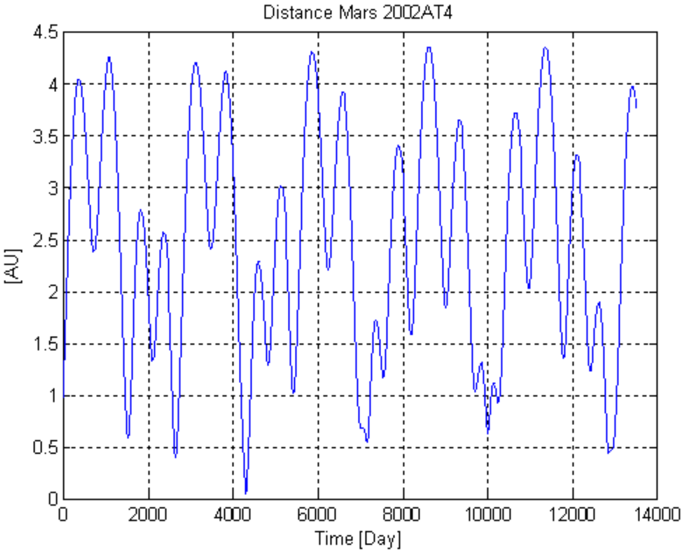


Figura 3.3: Distance between Mars and 2002AT4.

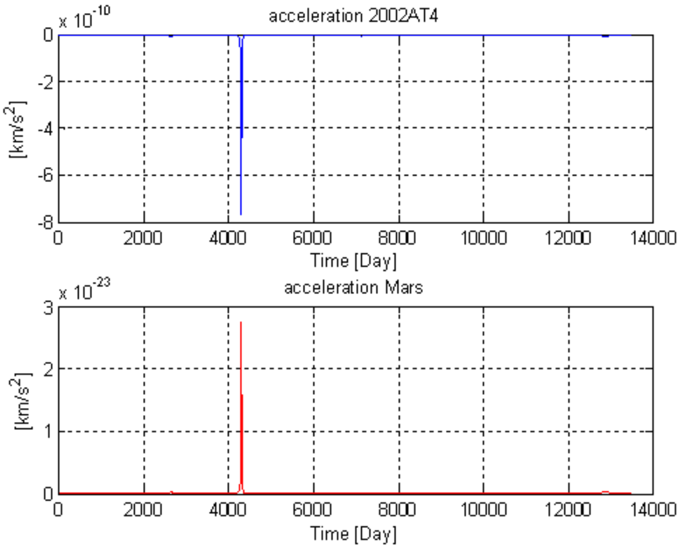


Figura 3.4: Acceleration between Mars and 2002AT4.

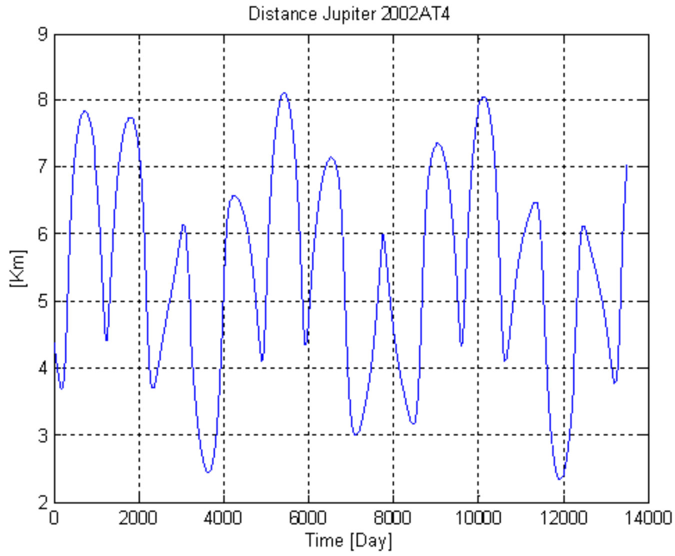


Figura 3.5: Distance between Jupiter and 2002AT4.

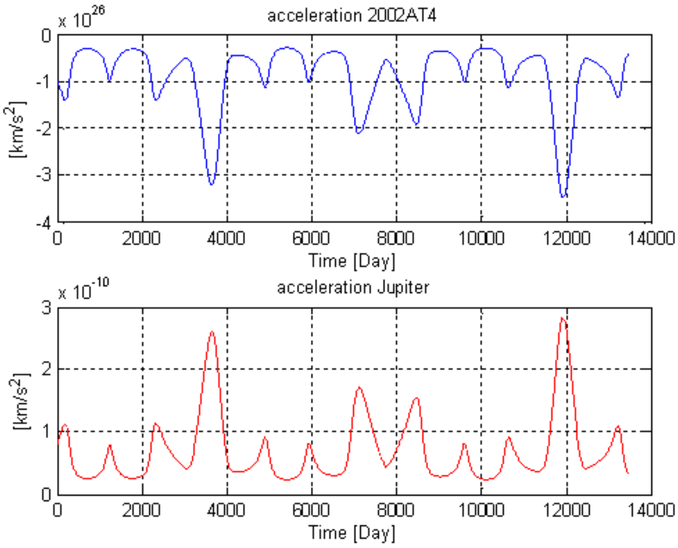


Figura 3.6: Acceleration between Jupiter and 2002AT4.

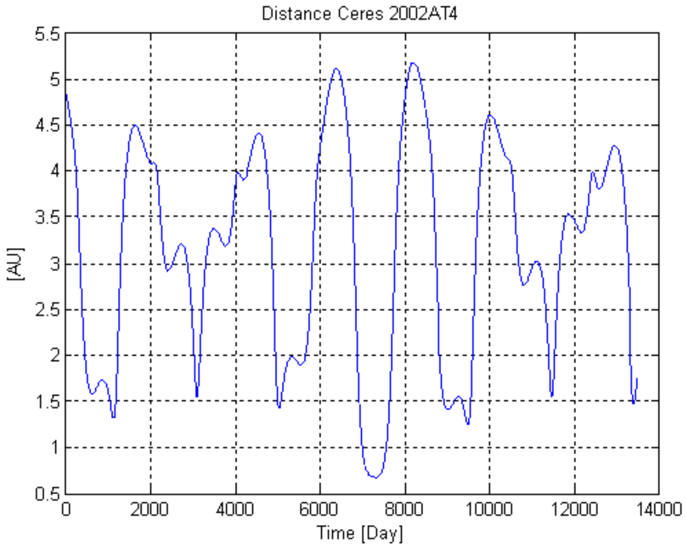


Figura 3.7: Distance between Ceres and 2002AT4.

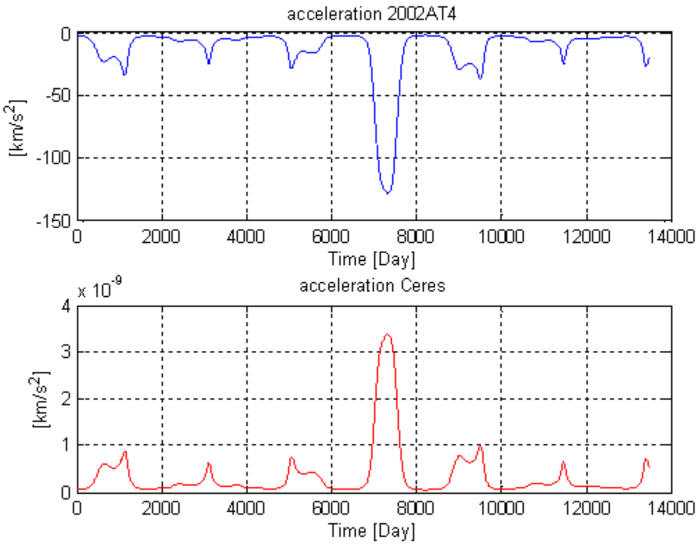


Figura 3.8: Acceleration between Ceres and 2002AT4.

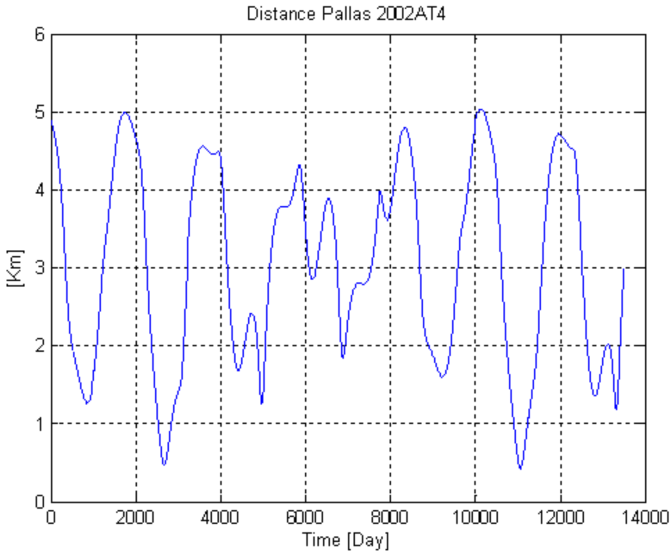


Figura 3.9: Distance between Pallas and 2002AT4.

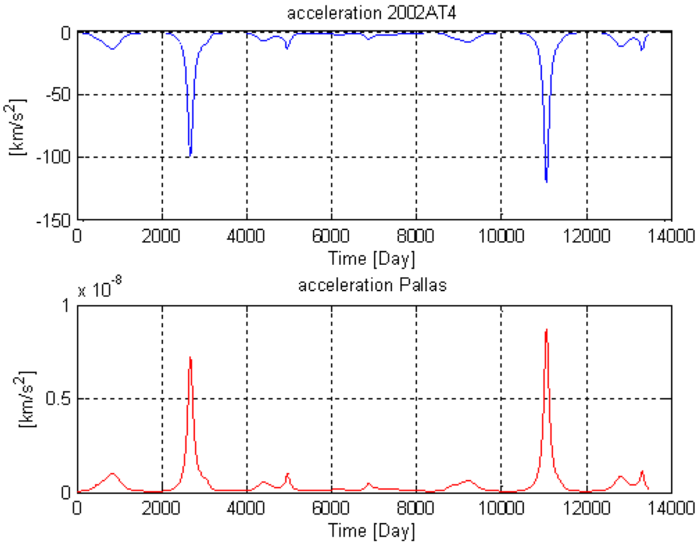


Figura 3.10: Acceleration between Pallas and 2002AT4.

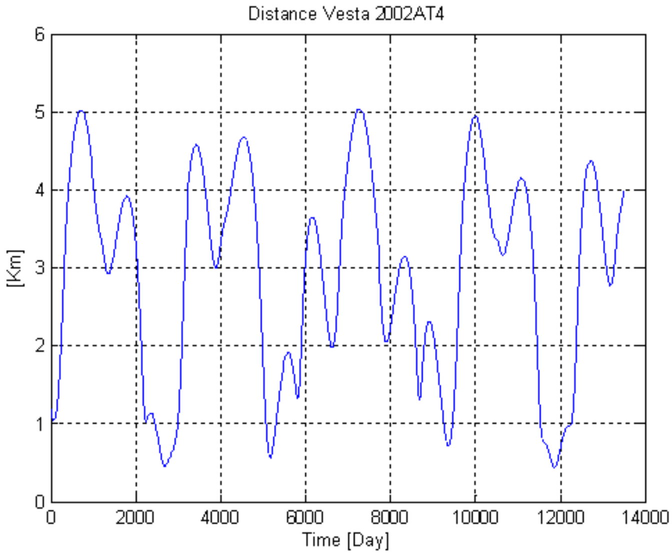


Figura 3.11: Distance between Vesta and 2002AT4.

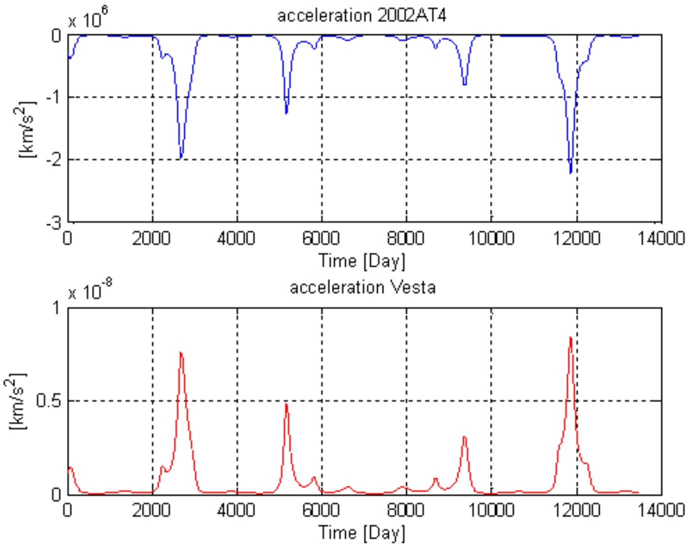


Figura 3.12: Acceleration between Vesta and 2002AT4.

Reference case	Earth	Mars	Jupiter	Ceres	Pallas	Vesta
10^{19}	10^{14}	10^{13}	10^{16}	10^{10}	10^{10}	10^{10}

From Table 2 the 'restriction' hypothesis could not be applied for planet and asteroids. In these cases the relative acceleration is not as big as the reference case, but for a shorter period (i.e. 20 years) these values can not change their magnitude. Doing so these finals results are not as far as the reference case and the 'restriction' hypothesis will be implemented in the following analysis.

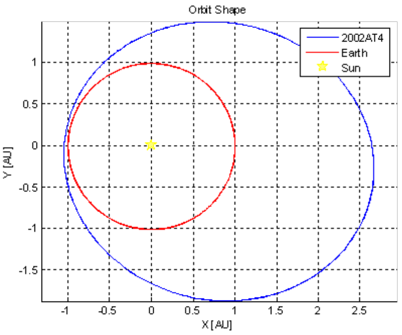


Figura 3.13: Orbit Shape 2002AT4 and Earth.

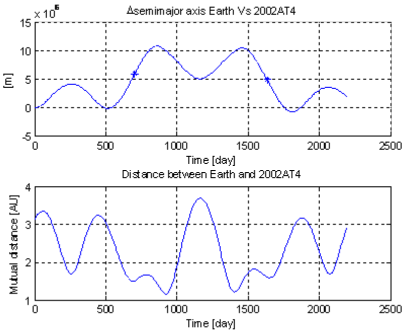


Figura 3.14: Earth - 2002AT4 semimajor axis variation.

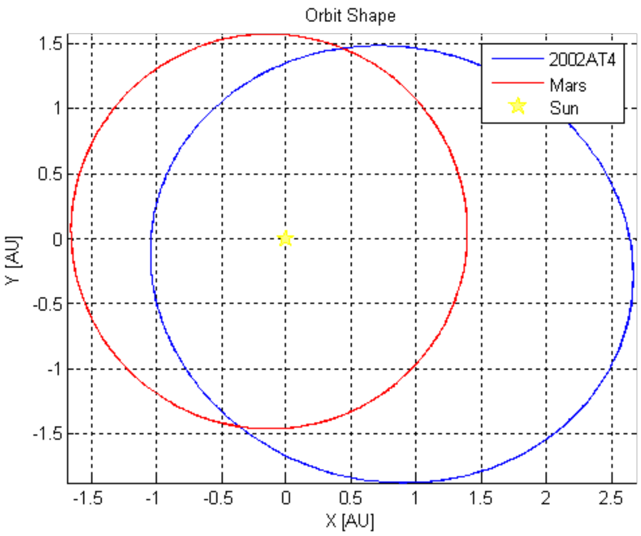


Figura 3.15: Orbit Shape 2002AT4 and Mars.

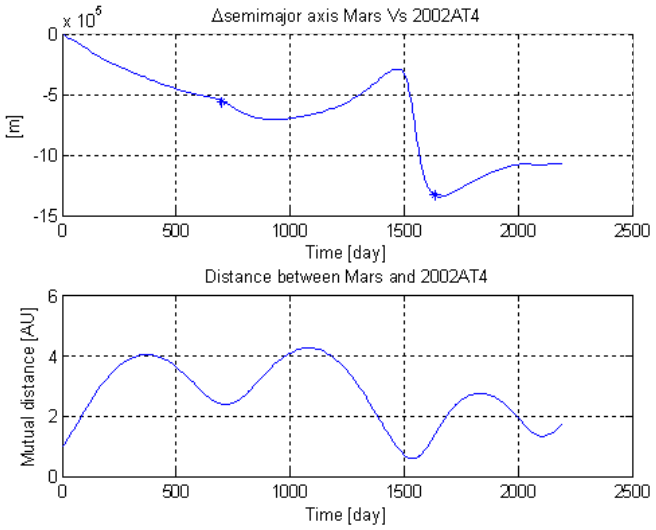


Figura 3.16: Mars - 2002AT4 semimajor axis variation.

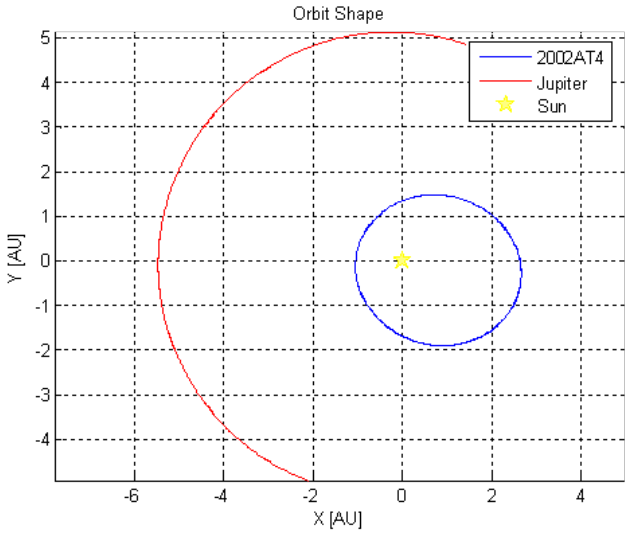


Figura 3.17: Orbit Shape 2002AT4 and Jupiter.

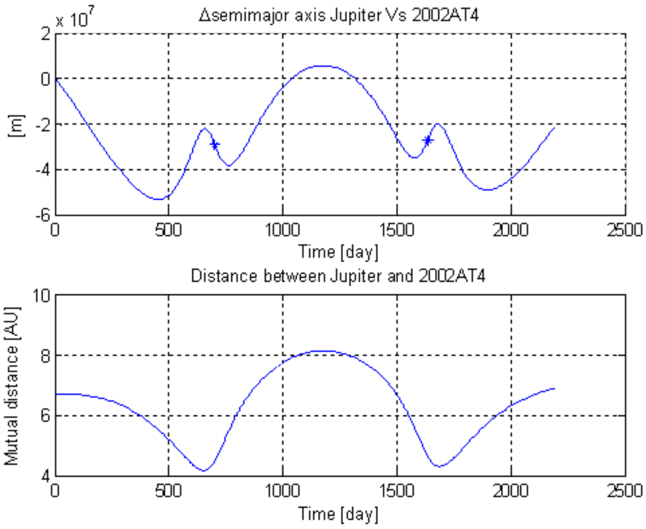


Figura 3.18: Jupiter - 2002AT4 semimajor axis variation.

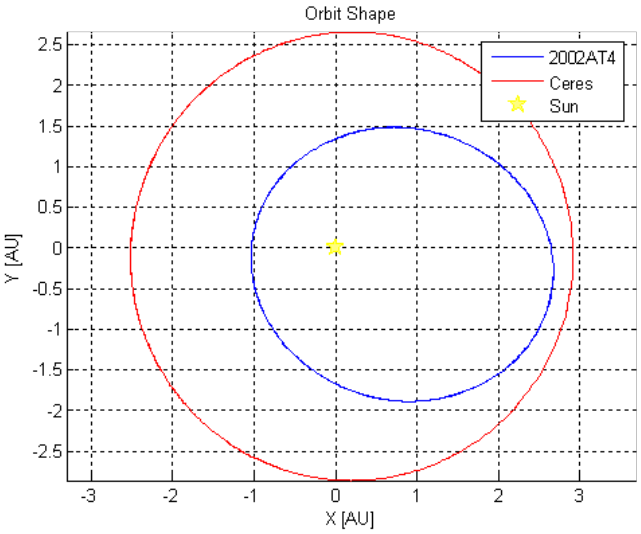


Figura 3.19: Orbit Shape 2002AT4 and Ceres.

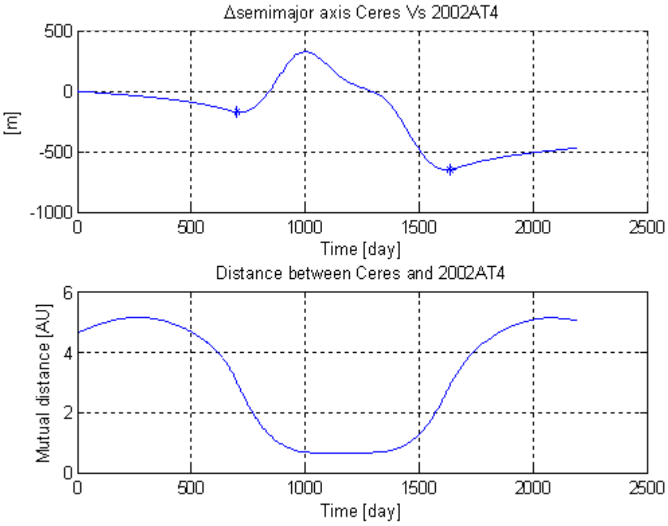


Figura 3.20: Ceres - 2002AT4 semimajor axis variation.

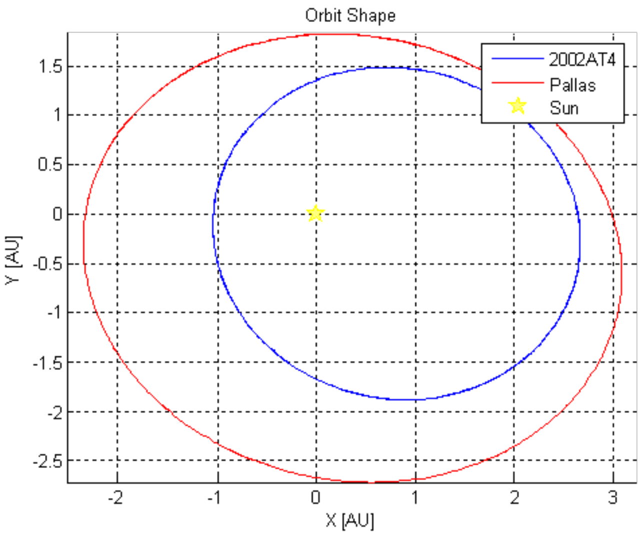


Figura 3.21: Orbit Shape 2002AT4 and Pallas.

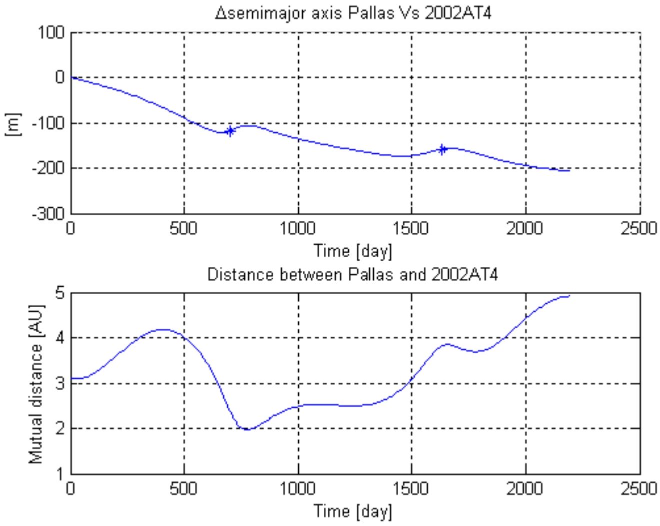


Figura 3.22: Pallas - 2002AT4 semimajor axis variation.

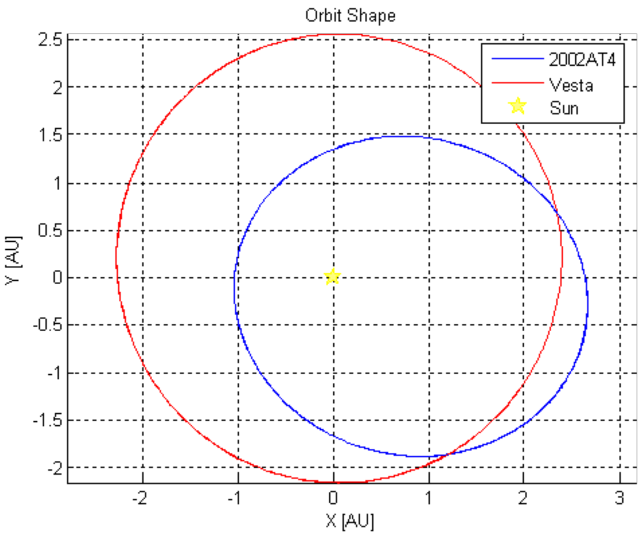


Figura 3.23: Orbit Shape 2002AT4 and Vesta.

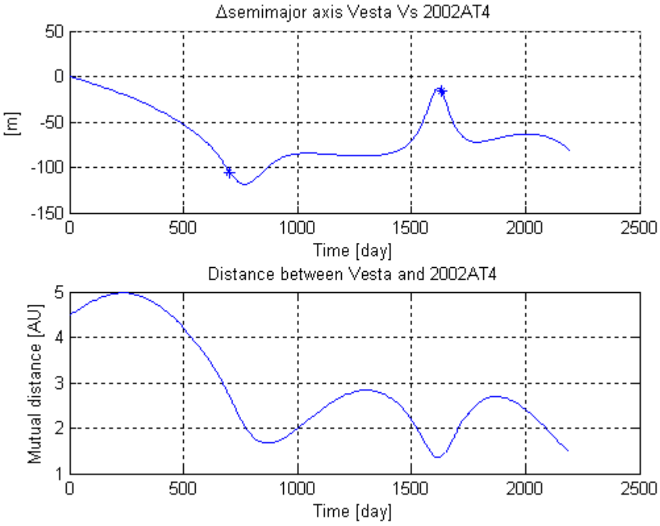


Figura 3.24: Vesta - 2002AT4 semimajor axis variation.

To validate the previously analysis one simulation is made up without the interaction of noone celestial body. The validation is visible in order of the magnitude of the semimajor axis variation.

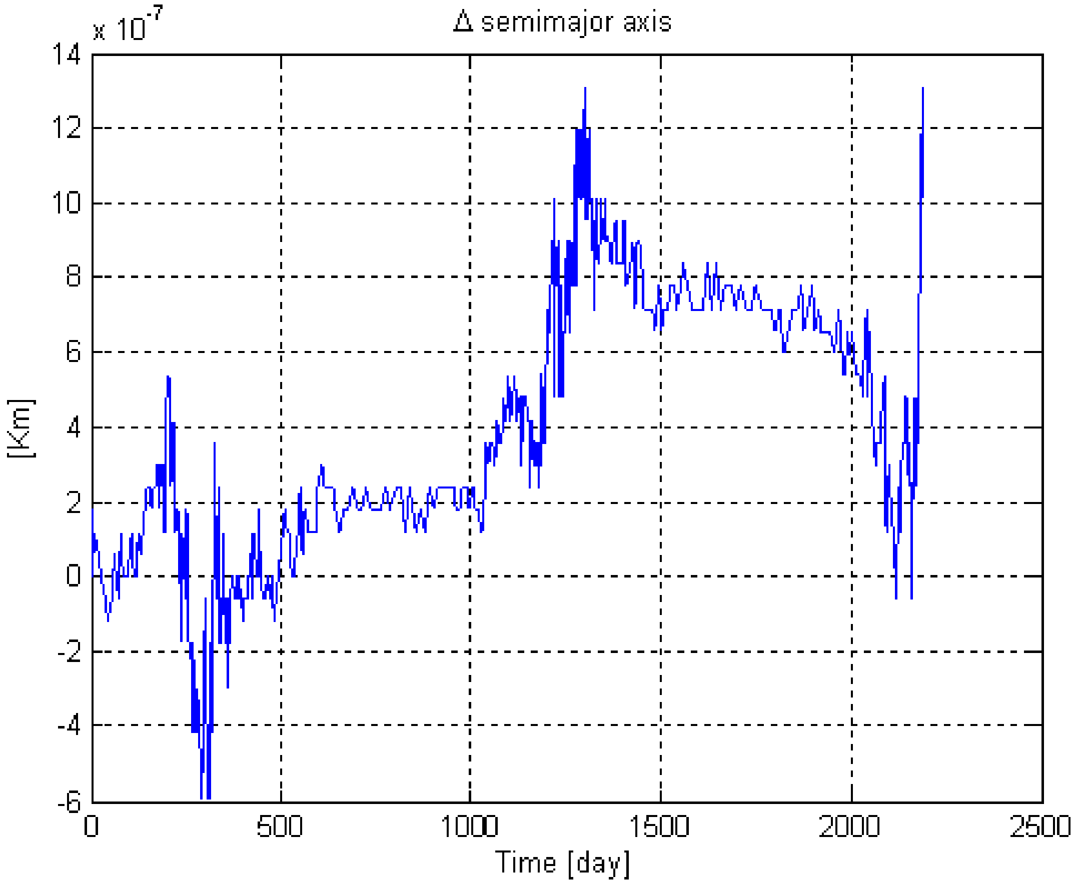


Figura 3.25: None - 2002AT4 semimajor axis variation.

An uncertainty factor inside this analysis is due to the error of the knowledge of the mass of each asteroid.

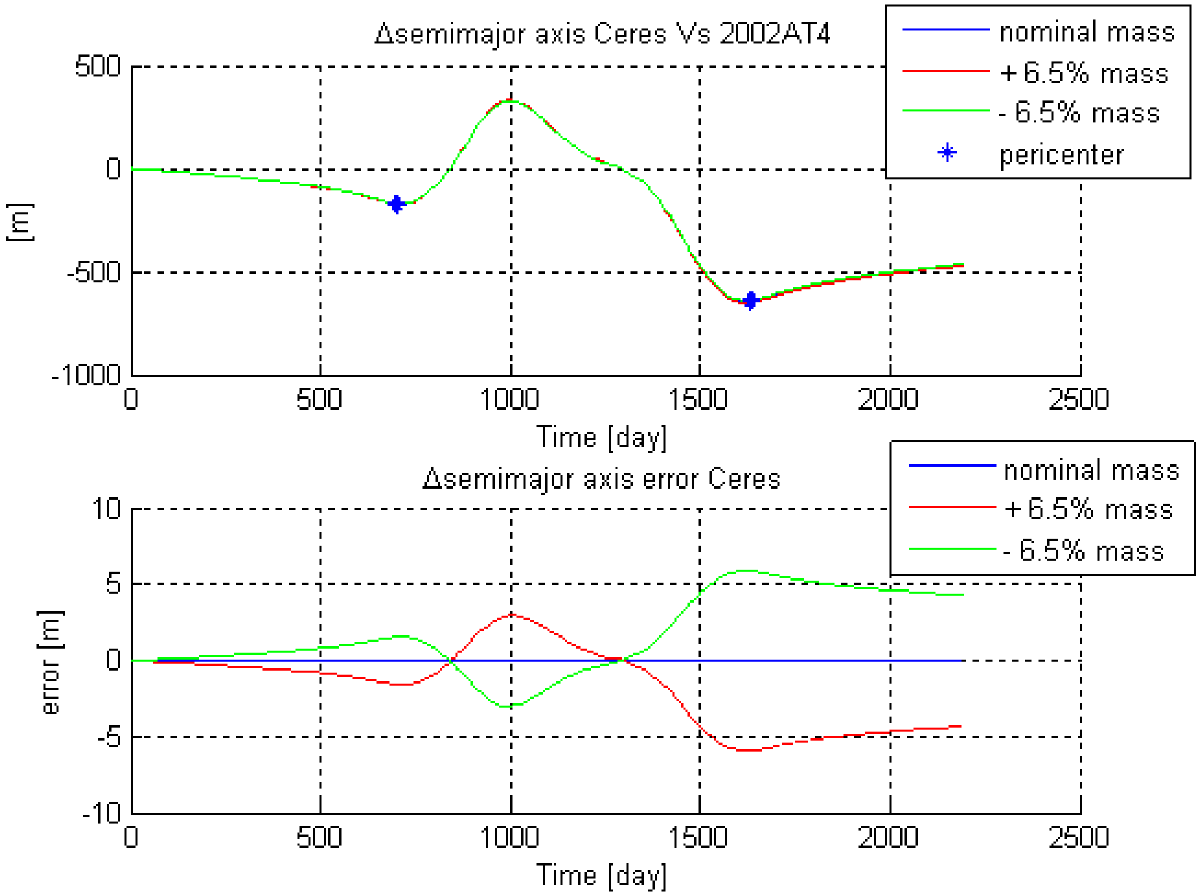


Figura 3.26: Ceres - 2002AT4 semimajor axis variation with uncertain mass of 6.5%.

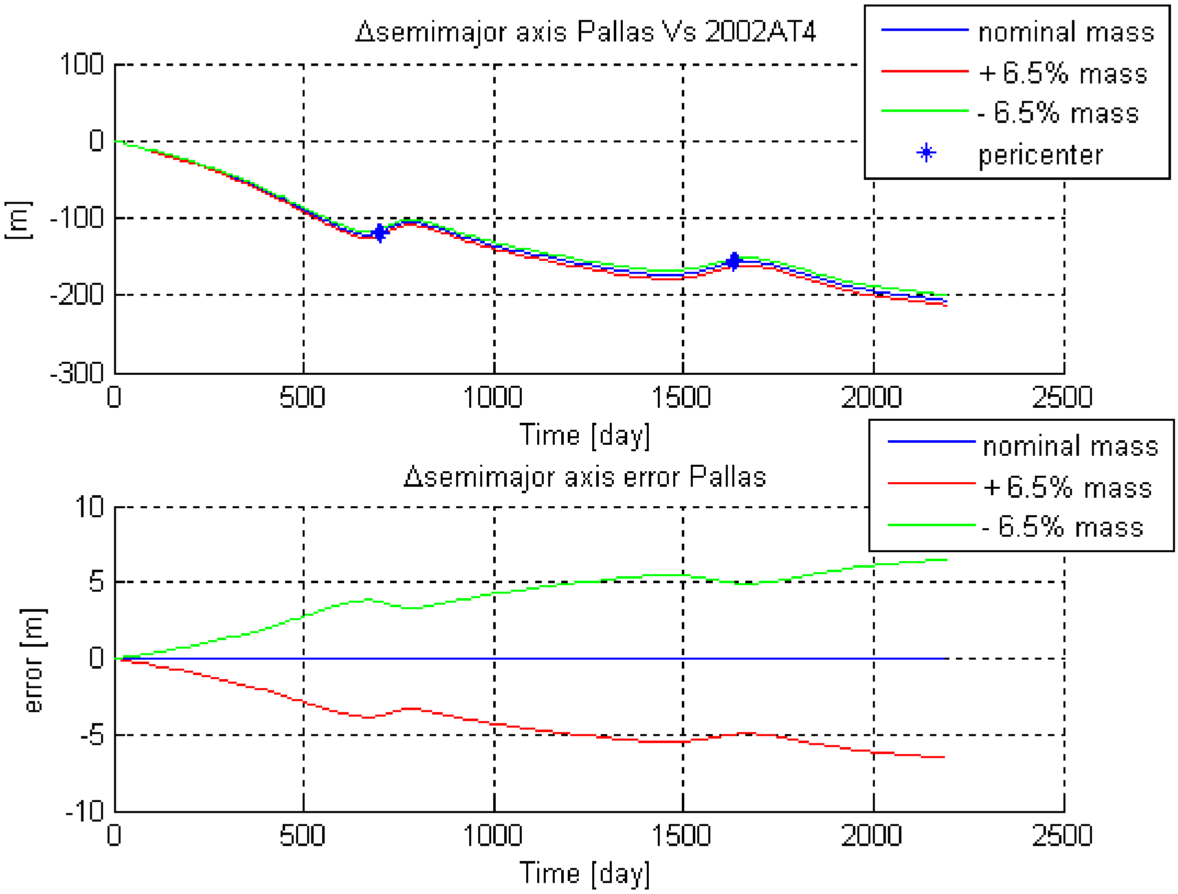


Figura 3.27: Pallas - 2002AT4 semimajor axis variation with uncertain mass of 6.5%.

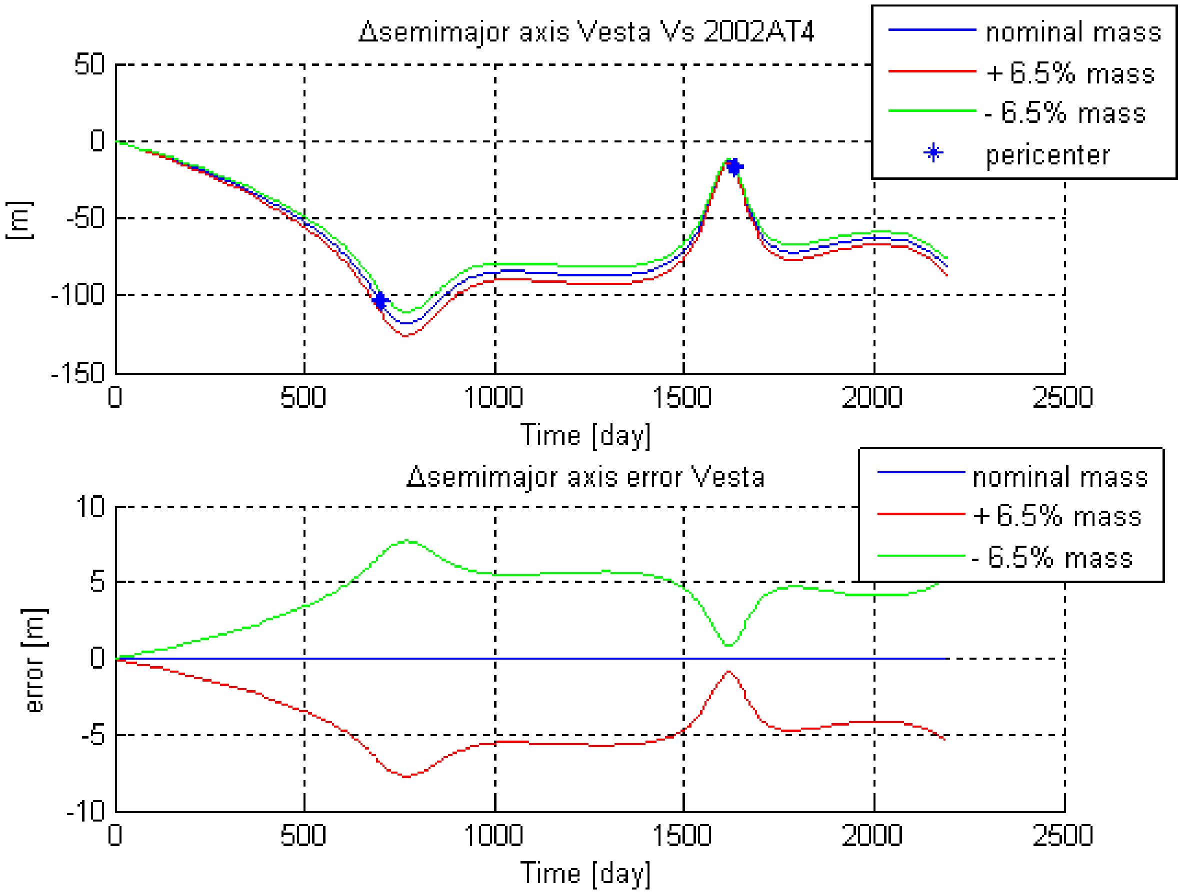


Figura 3.28: Vesta - 2002AT4 semimajor axis variation with uncertain mass of 6.5%.

Subsequently they are show the perturbation induced by the 2002AT4 asteroid on : Earth, Mars, Jupiter, Ceres, Pallas and Vesta ; these perturbation are 0.1 mm therefore this takes advantage our hypothesis of the restriction of 3^{rd} bodies problem.

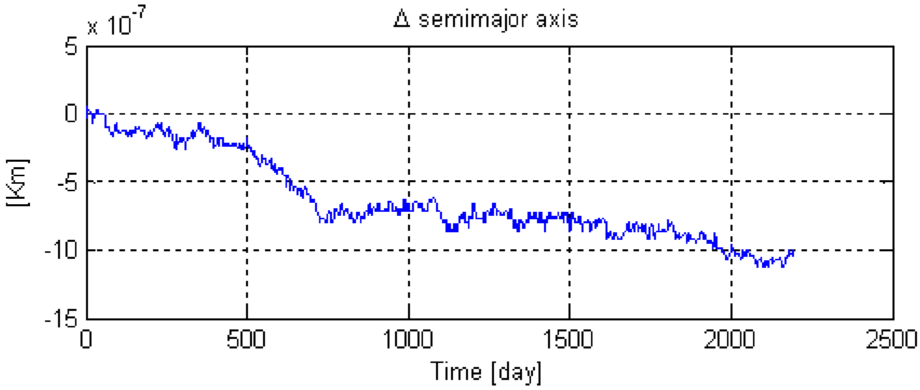


Figura 3.29: Delta semimajor axis variation induced by 2002AT4 on Earth.

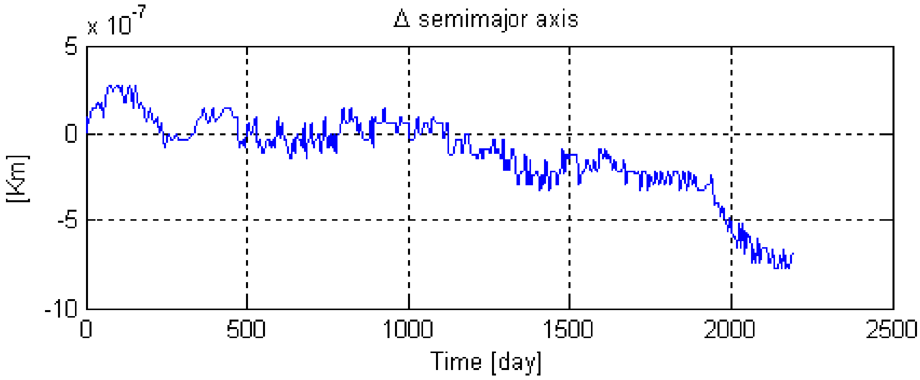


Figura 3.30: Delta semimajor axis variation induced by 2002AT4 on Mars.

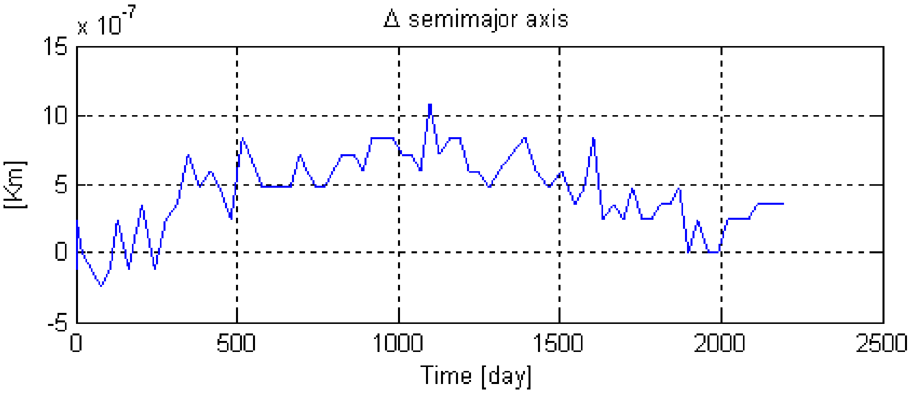


Figura 3.31: Delta semimajor axis variation induced by 2002AT4 on Jupiter.

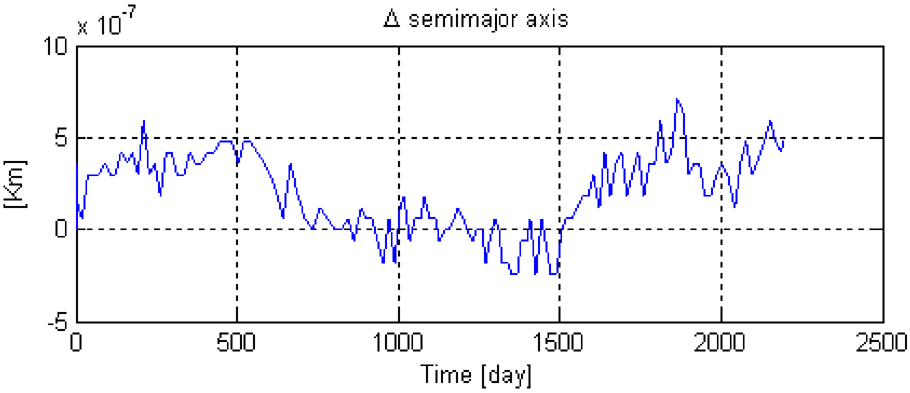


Figura 3.32: Delta semimajor axis variation induced by 2002AT4 on Ceres.

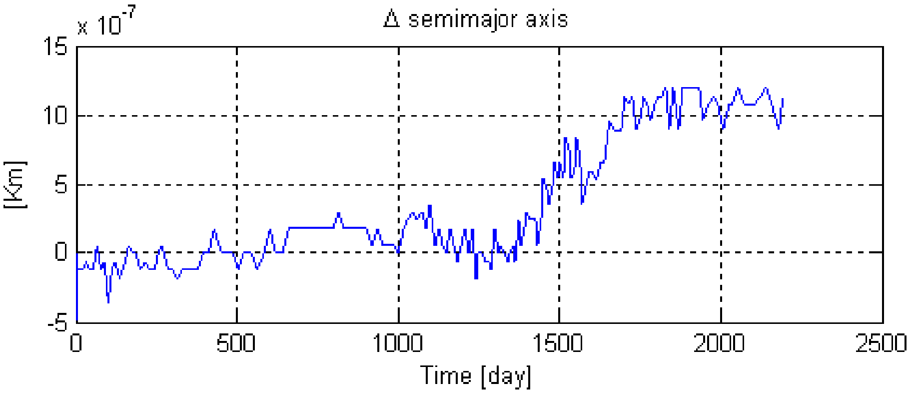


Figura 3.33: Delta semimajor axis variation induced by 2002AT4 on Pallas.

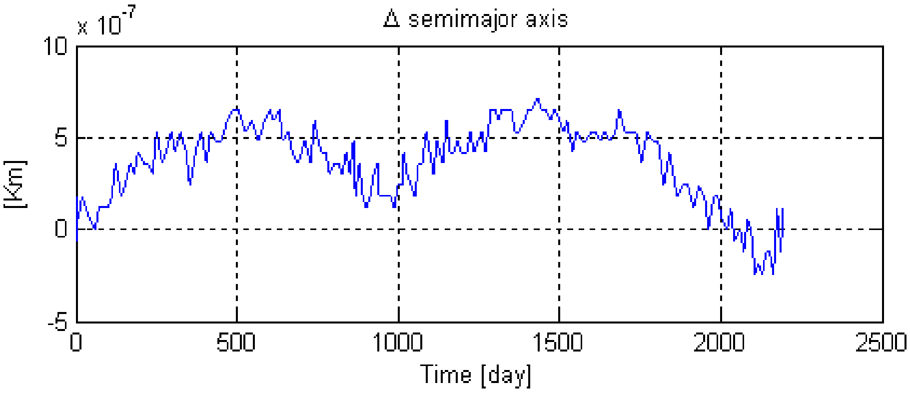
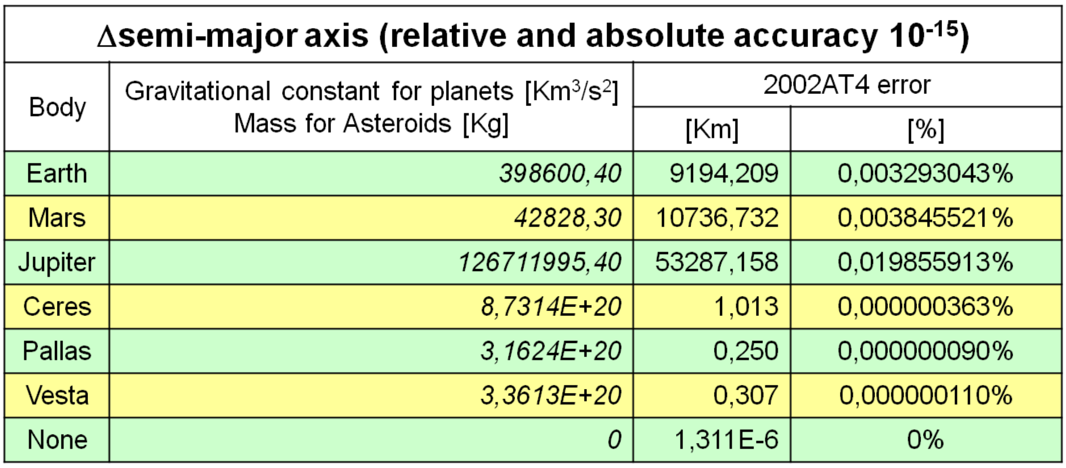


Figura 3.34: Delta semimajor axis variation induced by 2002AT4 on Vesta.

The 2002AT4 semi-major axis variation due to a singular perturbation at time is shown in the next Table.



Δsemi-major axis (relative and absolute accuracy 10^{-15})

Body	Gravitational constant for planets [Km^3/s^2] Mass for Asteroids [Kg]	2002AT4 error	
		[Km]	[%]
Earth	*398600,40*	9194,209	0,003293043%
Mars	*42828,30*	10736,732	0,003845521%
Jupiter	*126711995,40*	53287,158	0,019855913%
Ceres	*8,7314E+20*	1,013	0,000000363%
Pallas	*3,1624E+20*	0,250	0,000000090%
Vesta	*3,3613E+20*	0,307	0,000000110%
None	*0*	1,311E-6	0%

Figura 3.35: Delta semimajor axis variation.

From previous Table it can be state that:

- the variations caused by the considered planets are enormous w.r.t those due to asteroids,
- the variation caused by asteroids are comparable with the 2002AT4 semi-major axis variation that will be investigated during the mission (100m),
- the mathematical computation error is $0,1$mm evaluated by last Table 3 row where no perturbing body is considered,
- maximal mutual distance error due to integration method (Runge-Kutta based on Dorman and Prince VII-VII formulae order) is 1mm,
- a restricted n-body problem it will led to have a complete 2002AT4 semi-major axis variation analysis.

3.2.2 Yarkovsky effect

The Yarkovsky effect is a subtle non-gravitational phenomenon related to the anisotropic thermal emission of Solar System objects. Its importance has been recently demonstrated in relation to the transport of material from the main asteroid belt (both to explain the origin of near-Earth asteroids and some properties of meteorites) and also in relation to the aging processes of the asteroid families. However, unlike the case of the artificial satellites, the Yarkovsky effect has never been measured or detected in the motion of natural bodies in the Solar System. In this paper, we investigate the possibility of detecting the Yarkovsky effect via precise orbit determination of near-Earth asteroids. Such a detection is feasible only with the existence of precise radar astrometry at multiple apparitions. Since the observability of the Yarkovsky perturbation accumulates quadratically with time the time span between radar observations is a critical factor. Though the current data do not clearly indicate the Yarkovsky effect in the motion of these bodies, we predict that the next apparition of several asteroids (in particular, 6489 Golevka, 1620 Geographos, and possibly 1566 Icarus) might reveal its existence. Moreover, we show that the Yarkovsky effect may play a very important role in the orbit determination of small, but still observable, bodies like 1998 KY26. If carefully followed, this body may serve as a superb probe of the Yarkovsky effect in its next close approach to the Earth in June 2024.

The Yarkovsky effect is a force felt by a body caused by the anisotropic emission of thermal photons, which carry momentum. It is usually considered in relation to meteoroids or small asteroids (about 10 cm to 10 km in diameter), as its influence is most significant for these bodies.

The effect was discovered by the Russian civil engineer Ivan Osipovich Yarkovsky (1844 1902), who worked on scientific problems in his spare time. Writing in a pamphlet around the year 1900, Yarkovsky noted that the diurnal heating of a rotating object in space would cause it to experience a force that, while tiny, could lead to large long-term effects in the orbits of small bodies, especially meteoroids and small asteroids.

Yarkovsky's remarkable insight would have been consigned to oblivion had it not been for the Estonian astronomer Ernst J. Öpik (1893 1985), who read Yarkovsky's pamphlet sometime around 1909. Decades later, Öpik, recalling the pamphlet from memory, discussed the possible importance of the Yarkovsky effect for moving meteoroids about the solar system.[1]

In a nutshell, the Yarkovsky effect is a consequence of the time needed for the surface to warm up or cool down. In general there are two components to the effect:

Diurnal effect: On a rotating body (e.g. an asteroid) illuminated by the Sun, as on the Earth, the surface is warmer in the afternoon and early night, than in the morning and late night. The result is that more heat is radiated on the dusk side than the dawn side, leading to a net radiation pressure thrust in the opposite dawn direction. For pro-grade rotators, this is in the direction of motion on their orbit, and causes their semi-major axis to steadily increase, spiraling away from the Sun. Retrograde rotators spiral inward. This is the dominant component for larger bodies greater than about 100 m diameter.

Seasonal effect: This is easiest to understand for the idealized case of a non-rotating body orbiting the Sun, for which each year consists of exactly one day. As it travels around its orbit, the dusk hemisphere which has been heated over a long preceding time period is invariably in the direction of orbital motion. The excess of thermal radiation in this direction causes a braking force which always causes spiraling inward toward the Sun. In practice, for rotating bodies, this seasonal effect increases along with the axial tilt. It dominates only if the diurnal effect is small enough. This may occur because of very rapid rotation (no time to cool off on the night side, hence an almost uniform longitudinal temperature distribution), small size (the whole body is heated throughout) or an axial tilt close to 90°. The seasonal effect is more important for smaller asteroidal fragments (from a few meters up to about 100 m), provided their surfaces are not covered by an insulating regolith layer and they do not have exceedingly slow rotations. Additionally, on very long timescales over which the spin axis of the body may be repeatedly changed due to collisions (and hence also the direction of the diurnal effect changes), the seasonal effect will also tend to dominate.

The above details can become more complicated for bodies in strongly eccentric orbits.

The effect was first measured in 1991-2003 on the asteroid 6489 Golevka. The asteroid drifted 15 km from its predicted position over twelve years (the orbit was established with great precision by a series of radar observations in 1991, 1995 and 1999).

In general, the effect is size dependent, and will affect the semi-major axis of smaller asteroids, while leaving large asteroids practically unaffected. For kilometer-sized asteroids the Yarkovsky effect is minuscule over short periods: 6489 Golevka is estimated to be subjected to a force of about 0.25 newton, for a net acceleration of 10-10 m/s2. But it is steady; over millions of years an asteroid's orbit can be perturbed enough to transport it from the main belt to the inner solar system.

For a specific asteroid, it is very hard to predict the exact impact of the Yarkovsky effect on its orbit. This is because its magnitude depends on many variables that are hard to determine from the limited observational information that is available. These include the exact shape of the asteroid, its orientation, and its albedo, along with its variations over the surface and with wavelength. Calculations are further complicated by the effects of shadowing and thermal re-illumination, whether caused by local craters or a possible overall concave shape. The Yarkovsky effect also competes with radiation pressure whose net effect may cause similar small long-term forces for bodies with albedo variations and/or non-spherical shapes.

As an example, even for the simple case of the pure seasonal Yarkovsky effect on a spherical body in a circular orbit with 90° obliquity, semi-major axis changes could differ by as much as a factor of two between the case of a uniform albedo and the case of a strong north/south albedo asymmetry. Depending on the orbit and spin axis, the Yarkovsky semi-major axis change may be reversed simply by changing from a spherical to a non-spherical shape.

Despite these difficulties, utilizing the Yarkovsky effect is one scenario under investigation to alter the course of potentially Earth-impacting Near Earth asteroids. Possible asteroid deflection strategies include painting the surface of the asteroid or focusing solar radiation onto the asteroid to alter the intensity of the Yarkovsky effect and so alter the orbit of the asteroid away from a collision with Earth.

The Force generated by the Yarkovsky effect is possible to calculate with the next expression:

$$F_X = -\frac{2}{3} \cdot \frac{\Phi}{\rho \cdot D \cdot c} \cdot \frac{1 + k_1 \cdot \Theta}{1 + 2 \cdot k_1 \cdot \Theta + k_2 \cdot \Theta^2} \cdot cos(\theta_0)$$

$$F_Y = -\frac{2}{3} \cdot \frac{\Phi}{\rho \cdot D \cdot c} \cdot \frac{1 + k_3 \cdot \Theta}{1 + 2 \cdot k_1 \cdot \Theta + k_2 \cdot \Theta^2} \cdot \cos(\theta_0)$$

$$F_Z = -\frac{2}{3} \cdot \frac{\Phi}{\rho \cdot D \cdot c} \cdot \frac{\sqrt{2} \cdot R'}{\Theta + \sqrt{2} \cdot R'} \cdot \sin(\theta_0)$$

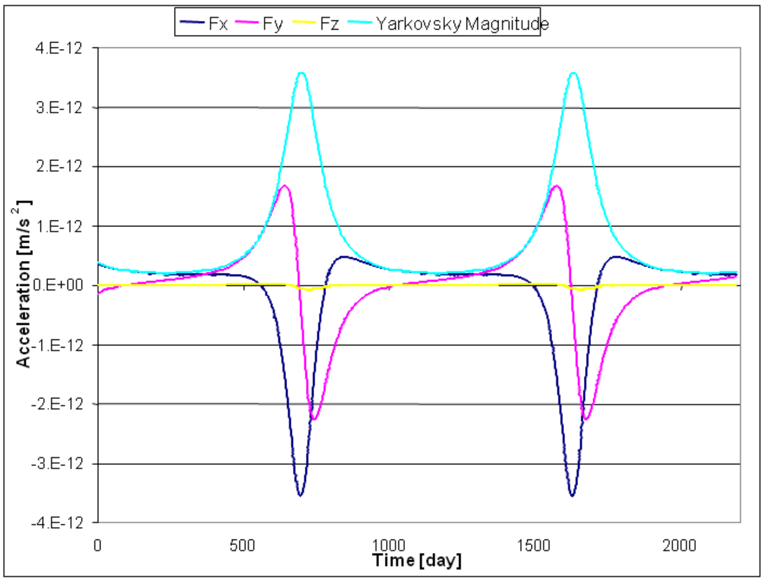


Figura 3.36: Yarkovsky effect on 2002AT4.

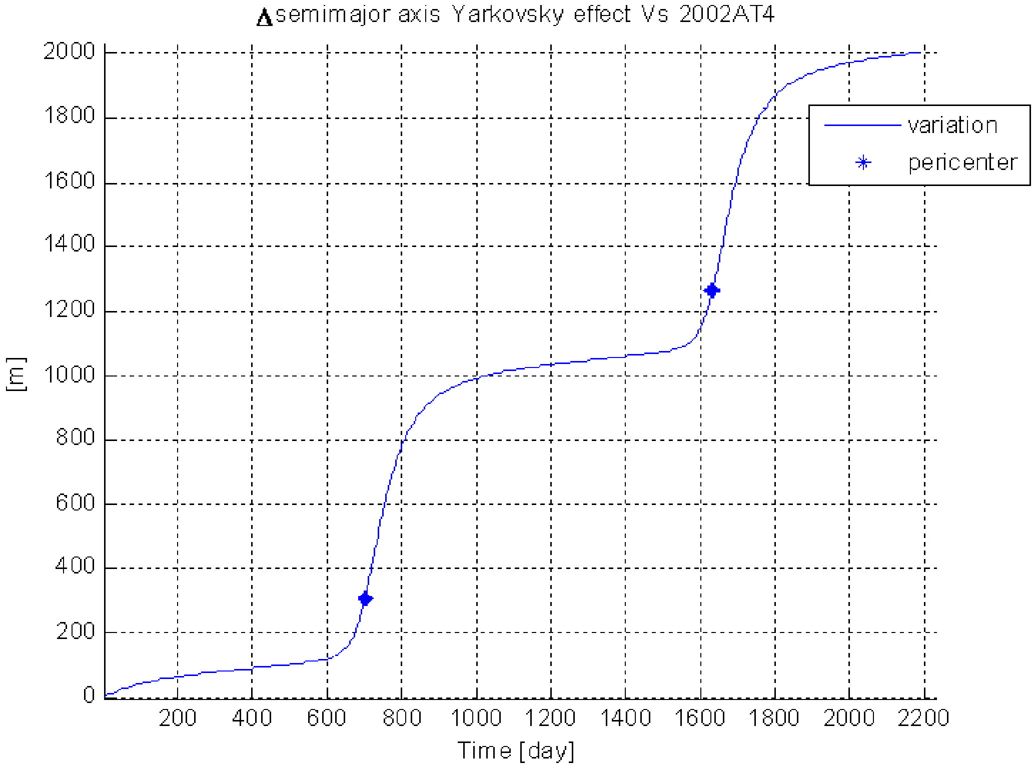


Figura 3.37: Semimajor axis variation induced on 2002AT4 from Yarkovsky effect.

A uncertainty factor inside this analysis is due to the error of the knowledge of the thermal inertia of each asteroid. To check the importance of uncertainty of 2002AT4 asteroid's thermal inertia a further analysis has been conducted.

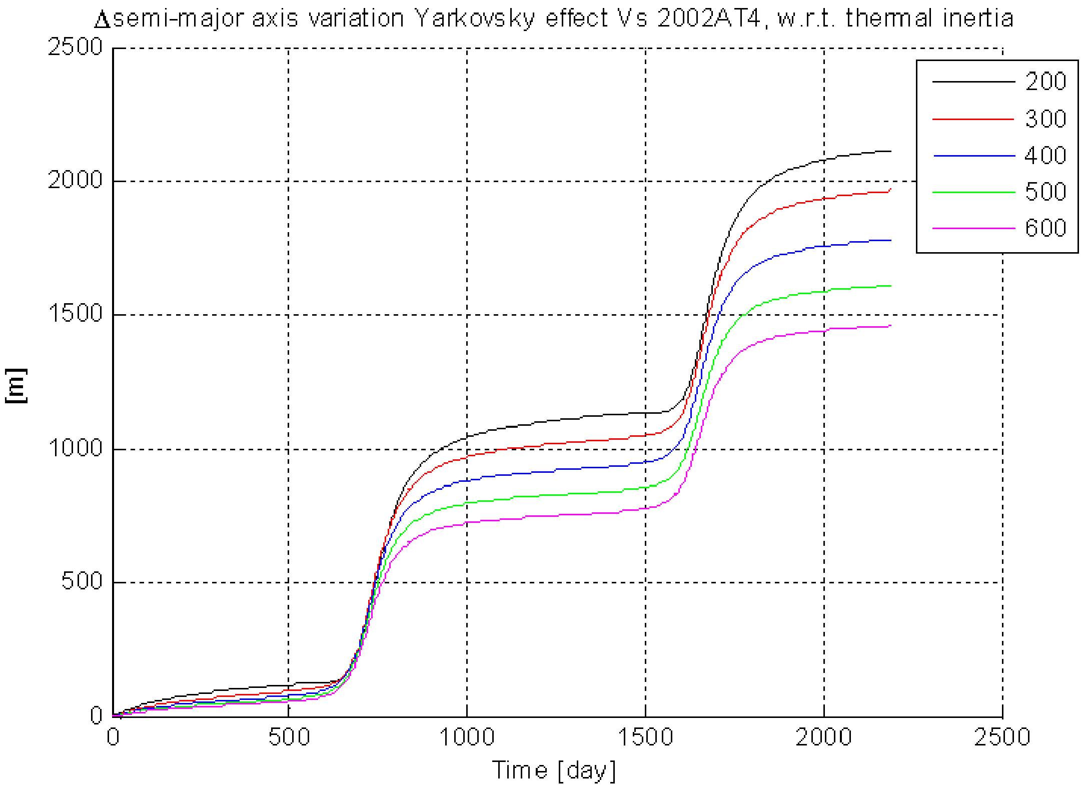


Figura 3.38: Semimajor axis variation function of Thermal Inertia.

3.2.3 Sun Radiation

This study should investigate the semi-major axis perturbation inducted by the solar pressure on 2002AT4 asteroid. The absorption or reflection of photons associated with solar radiation causes an asteroid to accelerate. A simplified model that assumes the surface normal of the 2002AT4 asteroid is pointing to the Sun is sufficient to account for the effect of solar radiation. This acceleration is:

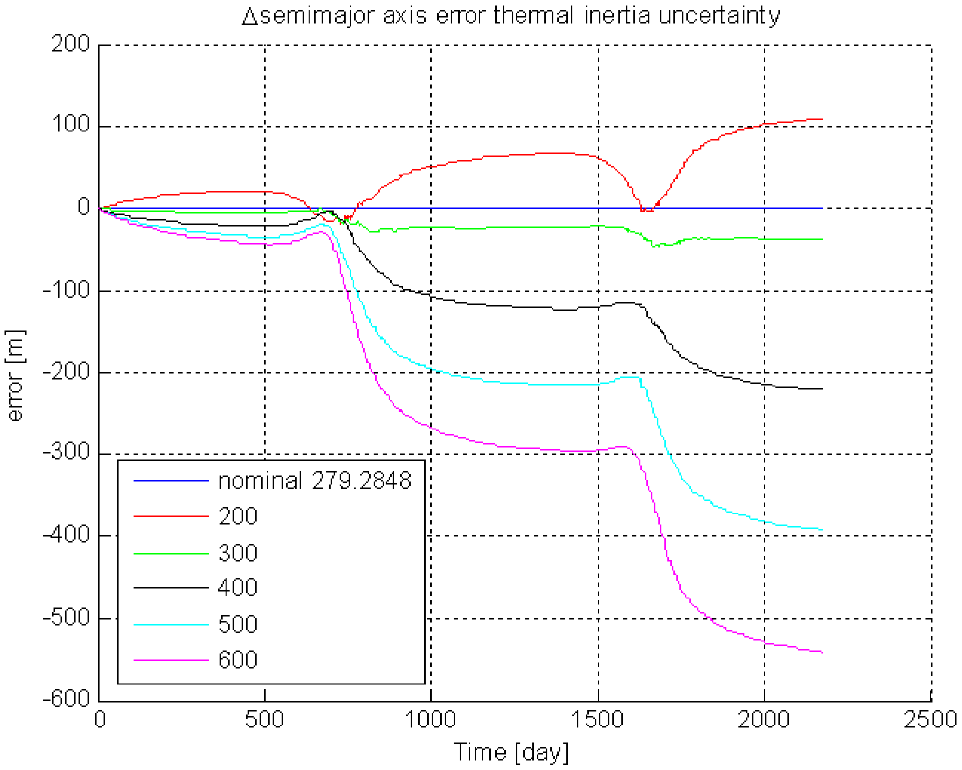


Figura 3.39: Error Thermal Inertia uncertainty.

$$\bar{\ddot{r}} = -C_r \cdot \frac{A}{m} \cdot \frac{\Phi}{c} \cdot \frac{\bar{r}}{\|\bar{r}\|}$$

The used parameters are:

- CR = 1, is the solar radiation pressure coefficient;
- A is the effective 2002AT4 asteroid cross section for solar radiation pressure;
- m is the 2002AT4 asteroid mass;
- Φ is the solar constant at the distance of the 2002AT4 asteroid;
- c = 3*108 m/s, is the speed of light;
- $\bar{r}$ is the Sun-2002AT4 asteroid vector.

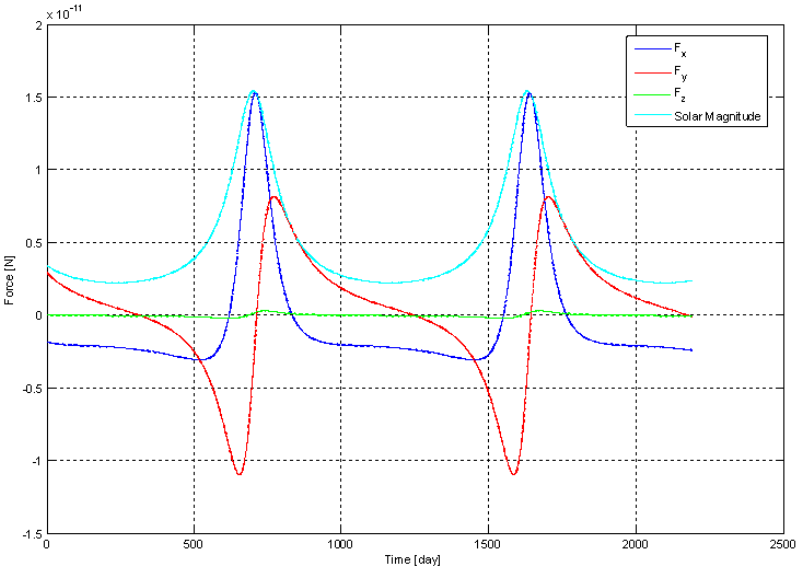


Figura 3.40: Solar Radiation force on 2002AT4.

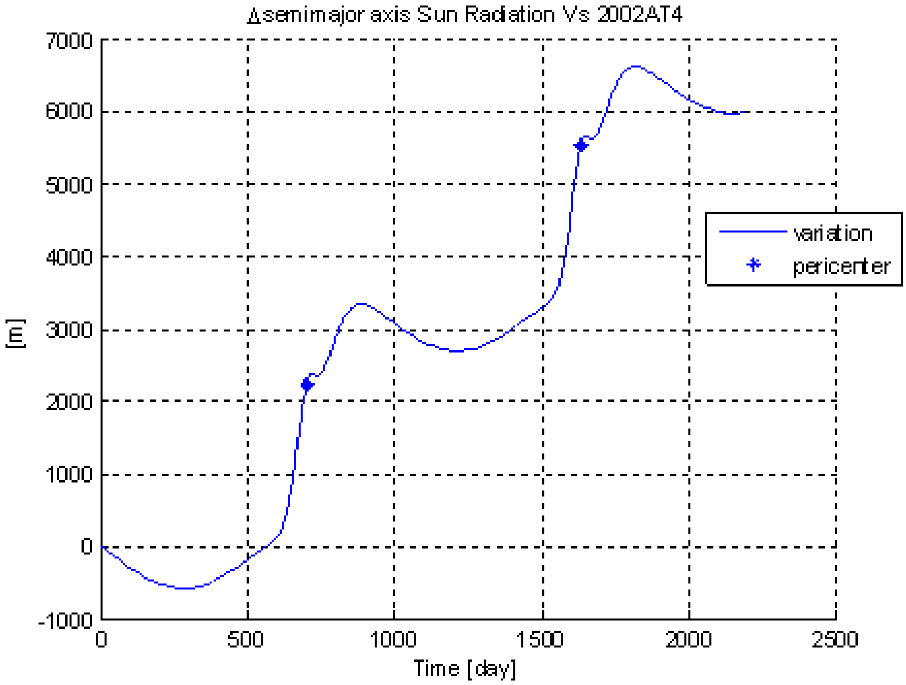


Figura 3.41: Semimajor Axis induced by Solar Radiation on 2002AT4.

Instead it can be seen that there is a variation during an orbital period. This discrepancy is due to the non-circular 2002AT4 orbit. It means that the Sun pressure acceleration upon the asteroid varies in order of $1/r^2$.

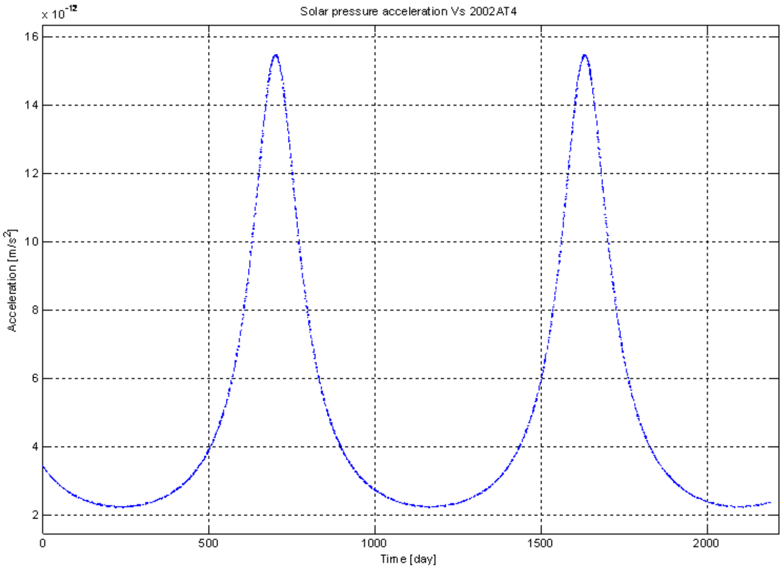


Figura 3.42: Solar pressure acceleration 2002AT4.

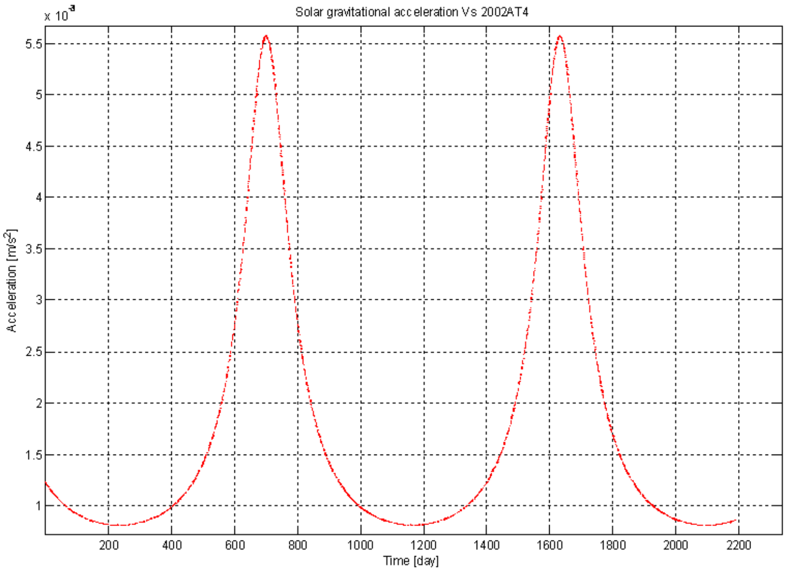


Figura 3.43: Solar gravitational acceleration on 2002AT4.

Capitolo 4

Models validation for RSE

4.1 Sun-Synchronous Terminator Orbits

On a sun-synchronous terminator orbit (also known as dusk-dawn orbit), the sun direction is nor-mal to the orbit plane. Then, the forces induced by SRP and solar gravity also are normal to the orbit plane and approximately even out during one orbital revolution. Thus, theoretically, a terminator orbit is the most stable kind of orbit around a small body in the presence of perturbations. The problem is how to maintain a terminator-type configuration over an extended period of time. The Sun direction changes as the asteroid moves along its orbit. Oblateness effects typically are of no use in this case, unlike for a planetary orbit. Numerical analysis has shown that SRP actually helps here. For a wide range of cross-section-to-mass ratios, the effect of continuous SRP forces on an orbit that is initially perpendicular to the sun direction, was seen to result in a rotation of the orbit plane such that near-terminator conditions are maintained even for prolonged periods. In other words, SRP forces maintain a sun-synchronous orbit.

4.2 Operations Around 1989 ML

With a diameter of approximately 650 m and an assumed mass of around 1.78E11 kg, 10302 / 1989 ML, though large compared to other regarded targets, is smaller than , e.g., 433 / Eros by more than an order of magnitude in dimensions, and more than three orders of magnitude in mass.

4.2.1 SELF-STABILIZING TERMINATOR ORBITS

Figure 41 shows the evolutions of radius and solar aspect angle over a period of 180 days. Even without thruster control interactions, the altitude remains in the range between 2.1 and 2.9 km. For a radius of 2.5 km, the period is 65 h and the orbital velocity 6.7 cm/s. The solar aspect angle starts out from 180° (a value of 180° or 0° indicates a terminator orbit) and remains in the vicinity of the value, never straying by more than 10°, as the orbit plane is rotated in the right direction by natural forces. Figure 42 illustrates this interesting effect. The 3D-projection of the orbit around the asteroid (whose rotation is not shown here) shows that the orbit plane undergoes a significant rotation and maintains its orientation with respect to the Sun.

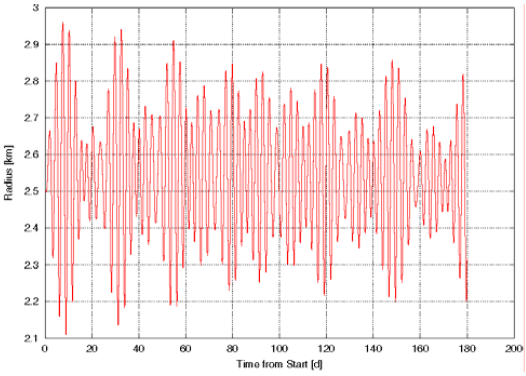


Figura 4.1: Terminator orbit radius around 1989ML.

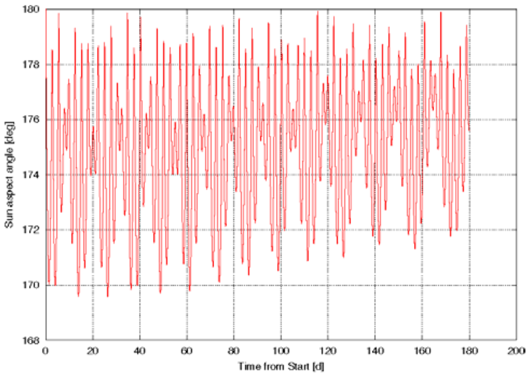


Figura 4.2: Solar aspect angle around 1989ML.

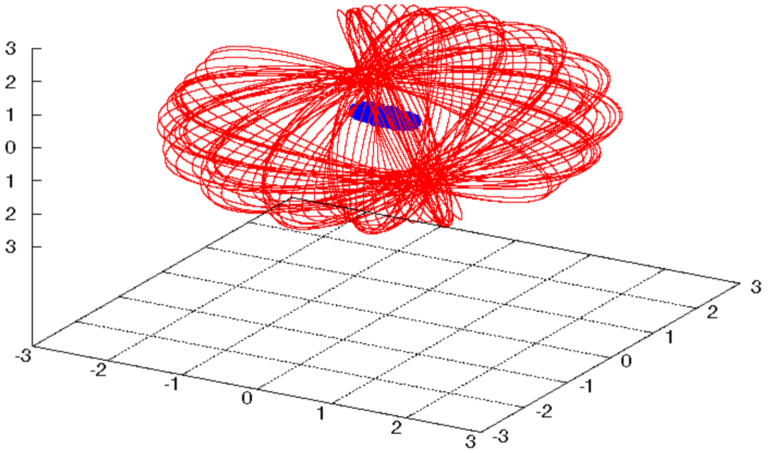


Figura 4.3: Evolution orbit in 180 days.

4.2.2 ACTIVELY MAINTAINED ORBITS

As shown in the preceding section, cases can be found where a perturbed orbit around a small asteroid naturally remains within given altitude deadbands. This of course requires a special orbital configuration. In other cases, the orbits have to be actively controlled with thruster maneuvers to preclude impact or escape. Numerical analysis showed that a very simple control scheme was applicable, where altitude deadbands are defined. To maintain the orbit, it suffices to apply radial thruster maneuvers. If the upper deadband is transgressed, the applied thrust direction is inward, if the lower deadband is transgressed, the thrust must be outward. This scheme, which was verified by numerical simulation, requires no prediction of the orbital state and relies solely on measurements of the radius or altitude, which can be obtained via Radar or Lidar. Therefore, the strategy is robust and appropriate for autonomous operations. The cost of control depends on the spacecraft orbital conditions, the current distance from the sun, the properties of the central body, and also the characteristics of the spacecraft, especially its mass and solar array area. In a series of parametric simulations, a stationkeeping cost in the order of several (at most 3) m/s/month was observed. The control cost may rise somewhat for very close orbits; it will lessen at larger distances.

Typical maneuver sizes are in the order of 0.4 mm/s. In the simulation, it was assumed that long control sequences with small burns every few minutes occur. Assuming SEP, this would lead to an acceleration of 8*10-6 m/s2. For a 650 kg spacecraft, this would require a thrust level of 5 mN, which is easily consistent with the regarded engine types. It should be pointed out that non-terminator orbits can lead to passes through the asteroid shadow cone. Due to the low orbital velocity of typically less than 10 cm/s, such eclipses could easily last several hours.

4.3 Operations around 2002 AT_4

2002 AT_4 is only half as large as 1989 ML in dimension, its mass, with 2E10 kg, is around one eighth. Numerical simulations were performed to ascertain that the findings summarized in Section 9.3 also hold for orbits around such a small body. Also here, the results prove the feasibility of maintenance-free, self-stabilizing sun-synchronous terminator orbits within a range of orbital radii of around 1 km, considerably less than the 2.5 km assumed for orbits around 1989 ML. The orbital period for 1 km radius is 44 hours and the orbital velocity 4 cm/s. On a terminator orbit, there will be no passes through the asteroid's shadow. Figure 43 summarizes some results of the numerical orbit simulations. Starting out from an orbit insertion in mid-November 2016, the propagation covers one year and therefore extends almost half a year beyond the foreseen impact date. In the regarded time frame, natural perturbations lead to radius variations between 900 and 1150 m, which should be safe. The sun aspect angle drifts to around 12° and then decreases again. This induces neither excessive radius oscillations nor eclipse passes. The Earth aspect angle rises to around 45°, which helps the Doppler observation of the spacecraft orbit.

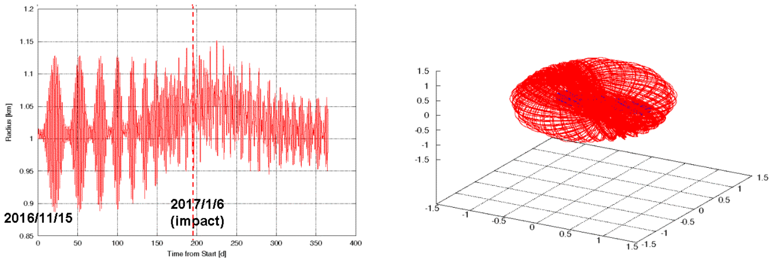


Figura 4.4: Terminator orbit radius around 2002at4 and 3D evolution orbit in 180 days.

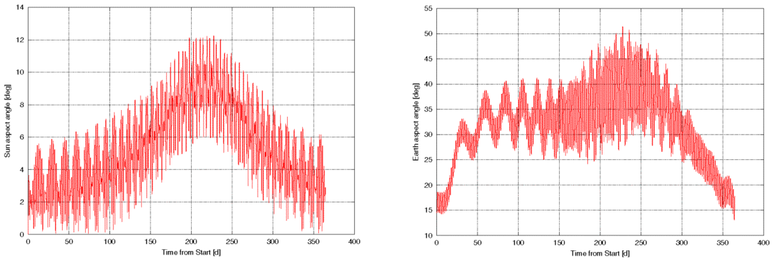


Figura 4.5: Sun aspect angle and Earth aspect angle.

4.4 Optimal conditions for the RSE

In the following charts you can see the period of better measurement condition as a function of the sun synchronous orbit, with orbit normal aligned with sun direction (terminator dawn dusk orbit), with orbit normal forming an angle of 30, 60 and 90 with sun direction (the latter noon midnight). The best condition for the measure is when the angle is 0. An impact in these periods will be measured the best possible. The run has been started at 01 01 2013 up to 01 01 2019.

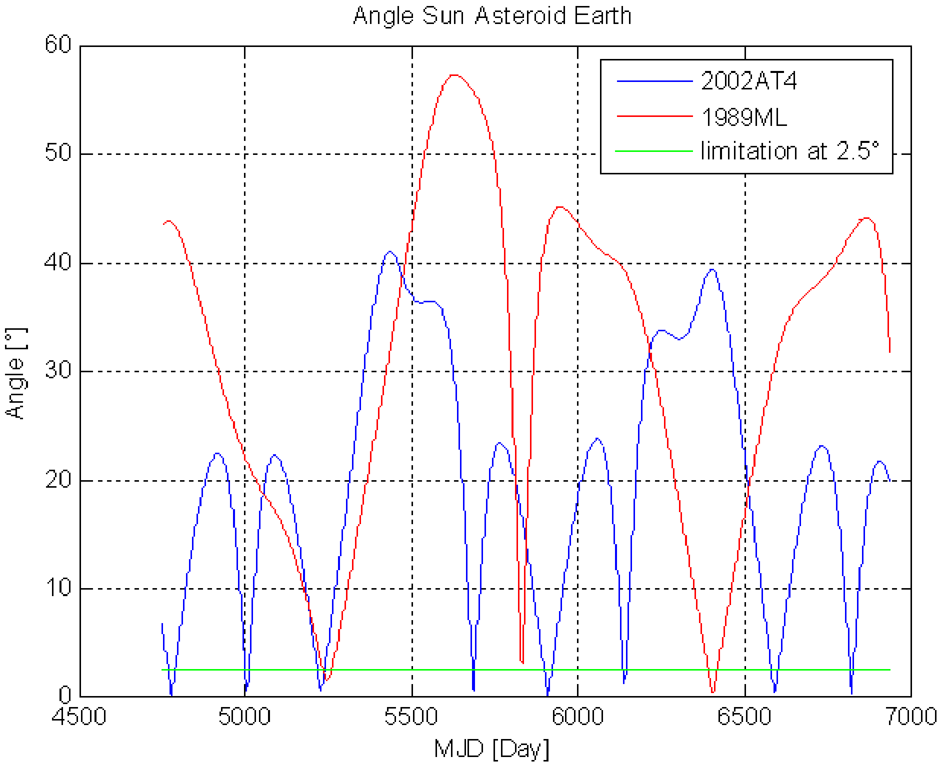


Figura 4.6: Angle Sun-Asteroid-Earth.

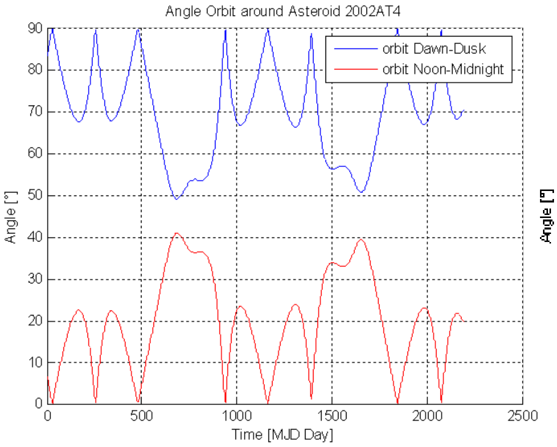


Figura 4.7: Angle orbit around 2002 AT_4 asteroid with 90 degree.

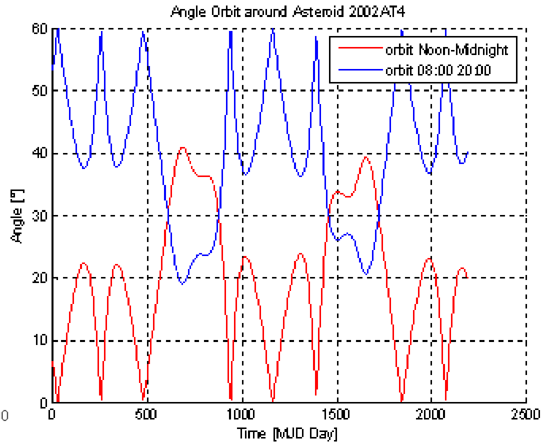


Figura 4.8: Angle orbit around 2002 AT_4 asteroid with 60 degree.

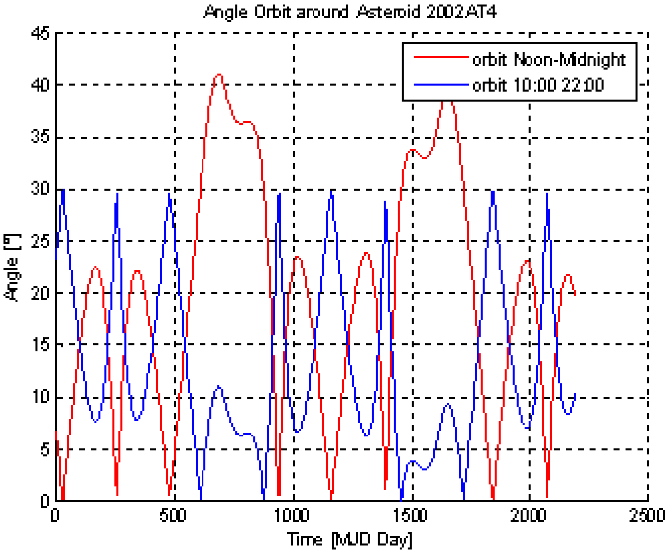


Figura 4.9: Angle orbit around 2002 AT_4 asteroid with 30 degree.

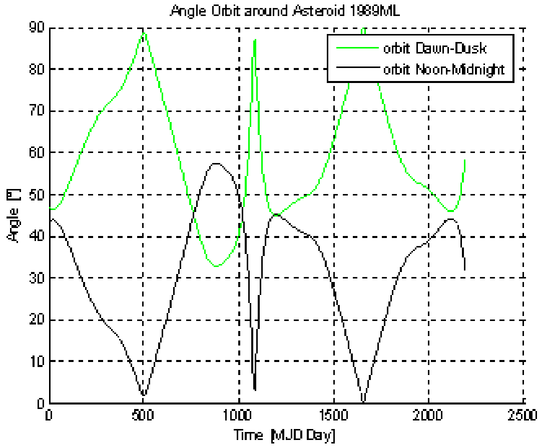


Figura 4.10: Angle orbit around 1989 ML asteroid with 90 degree.

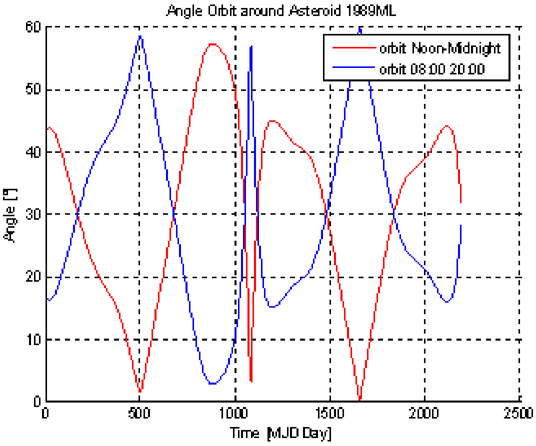


Figura 4.11: Angle orbit around 1989 ML asteroid with 60 degree.

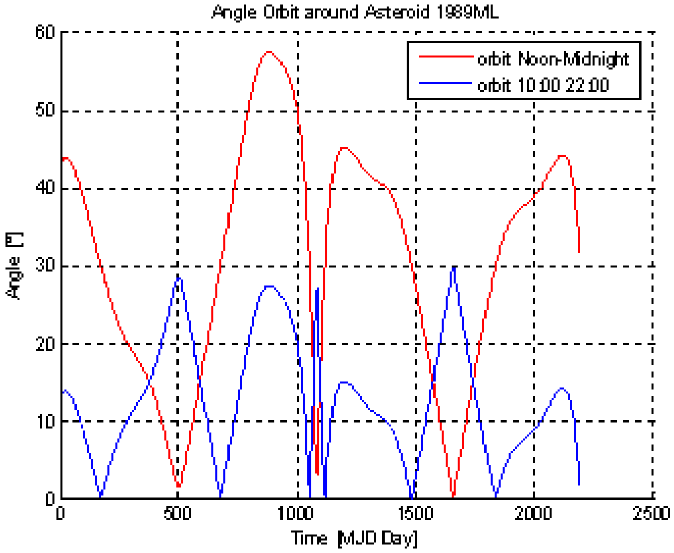


Figura 4.12: Angle orbit around 1989 ML asteroid with 30 degree.

Capitolo 5

Conclusion and Next Step

As shown in this paper, the analysis deployment models have lead to very complex. Complete simulations with all the noise modeled with the following types of orbits.

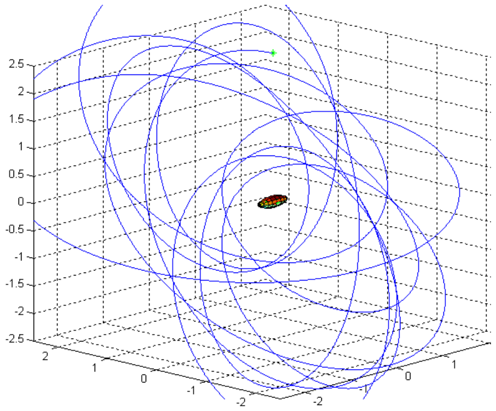


Figura 5.1: 3 km terminator active orbit waiting impactor Hidalgo.

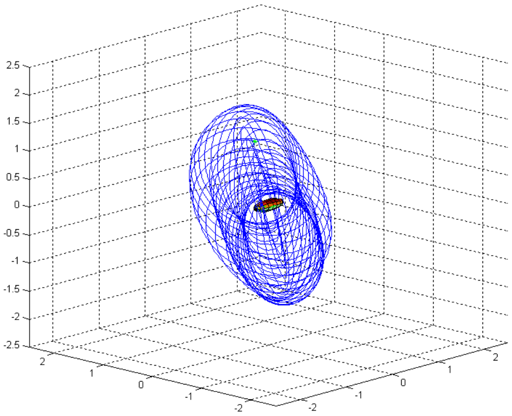


Figura 5.2: Active terminator orbit normal maintenance.

As you can see, the orbits are very irregular without any control type active.

The next steps will be as follows:

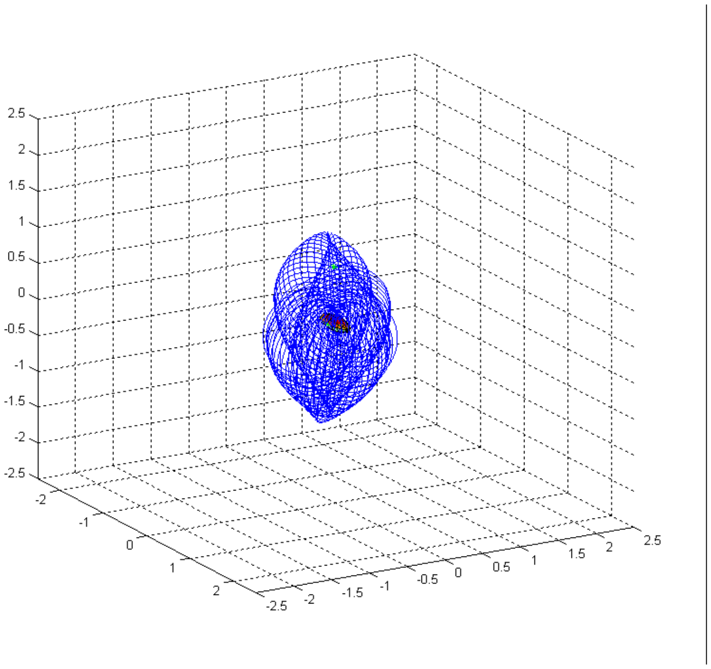


Figura 5.3: Near Active Terminator orbit during topography seismic experiment.

- Model a simulator control to optimize and stabilize the orbits around asteroid;
- simulation to estimate the impulse to give the satellite to escape and reverting later during the impact of Hidalgo;
- Estimate a timelife of Sancho around the asteroid;

In conclusion, has been chosen the 2002AT4 asteroid as optimal, more similar with the structure of the 2004MN4, also called Apophis.

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