PRIMA
Precursor Rendezvous for Impact Mitigation of Asteroids
Summary of the Group Design Project
MSc in Astronautics and Space Engineering 2006/07
Cranfield University

College of Aeronautics Report 0703

ISBN 978-1-86194-130-5

Dr. Stephen Hobbs
Cranfield Space Research Centre
School of Engineering
Cranfield University
Cranfield
Bedford MK43 0AL UK
s.e.hobbs@cranfield.ac.uk

10 September 2007

Abstract

Students of the MSc course in Astronautics and Space Engineering 2006/07 at Cranfield University took the Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA) mission as one of their group projects. This report summarises their findings.

Asteroid impacts have shaped Earth's development in the past and they will continue to do so in the future. Large asteroid impacts are acts of nature beyond our ability to mitigate, but the much more frequent impacts with continental rather than global scale can now be prevented in many cases. Effective impact prevention depends on good knowledge of the asteroid threat: the PRIMA mission's goal is to obtain enough information about an asteroid's orbit and composition to enable impact prevention.

This PRIMA study's objective is a feasible mission design. The asteroid Apophis was chosen as the prime target because it is representative of the most likely impact risk and it is also the highest current asteroid threat to Earth. To develop the baseline design the team initially identified a range of mission concepts and then chose the best of these using a trade-off based on the concepts' various attributes. The next phase was to develop outline designs for each sub-system, focussing on issues which could affect mission feasibility. The resulting baseline design consists of a 600 kg spacecraft with electric propulsion and a lander containing a tracking beacon which is placed on Apophis. Asteroid composition is measured by radar and seismometry.

All results so far indicate that this concept is feasible, although further work is required especially in the areas of low-thrust trajectories for asteroid rendezvous, and technologies for the tracking transponder, measuring asteroid composition, and attaching equipment to an asteroid where gravity is weak and surface composition is uncertain.

ISBN 978-1-86194-130-5

This report is available electronically from Cranfield University's QUEprints service (`https://dspace.lib.cranfield.ac.uk/`).

Acknowledgements

The project is very much a team effort, and contributions from all those involved are much appreciated.

First of all, the work presented is primarily that of the MSc students (Sandy Bradley, Marie Campana, David de Muynck, Rachel Hayward, Gordon Mack, Simon Meik, Gunish Sharma, Jules Spencer-Jones), who each have contributed about 600 hours.

As well as these students, the project draws on inputs from Celine Ong, Wil Dube, Omais Javed and Bolanle Oluwa. The inspiration for the project came from Tom Bowling and Prof. John Junkins (Texas A & M, USA). Other members of staff in Cranfield's Space Research Centre and contacts in the space industry have often helped students by responding to queries or providing technical information: this encouragement is greatly appreciated.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Earth faces many potentially catastrophic natural hazards - earthquakes, volcanoes, extreme weather, tsunami, asteroid impact. Of these there is only one which we now have the technology to predict and to prevent: asteroid impact.

During Earth's history, asteroids have frequently collided with Earth - sometimes reshaping the whole history of life on the planet. Bryson (2003) tells the story of what we now know of the extinction of the dinosaurs. For more recent events, 2008 will be the centenary of the Tunguska impact. This was due to a "small" asteroid which still managed to flatten forests in Siberia across an area of 2000 km^2 and had an equivalent explosive energy of 20 megatonnes. Events like these are rare, but when they do occur their destructive potential is such that the probability of being killed by an asteroid has been estimated to be the same as that of dying in an aircraft accident (Atkinson, Tickell and Williams, 2000), i.e. although they may be very infrequent, when an asteroid does strike it has the potential to kill a large proportion of humankind. From our knowledge of the solar system we now appreciate that the issue is not *whether* there will be asteroid threats in the future, but rather *when*. Figures 1.1 and 1.2 show the sizes and numbers of typical Near Earth Objects (NEOs), and the historical impact rate.

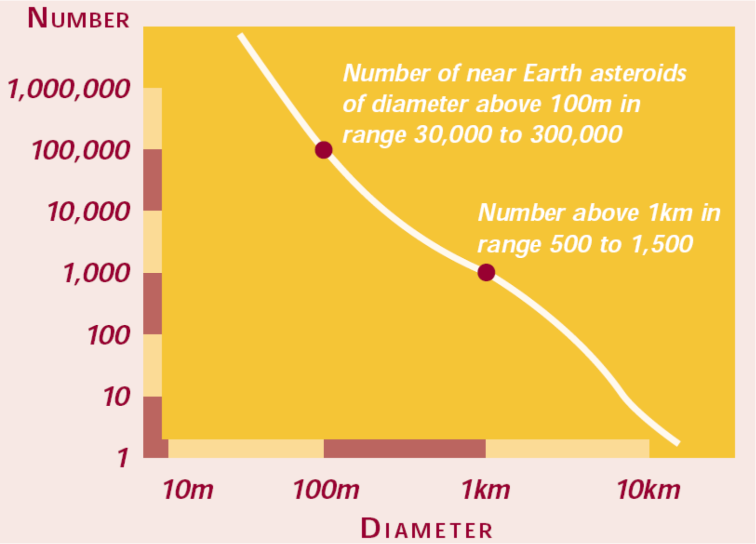


Figure 1.1: Approximate size distribution of Near Earth Asteroids (Atkinson, Tickell and Williams, 2000).

There is a developing international effort to build the infrastructure needed to detect and track threatening asteroids, and also to develop technology to mitigate threats when they are detected. Most of this work is led by the science community although the mitigation task requires expertise from many engineering disciplines too. A recent ESA study of asteroid deflection missions resulted

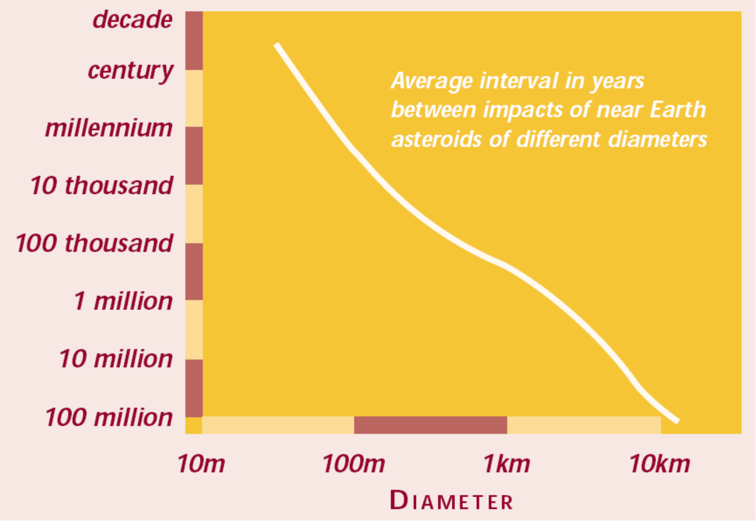


Figure 1.2: Average interval in years between impacts for different asteroid sizes (Atkinson, Tickell and Williams, 2000). Asteroids larger than roughly 50 m can cause significant damage (e.g. Tunguska event or worse).

in the Don Quixote mission proposal. Several other recent studies have been published on various aspects of asteroid interception, such as Izzo (2007) who considers optimization of trajectories for asteroid deflection and Davis, Singla and Junkins (2006) who discuss the "keyhole" concept for identifying possible asteroid collisions. The PRIMA MSc group project focusses on mitigation, and has the goal of developing a precursor mission to demonstrate relevant technology.

1.1 Space Technology

Mankind's first space mission was 50 years ago, and only in the last few decades have we been able to contemplate protecting Earth from asteroids. It may be that the greatest service of the space industry to mankind will be that one day its expertise is able to save Earth from a major asteroid impact.

1.2 MSc Group Project

Each year, students of the MSc in Astronautics and Space Engineering are given a current topic in the space industry as the theme for their group project. The project runs from October to the end of March. One of the projects for the year 2006/07 was an asteroid impact mitigation mission precursor. This is a concept which has been discussed several times (e.g. Norris, 30 March 2004) and is also being studied by ESA (Harris et al., July 2004). The project's title was Precursor Rendezvous and Impact Mitigation for Asteroids (PRIMA).

1.2.1 Organisation of the Project

The project runs over the first two terms (October to Easter) of the year long MSc course in Astronautics and Space Engineering at Cranfield University. The students work as one team, organised as several subgroups, and each student contributes about 600 hours' effort to the project; the total resource represented by the project is approximately 6000 hours' work (or 3–4 man-years) for the academic year 2006/07.

Students are given responsibility for all technical aspects of the mission and over the 6 months of the project are required to develop a credible baseline mission. There are formal weekly progress meetings which staff supervisors attend, and two key milestones. The first is a "PDR" presentation in early December and the second is the more formal "CDR" in late March. The project runs in a similar manner to many industry projects and is intended to teach both technical and transferable skills to students. The PRIMA project had the added challenge / realism of changes in personnel through the project: it is to the team's great credit that despite this they have continued to work well and developed a stimulating, credible mission concept.

Table 1.1 lists the students involved in the project and their technical responsibilities.

Table 1.1: PRIMA work package breakdown and allocation. The references are to the students' individual reports documenting their technical contributions.

Description	Student(s)
System engineering	Sandy Bradley (Bradley, 2007) Rachel Hayward (Hayward, 2007)
Payload	Gordon Mack (Mack, 2007)
Mitigation mission	Gunish Sharma (Sharma, 2007)
Mitigation options	Simon Meik, Gunish Sharma
Operations	Simon Meik (Meik, 2007)
Structure & Thermal	Marie Campana (Campana, 2007)
Electrical	David de Muynck (Muynck, 2007)
Orbits / AOCS	Jules Spencer-Jones (Spencer-Jones, 2007)

The whole team met weekly to share progress and make key decisions about the mission design. Students in each of the sub-groups also met between the main meetings as they worked on their individual responsibilities - with the system engineers working hard to coordinate all the separate tasks.

1.2.2 The PRIMA mission

The PRIMA mission's objective was to obtain all the information required about a potentially hazardous asteroid so that a later impact mitigation mission would have a high chance of success. When a potential threat is first detected we typically have only approximate information about the asteroid's orbital elements, mass, spin rate, composition and structure. Good knowledge of these parameters is needed for effective asteroid deflection. Therefore a precursor mission to provide this information could be very valuable.

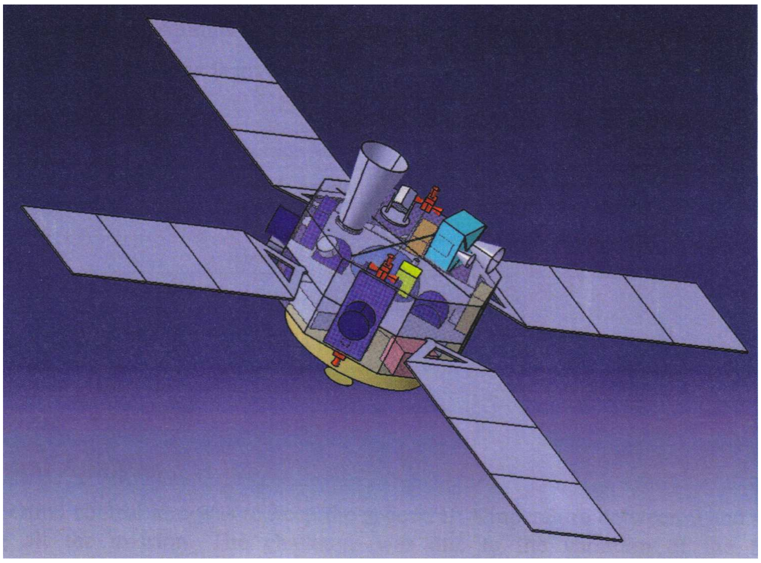


Figure 1.3: Configuration of the proposed PRIMA spacecraft during the transfer orbit from Earth to Apophis (Campana, 2007).

The mission concept was developed around a rendezvous with the asteroid currently thought to be Earth's highest collision threat: Apophis (Davis, Singla and Junkins, 2006). After rendezvous the satellite will orbit to obtain high resolution images. A small lander is then deployed to study the asteroid's internal structure by a combination of radar tomography and seismology. The final phase involves the orbiter itself landing and using its ion engine acting over several weeks to change the asteroid's spin rate by a detectable amount. This will demonstrate the capability of the propulsion system to provide enough thrust to deflect the asteroid without any risk that the experiment could increase the collision risk with Earth.

(For impact mitigation, the time available has a huge impact on the choice of technologies. For an asteroid like Apophis which makes repeated close approaches to Earth, a tiny ΔV early enough (e.g. prior to a "safe" close approach) can have enough effect to make subsequent close approaches well outside any danger zone. For Apophis the magnitude of this early ΔV is less than 10^{-6} m s^{-1} which is feasible with technologies much safer than nuclear weapons.)

The lander incorporates a transponder which will continue to operate for a few decades and allow Apophis' orbit to be tracked accurately so that collision risks can be assessed well into the future. PRIMA is designed to be suitable for precursor missions to a wide range of near Earth objects. There will be science benefits too from such a mission, but if ever such a mission is required in earnest, space agencies will have more than justified all the investment over the last 50 years.

1.3 Organisation of this report

This report is a summary of the project, and is based on the reports written by students describing their individual project responsibilities. The full reports are available from the School of Engineering, Cranfield University, and are summarised in Appendix B. *Readers should note that although gross errors in the individual reports should have been corrected, minor inconsistencies may remain in the detailed technical work presented.*

Following this Introduction, Chapter 2 gives an overview of the technical work performed by the students and summarises their findings (e.g. tables for the mass, power, cost and propulsion budgets). This chapter also serves as an overview of the constraints the design had to meet. Chapter 3 is a brief discussion of the the project's findings with some suggestions for further work. The main content of the report is Appendix B where Executive Summaries from the students' reports are presented.

Chapter 2

PRIMA Technical Summary

A very brief summary of the mission design is given here. More detail is available from individual reports written by each student on their sub-system responsibility (see the reference list for details). The mission is composed of several elements:

1. The main spacecraft which orbits the asteroid after rendezvous. (This spacecraft itself also lands on the asteroid at the end of the mission.)
2. A lander which separates from the orbiter on arrival at the asteroid and which is used to investigate the asteroid's structure as well as to provide a transponder to allow more accurate tracking of the asteroid in the future.
3. Small seismology probes and explosive charges which are deployed from the main spacecraft / orbiter and which work in collaboration with the lander.

Figure 2.1 and Table 2.1 summarise the different mission phases and the ways the three mission elements are used.

Table 2.1: Summary of the main PRIMA mission phases.

Mission phase		Events
1	Launch	Soyuz launch direct into the transfer orbit.
2	Transfer	Transfer orbit from Earth to the asteroid (Apophis). The electric propulsion provides a continual braking thrust calculated to achieve rendezvous.
3	Rendezvous	Establish the orbiter in a reasonably stable orbit about the asteroid with a period of approximately 24 hr.
4	Imaging	Initial orbit phase: imaging of the surface and calculation of the asteroid's gravity field.
5	Lander deployment	Deploy the lander to a chosen site on the asteroid where it will act as (1) the receiver for the radio transmission tomography experiment, then (2) one of the seismology experiment stations, and finally (3) the transponder to allow Apophis to be tracked accurately in the future.
6	Probe deployment	Once the tomography is complete, seismometer probes will be deployed to chosen locations and then a series of explosive charges will be used to generate shock waves to study the asteroid's internal structure.
7	Mitigation demonstration	The orbiter itself lands and uses its ion engine to demonstrate safely a potential orbit-change ΔV by slightly de-spinning the asteroid.

2.1 Background topics

It is useful to quantify basic asteroid parameters to understand much of the mission design developed. These sections describe simple orbits about an asteroid and the principles of the experiment to change an asteroid's spin rate.

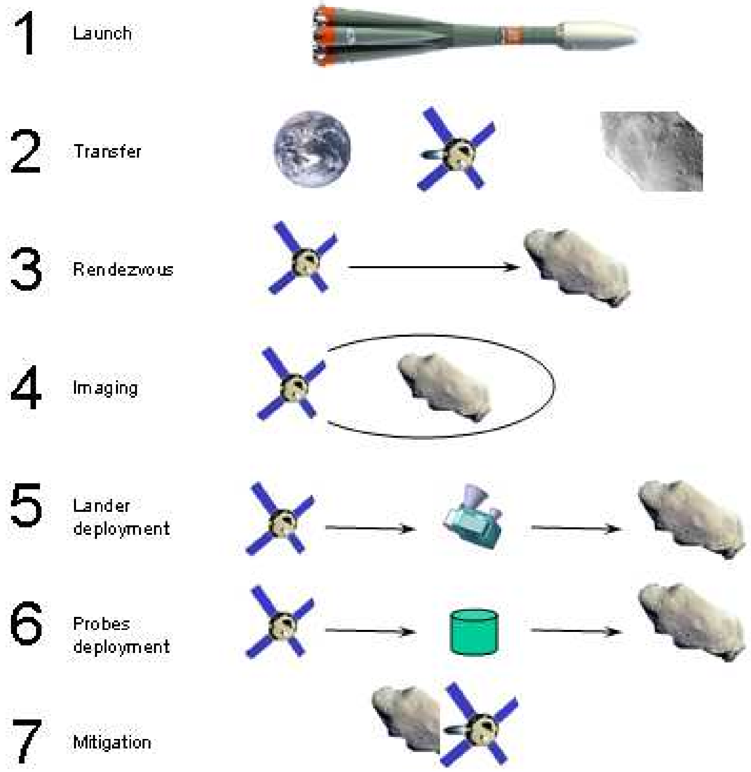


Figure 2.1: Overview of the main PRIMA mission phases (courtesy of David de Muynck).

2.1.1 Orbits around an asteroid

Asteroids are tiny compared to planets and orbiting an asteroid involves much lower speeds than "conventional" orbits. Of the following equations, Equations 2.2 and 2.3 are from Thomson (1986) and 2.4 is from Fortescue, Stark and Swinerd (2003, Eq. 5.34)

$$F = \frac{GmM}{r^2} \tag{2.1}$$

$$v_{circular} = \sqrt{\frac{\mu}{r}} \tag{2.2}$$

$$v_{escape} = \sqrt{2}v_{circular} \tag{2.3}$$

$$R_{SI} = r_d \left(\frac{m_p}{m_d}\right)^{\frac{2}{5}} \tag{2.4}$$

$$\omega = \frac{v}{r} \tag{2.5}$$

$$T = \frac{2\pi}{\omega} = \frac{2\pi r}{v} = 2\pi\sqrt{\frac{r^3}{\mu}} \tag{2.6}$$

For Apophis (mass = 2.1 x 10^{10} kg, radius = 150 m; G = 6.673 x 10^{-11} N m^2 kg^{-2}), these equations give $v_{circular}$ = 10 cm s^{-1} (at the asteroid's surface), and thus escape velocity from the surface is only 14 cm s^{-1} from the surface. The acceleration due to gravity at the surface is $g_{Apophis}$ = 6.2 x 10^{-5} m s^{-2} = 0.062 mm s^{-2}. Since solar radiation pressure (SRP) at 1 AU from the Sun is 4.5 x 10^{-6} N m^{-2} (ignoring a factor of magnitude approximately equal to 1 depending on the surface's optical properties), a small lander with mass to area ratio of 10 kg m^{-2} will have an acceleration due to SRP at 1 AU of 4.5 x 10^{-7} m s^{-2}, i.e. about 1% of that due to the asteroid's gravity at the surface.

The sphere of influence for Apophis using $m_d = m_{Sun} = 1.989 \text{ x } 10^{30}$ kg, $r_d = 1$ AU = $1.496 \text{ x } 10^{11}$ m, and $m_p = m_{Apophis}$ is $R_{SI} = 1530$ m. Since gravitational force decays as $1/r^2$, accelerations due to asteroid gravity and SRP are approximately equal for an object with a low mass to area ratio at a distance of 10 asteroid radii (1500 m), which is very close to R_{SI}.

To obtain an orbital period of 24 hr, the orbit height above Apophis has to be 642 m, and at this height the orbital speed and escape velocity are 4.7 cm s^{-1} and 6.6 cm s^{-1} respectively.

Assuming a rotation period of 16 hr, the angular velocity is $2\,\pi$ / (16 x 3600) = $1.09 \text{ x } 10^{-4}$ rad s^{-1}, and the tangential surface speed is 1.6 cm s^{-1}.

These values are approximate since we only have approximate values for the size and mass of Apophis, but they do illustrate the scale of the orbits feasible around an asteroid.

2.1.2 Asteroid de-spin experiment

The final task of the orbiter is an experiment to use the ion engine to change the spin rate of Apophis by a measurable amount. If successful this will demonstrate the ability to land a spacecraft in a controlled attitude on a low-gravity body and for electric propulsion to provide sufficient impulse to change an asteroid's orbit. The great advantages of de-spinning the asteroid are that there is negligible risk of making any change to the asteroid's orbit which could increase its probability of a collision with Earth, and that spin rate can be measured relatively accurately and easily.

The propulsion requirement is derived from the work of Kahle, Hahne and Kuhrt (2006) who suggest that a ΔV of only 10^{-6} m s^{-1} is required to deflect an asteroid such as Apophis if this is applied early enough.

For an ion engine of thrust T acting for time t, the change in velocity for an asteroid of mass m_a is

$$\Delta v = \frac{Tt}{m_a} \tag{2.7}$$

If this thrust is applied at radius r from the asteroid's spin axis (moment of inertia I_a), this creates a torque τ which changes the angular velocity:

$$\begin{aligned} \Delta\omega &= \frac{\tau t}{I_a} && (2.8) \\ &= \frac{Trt}{0.4 m_a r^2} && (2.9) \\ &= \frac{Tt}{0.4 m_a r} && (2.10) \end{aligned}$$

since

$$I_a = \frac{2 m_a r^2}{5} \tag{2.11}$$

The ΔV of the asteroid can then be expressed in terms of the change in angular velocity as

$$\begin{aligned} \Delta\omega &= \frac{\Delta v m_a}{0.4 m_a r} && (2.12) \\ \Delta v &= 0.4 r \Delta\omega && (2.13) \end{aligned}$$

For the PRIMA mission, typical values are $T = 0.1$ N, $r = 150$ m, and $m_a = 2.1 \text{ x } 10^{10}$ kg. This gives $\Delta\omega/t = 1.43 \text{ x } 10^{-10}$ rad s^{-1} day^{-1}, which is 1.3 ppm of the natural spin rate per day (allowing a total thrust duration per day of 1800 s). After a few days the change in spin rate should be easily measurable.

To achieve a ΔV of 10^{-6} m s^{-1} with Apophis, the ion engine will need to thrust for about 58 hr continuously. This is a surprisingly modest requirement for the engine.

To avoid changing the asteroid's orbit, it is important that only a torque is applied and that there is no net thrust. This requires that the thrust is applied in a plane perpendicular to the asteroid's spin axis, since the asteroid's spin does not cancel out any net thrust parallel to the spin axis. Figure 2.2 shows how a thrust offset from the centre of mass is equivalent to a couple plus a force through the centre of mass. For there to be no net thrust on the asteroid it is important also

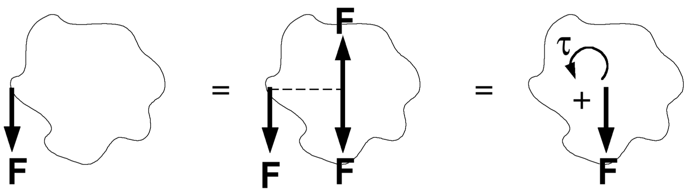


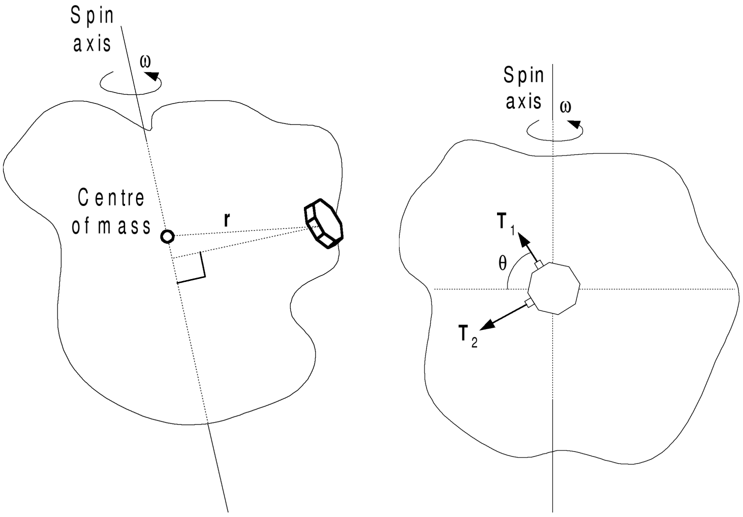
Figure 2.2: A single thrust applied away from the centre of mass is equivalent to a thrust through the centre of mass plus a torque.

that the thrusts are phased symmetrically around the asteroid's axis of rotation, e.g. use pairs of thrusts half a rotation period apart.

Figure 2.3(b) shows how the thrusts of the two engines can be adjusted to align the resultant perpendicular to the spin axis. This requires

$$T_1 \sin\theta = T_2 \cos\theta \tag{2.14}$$

$$T_2 = T_1 \tan\theta \tag{2.15}$$



(a) General view of the PRIMA orbiter on an asteroid.

(b) Side view of PRIMA orbiter on asteroid. The two ion engines' thrusts are used to ensure the resultant lies in the plane perpendicular to the spin axis.

Figure 2.3: Illustration of the principles of the experiment to change the spin rate of an asteroid

Hence, two ion engines on PRIMA's orbiter not only provide redundancy during the transfer orbit but also allow the thrust direction to be varied over a sector $\pi/2$ rad in size which significantly simplifies the orientation requirement for its landing on Apophis.

2.1.3 Final rendezvous with asteroid

Useful estimates of the timescales and corresponding ranges for the final stages of PRIMA's approach to Apophis can be obtained using simple models of the motion. Rendezvous missions tend to approach their target obliquely so that the target moves relative to the background stars, and therefore is more easily detected. For these initial calculations however a direct approach is assumed: the results are still relevant to sizing the key ranges and timescales.

The main assumptions are that the propulsion system provides a thrust of 0.1 N and that the spacecraft mass is 600 kg. The acceleration possible is thus up to 0.17 mm s^{-1}.

With this acceleration, the final 10 000 km of the rendezvous will take $t = \sqrt{\frac{2s}{a}} = 3.46 \text{ x } 10^5$ s = 4.0 day. At the start of this period, the spacecraft's speed relative to the asteroid is 57.8 m s^{-1}. Similarly, the final 10 km takes 3.04 hr, and the speed at the start of this period is 1.8 m s^{-1}. A high thrust propulsion system capable of these ΔV would be able to accomplish these manoeuvres in much shorter times.

These times are important because of how they affect the operations. Tasks which have timescales too short for control from Earth or which occur when there is no communication link must be autonomous.

2.2 Mission baseline overview

Rather than duplicate work in the students' reports, a few key points are highlighted here to give a clear understanding of PRIMA. One of the first steps was to identify a target asteroid. Although many aspects of the design are suitable for a generic NEO it helped the design to have a definite target in mind. The target asteroid is Apophis, chosen for several reasons:

- It has been identified as currently the most threatening asteroid.
- Its size and orbit are typical of the most likely asteroids to pose a significant risk to Earth. Larger asteroids would be more dangerous but are much less frequent.
- Apophis is due to pass close to Earth in the next decade so that a rendezvous mission is feasible in the short / medium-term.

Figure 2.4 shows the orbits of Earth and Apophis and an impulsive trajectory which provides a relatively low-energy transfer between them. For PRIMA it is proposed to use a more efficient ion engine propulsion system, but the general shape of the transfer orbit will be similar.

The general configuration of the spacecraft is shown in Figure 1.3. The orbiter is the largest element and the lander, probes and charges are all attached to the main spacecraft. The mass budget is given in Table 2.2, and the contributions to the structure mass are listed in Table 2.3. The total mass including a 20% margin is 675 kg.

Table 2.2: Mass breakdown for the PRIMA mission elements (total mass = 675 kg including a 20% margin) (Campana, 2007).

Subsystem	Mass / kg	Subsystem	Mass / kg
Payload	32	Thermal	14
Comms and CDH	28	Structure	94
AOCS	36	Power	88
Propulsion	218	Lander	52

Table 2.3: Structure mass budget for the main spacecraft (Campana, 2007).

	Components	Mass / kg
Orbiter	Outside panels	38.7
	Inside panels	19
	Decks	35.7
Lander	Box	5

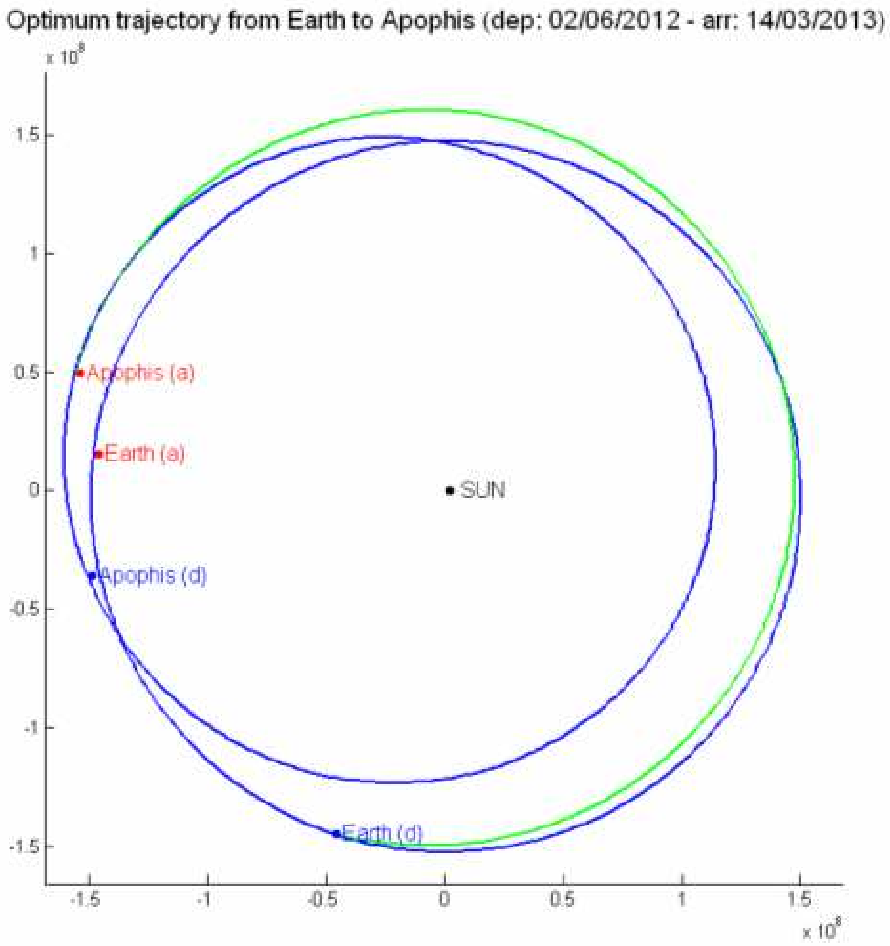


Figure 2.4: The impulsive trajectory to Apophis (Spencer-Jones, 2007).

Chapter 3

Discussion and Conclusions

The PRIMA mission concept appears feasible and affordable. It is certain that the task of asteroid impact mitigation will one day become urgent and a mission such as PRIMA could be extremely valuable. Some interesting ideas are included in the concept: for example,

- The use of 4 solar panels, with one rotation axis each, which (a) give a symmetrical configuration, (b) allow power to be raised effectively during the transfer orbit and (c) also raise power while in orbit around the asteroid when the orbiter could take any orientation relative to the Sun.
- The use of two methods (seismometry, tomography) of probing the asteroid's structure which is one of the key parameters for deciding the most appropriate mitigation method.
- The use of electric propulsion: this saves mass and also demonstrates a technology which may be able to provide enough ΔV to change an asteroid's orbit sufficiently for mitigation.

3.1 Future Work

As with any feasibility study like this, there are areas of further work where more study would usefully improve the proposal. Some of the areas where we would like to see more work include:

- Optimizing the low thrust trajectories for asteroid rendezvous and the propulsion system design.
- Navigation requirements and capabilities for such trajectories.
- Transponder technology and the precise requirements for a useful transponder. It may be possible to develop simple passive "transponders" (e.g. reflectors) which would continue useful operation beyond a few decades.
- Confirmation of the asteroid measurement principles (e.g. orbit tracking to determine gravitational parameters, internal structure) and their requirements on the mission.
- Technologies for attaching landers to low-gravity bodies with highly variable surfaces

Bibliography

Atkinson, Harry, Crispin Tickell and David Williams (2000). Report of the Task Force on potentially hazardous Near Earth Objects. Working party report. British National Space Centre.

Bradley, Alexander (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): System engineering'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Bryson, Bill (2003). *A short history of nearly everything.* Black Swan.

Campana, Marie (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): Mechanical sub-system, configuration, thermal design'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Davis, J., P. Singla and J. Junkins (2006). 'Indentifying near-term missions and impact keyholes for asteroid 99942 Apophis'. In: *Proceedings of the 7th Conference on Dynamics and Control of Systems and Structures in Space.* Cranfield University Press. 109–119.

Fortescue, P., J. Stark and G. Swinerd (2003). *Spacecraft systems engineering.* 3rd ed. Wiley.

Gritzner, Christian, et al. (2006). 'The asteroid and comet impact hazard: risk assessment and mitigation options'. In: *Naturwissenschaften* 93 (Aug. 2006). 361–373.

Harris, A.W., et al. (July 2004). The Near-Earth Object Mission Advisory Panel (NEOMAP). tech. rep. European Space Agency.

Hayward, Rachel (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): System engineering'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Izzo, Dario (2007). 'Optimization of interplanetary trajectories for impulsive and continuous asteroid deflection'. In: *Journal of Guidance, Control, and Dynamics* 30(2). 401–408.

Kahle, R., G. Hahne and E. Kuhrt (2006). 'Optimal deflection of NEOs en route of collision with the Earth'. In: *Icarus* 182.

Mack, Gordon (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): Payload'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Meik, Simon (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): Mitigation concepts; Operations'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Muynck, David de (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): Electrical power'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Norris, Guy (30 March 2004). 'Deep impact: Asteroid threat'. In: *Flight International.* 32–33.

Sharma, Gunish (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): Mitigation mission'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Spencer-Jones, Jules (2007). 'Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA): Mission analysis'. Group project report, MSc in Astronautics and Space Engineering. School of Engineering, Cranfield University.

Thomson, W.T. (1986). *Introduction to space dynamics.* Dover.

Appendix A

Organisation of the Project

The division of responsibilities of the project between the students taking part in the project is described in the following table.

Description	Student(s)
System engineering	Sandy Bradley Rachel Hayward
Payload	Gordon Mack
Mitigation mission	Gunish Sharma
Mitigation options	Simon Meik, Gunish Sharma
Operations	Simon Meik
Structure & Thermal	Marie Campana
Electrical	David de Muynck
Orbits / AOCS	Jules Spencer-Jones

Table A.1: PRIMA work package breakdown and allocation.

In addition to these students there were also contributions from Wil Dube, Omais Javed, Bolanle Oluwa and Celine Ong to the initial phase of the project.

Appendix B

Individual Report Executive Summaries

Executive summaries for all the project reports are given in this appendix. Full copies of the reports may be referred to at the School of Engineering, Cranfield University, UK.

The summaries presented here have been only lightly edited. Users of the summaries and reports should bear in mind that although efforts have been made to correct any significant errors, it is possible that some minor errors remain.

The reports are ordered alphabetically by author surname. Table B.1 lists the students and shows their individual responsibilities within the project.

Student	Work area
Bradley	System engineering
Campana	Mechanical / thermal design
de Munck	Electrical power, communications
Hayward	System engineering
Mack	Payload
Meik	Mitigation options; operations
Sharma	Mitigation options and mission
Spencer-Jones	Mission analysis

Table B.1: Sub-system responsibilities for each student

B.1 Executive Summary: PRIMA, System Engineer, Alexander Bradley

PRIMA (Precursor Rendezvous for Impact Mitigation of Asteroids) is a mission design for a precursor to an asteroid impact mitigation mission. The design was produced as a result of a group design project at Cranfield University in March 2007. This short report summarises the work of one of two system engineers in the group. The particular areas covered were: project management; system requirements; system budgets and international framework.

Asteroid impacts are perhaps the most infrequent but certainly the most devastating form of natural disaster occurring on our planet. Despite the rarity of their occurrence, these events present a real threat for modern society. Although there has been an increasing recognition of the reality of this threat, the potential means by which the disaster could be avoided remain poorly understood. It is, however, the only form of natural disaster for which the capability exists to predict and prevent a catastrophe.

Whilst potential mitigation technology exists on Earth, it may be ineffective against an asteroid whose characteristics are uncertain and cannot be adequately determined by ground based measurements. Such a scenario therefore requires a precursor mission to visit the asteroid and collect valuable information in support of impact mitigation.

The mission objectives were as follows:

1. Rendezvous with a threatening asteroid
2. Determine precise orbit of asteroid
3. Characterise asteroid
4. Demonstrate a mitigation option
5. Perform additional tasks to widen the mission appeal if it does not compromise the above

Key performance requirements included selecting one of the most threatening asteroids to visit and selecting the most reliable mitigation option. Key constraints included not perturbing the asteroid's orbit during mitigation demonstration and limited launch windows.

The following outlines the mission overview: PRIMA is scheduled to launch in 2012 from Kourou via the Soyuz launch vehicle. The spacecraft will be directly injected into a transfer orbit to rendezvous with an Earth threatening asteroid called Apophis. The spacecraft will tag the asteroid with a transponder for tracking and perform scientific measurements to ascertain certain physical characteristics. Post-measurements, the spacecraft will land on the asteroid and attempt to alter its spin rate with a low thrust engine to demonstrate mitigation technology. The transponder will continue to operate for a few decades to enable accurate tracking of the asteroid's position. The total estimated launch mass of the spacecraft is 612 kg and the whole mission is predicted to cost € 165 M.

In summary, the PRIMA design overcame any feasibility issues and the design meets all mission objectives at low risk and low cost.

The process for protection against asteroid impacts comprises three parts; an early warning system, mitigation options and decision making. Whilst the early warning system and decision making are far from trivial to complete, action is underway in these areas. In contrast, there is currently no action in the field of mitigation technology options. This project represents a significant step towards bridging this gap. Logically, the next phase would be to formalise this design and implement it into production.

B.2 Executive Summary: PRIMA, configuration, structure and thermal analysis, Marie Campana

B.2.1 Abstract

This report is a part of the PRIMA project. It focuses on the mechanical design, and particularly on the Configuration, Structure and Thermal Analysis.

The main shape and characteristics of the Spacecraft has been obtained from the top level requirements: octagonal shape, four solar arrays and one face for all payload components facing the asteroid. Then all subsystems components have been placed to obtain a precise mass budget.

The structure is made of aluminium panels. The analysis has been strongly idealised and some initial thickness values have been obtained for the different panels. Concerning the thermal control, it has been designed with multi layer insulation and louvers. It achieves a stable temperature in a 40° C range, in spite of a strongly varying environment, and it does not use any components needing additional power.

These three objectives were correctly met, with a mass budget far lower than the initial requirements.

B.2.2 Introduction

PRIMA means "Precursor Rendezvous for Impact Mitigation of Asteroids".

The mission goal is to "improve our knowledge and understanding of asteroid impact threat and mitigation with particular focus on optimising reliability to the follow-up mitigation mission". The PRIMA mission has five objectives: rendezvous with a threatening asteroid, determine precise orbit, characterise asteroid, demonstrate mitigation option, additional tasks to widen mission appeal. The first three objectives are the most important ones. They are the main goal of the mission and any additional objectives must not compromise them.

B.2.3 Configuration

The configuration has to meet five main requirements:

- The spacecraft has to comply with the Soyuz launcher requirements, mainly mass, dimensions, strength and balance,
- The payload has to point toward Apophis,
- The electric propulsion requires two propulsion modules 90 apart,
- the spacecraft must have 11.2 m^2 of solar arrays pointing constantly towards the Sun during the travel, and they must be able to track the Sun when in orbit,
- the communication with Earth requires an orientable high gain antenna at the end of a beam.

From these requirements, it was decided that the spacecraft would have an octagonal shape and four solar arrays. Then, each subsystem has been configured to obtain the overall configuration shown below.

During this configuration, a precise mass budget has been defined. Each subsystem mass has been written in the Table B.2. This give an initial mass of 553 kg. A 20% margin for mass grow was added and the present mass of the PRIMA mission is 675 kg.

Table B.2: Mass breakdown

Subsystem	Mass / kg	Subsystem	Mass / kg
Payload	32	Thermal	14
Comms and CDH	28	Structure	94
AOCS	36	Power	88
Propulsion	218	Lander	52

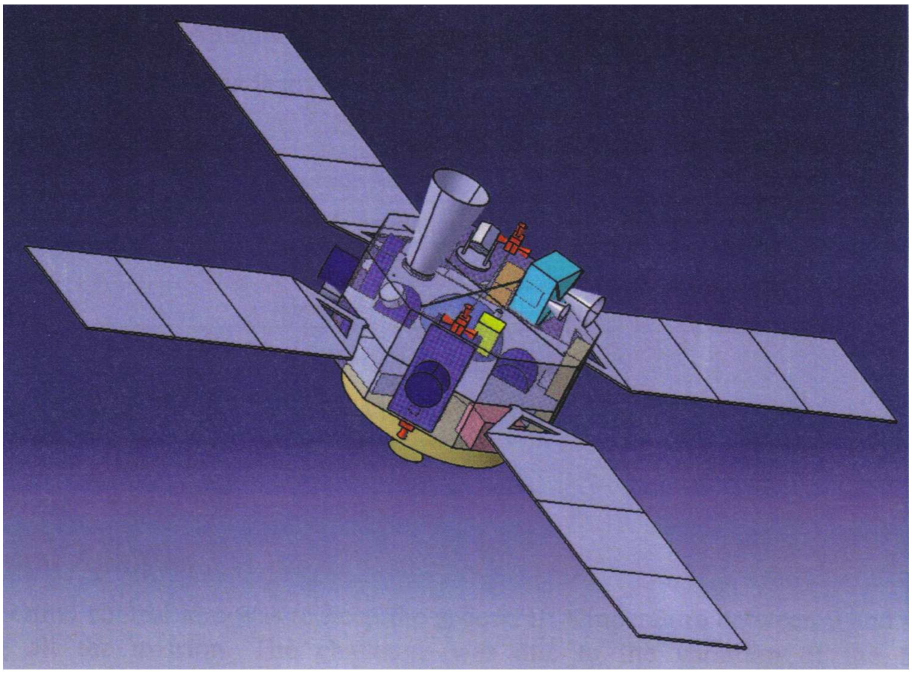


Figure B.1: Overview of the Orbiter configuration

B.2.4 Structure

The structure analysis was done to obtain initial, conservative value for the structure mass.

The structure is made of panels attached together, there are eight outside rectangular panels, three octagonal decks (top, middle and bottom) and two orthogonal inside vertical panels.

After a trade-off, the Aluminium 70-75 was chosen for all the panels. The resulting mass budget is given in Table B.3.

Table B.3: Structure mass budget

	Components	Mass / kg
Orbiter	Outside panels	38.7
	Inside panels	19
	Decks	35.7
Lander	Box	5

The mass total for the Orbiter is 93.4 kg and for the Lander 5 kg.

B.2.5 Thermal Analysis

The thermal control aim was to keep the spacecraft temperature between 0 and 40° C, during all the mission. The challenge was due to the variation of the thermal environment. The solar radiation ranges from 2260 W m^2 to 0 W m^2 during eclipse time. In addition, the internal dissipation has also a large range, from 400 W to 1000 W.

The solution was to combine Multi Layer Insulation and Louvers. Multi Layer Insulation blankets are made of many thin metallic sheets that decrease greatly the interaction between the spacecraft and the space medium. Louvers are like Venetian blinds, that open or close by thermal contraction to adapt the area emissivity.

The resulting thermal balance is drawn below. The power along the X axis is the total power to dissipate. It takes into account the internal dissipation and the solar radiation.

We can see (Figure B.2) that the equivalent power range from 400 W to 1150 W and the resulting temperature is well within the required range of 0 and 40° C.

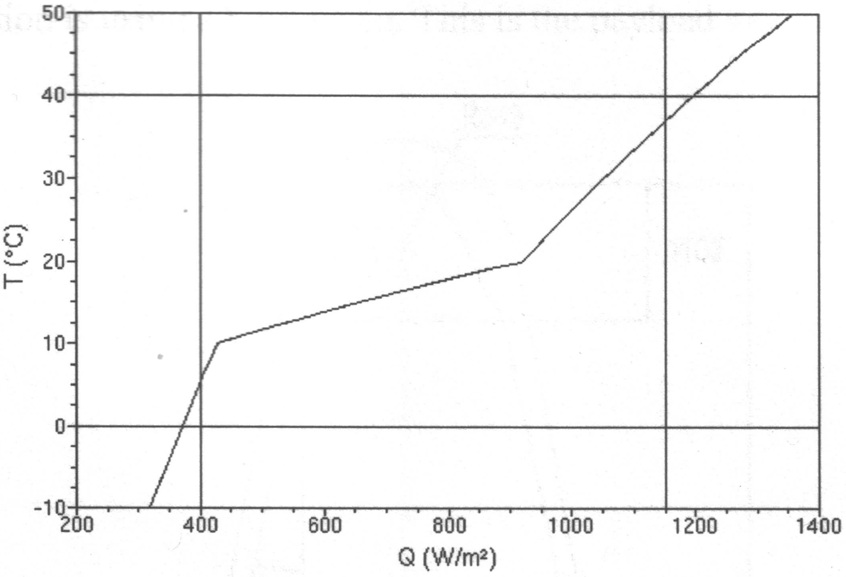


Figure B.2: Orbiter thermal balance

The Lander thermal balance can be achieved using only Multi Layer Insulation blankets.

B.2.6 Conclusion

The work covered here was the configuration, the structure and the thermal control of the spacecraft. The requirements have been met with minimum mass and power.

However, work is still needed before considering the mechanical design concluded. This work should focus on attachments and mechanisms and in Finite Element modelling for both the structure and the thermal control.

B.3 Executive Summary: PRIMA, Power Subsystem, David de Muynck

B.3.1 Introduction

Earth-Crossing Asteroids are asteroids threatening to enter in collision with Earth and cause disasters. The current space technology might be able to avoid such a collision, but it is indispensable to know better the asteroids. The PRIMA project aims at sending a spacecraft orbiting around a threatening asteroid named 99942 Apophis to collect data and demonstrate a mitigation option.

The spacecraft comports different parts with an Orbiter, a Lander and several probes.

B.3.2 Project Organisation

PRIMA is a project of Cranfield University. The goal is to define a top-level concept and to do a feasibility study of a mission toward Apophis. The author of this report is in charge of the power subsystem but also part of the communication and data handling subsystem. There are many interactions with other subsystems and especially with the propulsion subsystem, because of the choice of electrical propulsion.

B.3.3 Literature

Several power sources are already available for spacecraft. Solar arrays and secondary lithium ion batteries are commonly used for spacecraft orbiting around Earth or even interplanetary missions. Radioisotope generators derived of different technologies are used for deep space mission where the light of the Sun is no more available.

Several mission can give examples of what can be done to go in a far from Earth environment, use an electric propulsion (Deep Space 1), orbit an asteroid (NEAR) or land on a small body (Rosetta). The understanding of these missions leads to an understanding of the different constraints of the PRIMA mission.

B.3.4 Description of Selected Equipment

As the spacecraft is divided into different part achieving different missions, the power subsystem provides different power sources.

- Solar concentrator arrays generate power for the spacecraft during the travel mode and especially for the engine.
- Secondary batteries provide energy while the Orbiter is in the eclipse of the asteroid.
- An advanced radioisotope generator called AMTEC converts thermal heat of Plutonium into electricity to ensure energy feeding for the Lander, even in shadow. This generator can be used as a back-up power source for the spacecraft during the travel in case of failure of the solar arrays.
- Batteries provide energy for the probes while they are doing seismology science experiments.

B.3.5 Discussion

This chapter aims at explaining the different choice of power sources and describe what the sizes of the different elements are.

Orbiter Power Source

The solar concentrator must generate enough power for the whole spacecraft in travel mode (2.2 kW).

The batteries are sized to support 2 hours of eclipse while the spacecraft orbits around Apophis. Space tested lithium-ion batteries with an average weight energy density of 150 Wh kg^{-1} can provide the energy during the eclipse.

Tables B.4 and B.5 show the exact dimensions of solar arrays and batteries.

Table B.4: Solar array characteristics

Power needed	2200 W
Minimum solar flux	1226 W m^{-2}
Efficiency of the conversion	23%
Mass power density	150 W kg^{-1}
Stowed power	9 kW m^{-3}
Overall efficiency (off-pointing, degradation...)	69%
Mass of PRIMA solar arrays	21.3 kg
Area of PRIMA solar arrays	11.3 m^2
Thickness of PRIMA solar array	3.7 cm

Table B.5: Orbiter's secondary batteries' characteristics

Type of battery	present Lithium-ion
Volumetric Energy Density (Wh l^{-1})	300
Weight Energy Density (Wh kg^{-1})	150
Power in eclipse (W)	340
Time in eclipse (h)	2
Energy (Wh)	680
DOD (%)	50
Efficiency (%)	50
Volume (l)	9.06
Mass (kg)	18

Lander power source

The Alkali Metal Thermal to Electric Converter (AMTEC) is used to convert the heat provided by the natural decay of a radioactive element into electrical power. The AMTEC is constituted of several 10 W small cells. A mass of 1.9 kg of plutonium is required to generate 170 We BOL. The total mass of the generator is 22 kg.

Communication Links

The Orbiter is a relay for all science data sent to Earth. The Lander and the Orbiter have data handling unit and the probes data storage units.

Mass Breakdown

Table B.6: Electrical power sub-system mass budgets

System	Sub-system	Mass / kg
Orbiter	Solar concentrator arrays	21.3
	Batteries	18
	Power Management Unit	18
	Harness	20
Lander	AMTEC	22
	Power Management Unit and Harness	3
Probe	Batteries	0.042
	RHU	0.076
	Electronics and wiring	0.10

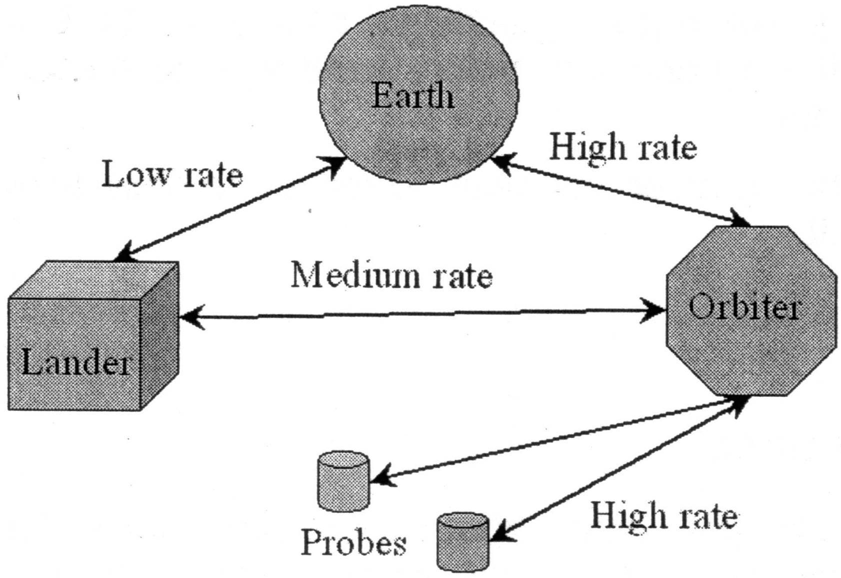


Figure B.3: Overview of the communication links

B.3.6 Conclusion

This report shows the top level power sources design and the very top level of the communication and data handling subsystem. But some work has still to be done on all of these subjects.

First the power buses are not completely sized. The different converters and power management units have to be design for the special needs of the mission, for instance taking account of the links between Lander, Orbiter and probes.

The Orbiter's data handling unit must be able to gather the data from probes and the Lander before compressing it and sending it back to Earth. The probes units have to store the data of the experiments before sending it to the Orbiter when there is a communication window.

At last the design of the antennas must be refined to answer at best to the design of the whole spacecraft.

B.4 Executive Summary: PRIMA system engineering, Rachel Hayward

B.4.1 Introduction

The scientific evidence shows that asteroids pose a significant threat to Earth. It is a global threat and would cause a catastrophic event if one were to ever impact Earth. Figure B.4 shows that an asteroid any larger than 200 m impacting would have serious consequences for society economically, socially and politically. Out of all the natural disasters this is only one that we can effectively predict and prevent from happening, more importantly this is achievable with currently available technology.

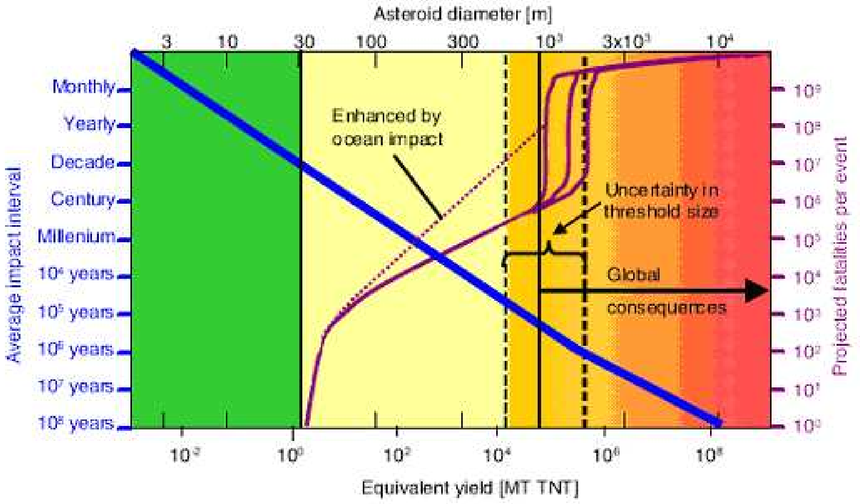


Figure B.4: Risk from asteroid impact and consequences dependent on size (Gritzner et al., 2006).

This report documents the systems engineering responsibilities carried out by the author as part of the Precursor Rendezvous for Impact Mitigation of Asteroids (PRIMA) mission, describing in detail the development of the ideas associated with designing the precursor mission. The success of such a mission will be determined by the quality and quantity of the information that can be obtained by a precursor mission as the methods for assessing risk via ground station detection are inadequate to design a successful mitigation mission.

The mission aims to rendezvous with the potentially hazardous asteroid Apophis. This asteroid could potentially impact Earth in 2036. Uncertainty in this statement comes from the current quality that ground based optical methods of orbit determination provide. The mission hopes to determine its precise orbit confirming or rejecting this statement. It also hopes to determine the internal structure and elastic properties of Apophis Finally the mission will demonstrate the possibility of low thrust deflection using electric propulsion. The mission will include an orbiter and lander that have travelled together to Apophis, once in orbit the lander will be deployed. The lander contains a self supporting transponder and science package. The lander and orbiter will work in conjunction to perform necessary characterisation science for 3 months. After all science has been completed the orbiter will be landed on to Apophis when an attempt to de spin the asteroid will be made using electric thrusters. The systems engineering tasks for this project were to oversee the system design processes involved in the mission, undertaking any organisational roles that were required.

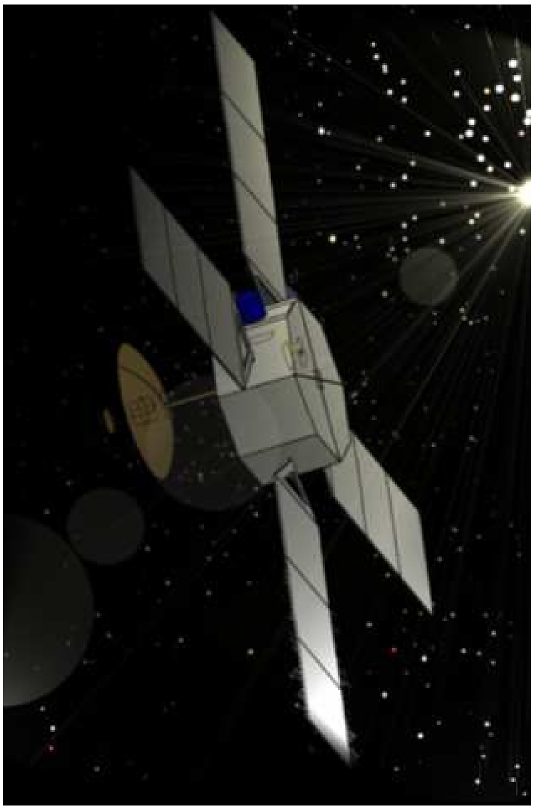


Figure B.5: PRIMA spacecraft during transfer orbit.

B.4.2 Design Concepts

The missions design drivers are that of science as the success of a mitigation mission will depend on the accuracy of information provided on the target asteroid. In many ways a precursor mission will be just as important as the mitigation itself. This had a direct impact on the mission concept that was chosen. The design had to provide the maximum amount of science return as possible, as a result the most comprehensive and complex mission concept scored highest employing both a lander and orbiter, deploying a seismic network after rendezvous to determine the internal dynamic behaviour. Trade offs that came later would therefore be controlled by this concept choice.

B.4.3 Project Management

Project management was the main task of the other systems engineer and the author. A timeline was drawn up to assess the progress of the subsystems and in turn the project. Weekly meetings were organised along with smaller more specific meetings which allowed the group to review actions that had been taken and identify any potential problems. Generally the interactions between group members was to a high level increasing toward the end of the project and the presentation at the critical design review. The trade off for the design concept was documented by the author and an analysis of the risk encountered at each stage of the mission.

B.4.4 Deployment of Seismic Charges

The mechanism work package was reallocated late in the design process allowing a limited amount of work to be completed. Velocity must be applied to the charges by a spring mechanism to ensure the charge reaches the surface of Apophis in an appropriate timescale. This must be done with imparting a velocity in the apposing direction that is greater than the escape velocity of the spacecraft orbiter. This means that some of the velocity should be applied after the initial separation from the orbiter. The deployment mechanism currently includes a collection of seven launch tubes in a hexagonal formation. The cylinders will be isolated and controlled separately. The actual deployment mechanism will be using thermal separation nuts that will release the doors to the launch cylinders.

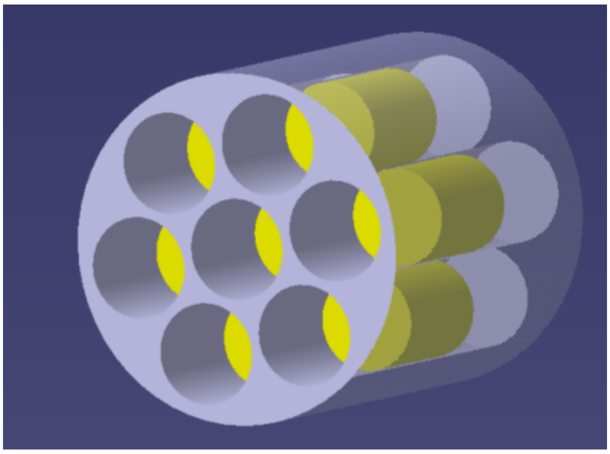


Figure B.6: Cylindrical housing for seismic charges.

B.4.5 Risk and Redundancy

The mission is subject to a large amount of risk due to the number of unknowns in the mission are high. An adequate level of redundancy has been employed by the PRIMA mission as to ensure a high probability that as many of the possible targets are achieved, with little sacrifice to be made to mass and cost restrictions.

B.4.6 Conclusions

PRIMA satisfies all the identified precursor requirements, having the ability to provide the necessary data for the highly complex simulation and design of a deflection mitigation mission. It goes further in demonstrating technology for a low thrust mitigation mission using electric propulsion.

B.5 Executive Summary: Payload, Gordon Mack

(99942) Apophis is a Near Earth Asteroid with an estimated diameter of 250 meters and a non-zero probability of impact with the Earth in 2036. Asteroids of this size have been identified as potential targets for future impact mitigation missions. Any such mission would require a precursor mission to undertake an initial survey of the target asteroid to shape the mitigation mission. The aim of this work is, with particular attention to Apophis, to investigate the possible methods of measuring key properties of these asteroids, choose an optimal scientific payload configuration, construct an initial design for any non-standard components and finally consider an operational scheme for the utilisation of the payload. The key physical parameter which was identified for study was the structural composition of the asteroid. A combination of radio transmission tomography and active seismology was chosen to study this aspect. The payload required for a precursor mission is not unfeasible particularly when one considers the potential value for future mitigation missions.

B.5.1 Payload Summary

The mission concept dictates an Orbiter and Lander which both require a scientific payload. The primary requirements on the scientific payload are that it be able to quantify:

- The Internal Structure and Dynamics,
- The Internal Density Distribution,
- The Spin Characteristics and State,
- The Total Mass,
- The Surface Shape of the Asteroid.

These requirements informed the choice of the payload which consists of the elements illustrated in figure B.7.

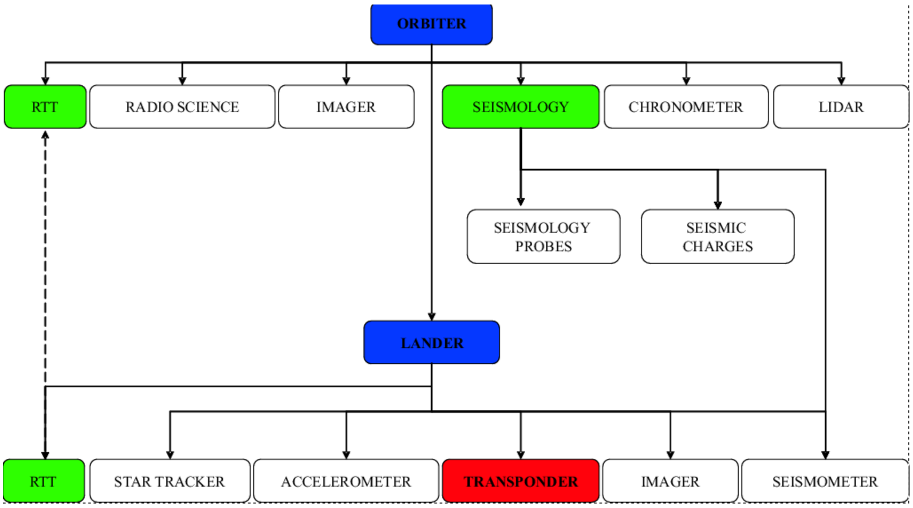


Figure B.7: This diagram summarises the payload components of the PRIMA mission and illustrates some of the interdependencies.

Optical Imager

The primary optical imager of the PRIMA mission is a Cassegrain style telescope with a CCD which obtains a ground resolution of 0.1 m when in an orbit at the edge of the sphere of influence of Apophis. The field of view of the imager - 8° - is sufficient to image the entire visible portion of Apophis when at this orbital altitude.

The imager will operate in an unfiltered broadband mode to aid in navigation from a range of $10,000$ *km* and whilst mapping from orbit. There will be the option to image in various filters, as indicated by the provision of a filter wheel in the design.

Radio Transmission Tomography

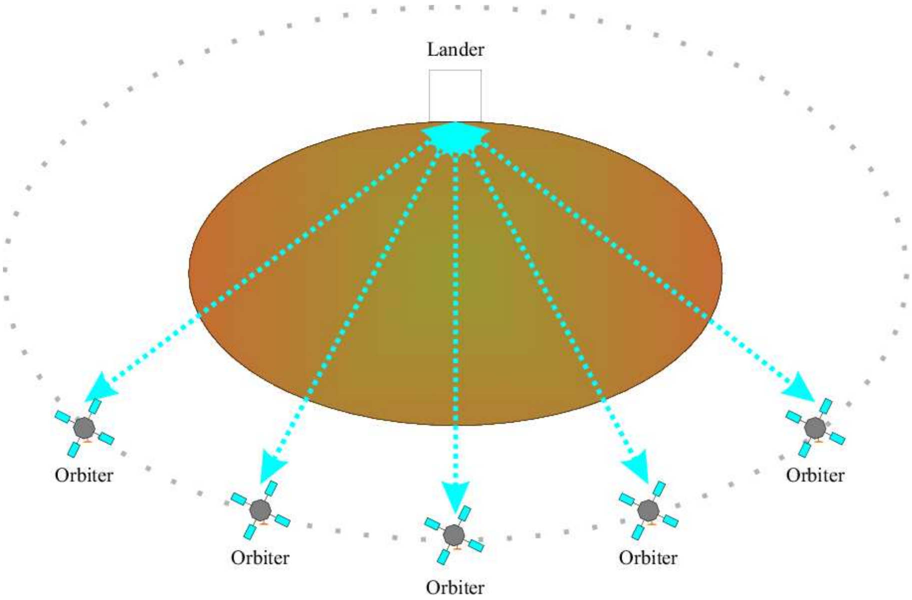


Figure B.8: This diagram provides a schematic representation of the operation of the RTT over one orbit with the dashed lines representing one signal path between the orbiter and lander, in reality far more samples would be generated and the propagation would not be along straight lines.

The internal structure and density distribution of the asteroid will be studied by a radio tomographer which will operate via a link between the Orbiter and Lander. A number of orbits, ≈ 20, will be required complete an interior map at the desired resolution of 30 *m*. This resolution was chosen in line with data which states that objects smaller than this size can reliably be assumed to burn up in the Earth's atmosphere. The configuration of the tomographer is based on that of the ROSETTA CONSERT experiment.

Seismology

In order to study the internal elastic properties of the asteroid, it is necessary to conduct a seismological survey. This was the only method identified as capable of providing the data needed to characterise the asteroid with regards to future external forcing e.g. nuclear detonations. A number of seismic charges will be deployed from the orbiter to provide a sounding source for seismometers placed within the main lander and in dedicated seismic probes. Five seismic probes will be deployed along with 5 seismic charges (100 *gramme* C4 explosive packages).

Anchor Accelerometer

Landing on a body with a mass as low as that of Apophis is a challenging prospect, which requires an anchoring mechanism for each landed craft. This will be accomplished by a small harpoon style projectile fired into the surface on landing. The harpoons will contain accelerometers in order to provide some characterisation of the local surface properties.

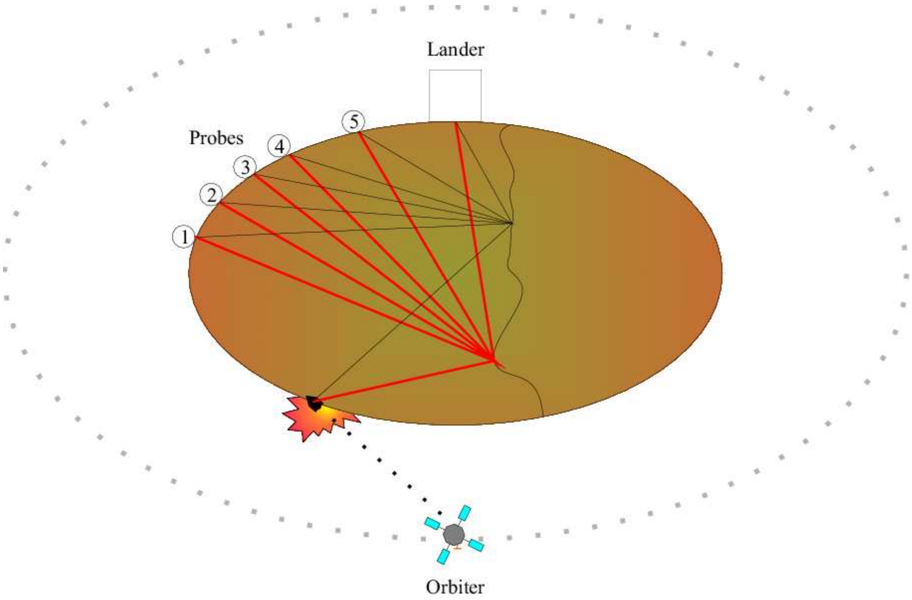


Figure B.9: This figure illustrates the placement of seismometers and the detonation of an explosive on the asteroid. Also indicated is a fault line inside the asteroid, operationally this would have been identified by RTT and then the seismometers are placed to conduct a further study. The propagation paths of the seismic waves are shown.

Lander Star Tracker

In order to measure the spin characteristics of Apophis accurately and for a long period, the measurement technology must be placed on the lander - for mission considerations. It was decided that a simple star tracker would be able to compute the details of the spin rate by comparing consecutive attitude measurements. The accuracy with which the spin rate is measured will be increased by stacking attitude measurements from the star tracker.

B.5.2 Conclusions

The payload presented in this report is indeed capable of satisfying the requirements placed upon it with a good level of reliability and redundancy. Multiple probes and charges aid to ensure the success of the seismology experiment which would provide data even in the event of a complete failure of the RTT experiment. In the event of a failure of the primary imager, the AOCS LIDAR, Lander star tracker and RTT could be used for mapping and/or navigation. It may be wise to include multiple landing anchors on the main Lander - as is the case on the orbiter - to increase the reliability of this element of the mission. The payload has the benefit of not being specific to Apophis, with the exception of the RTT element which has been would require alterations to the transmitted power for a larger object and an increase in timing accuracy for a smaller object. In the event that Apophis was no longer a target asteroid, a replacement target need only be of similar dimensions to Apophis to allow the payload to function.

B.6 Executive Summary: Mitigation Requirements and Operations, Simon Meik

The PRIMA mission requirements were to

- Land a transponder on an asteroid to track its orbit, so that its orbital perturbations are better understood
- Gather data on asteroid characteristics both from orbit and the surface
- Demonstrate a Mitigation option

All of these were to be achieved using off the shelf technologies.
The objectives of this report were to

- Define the requirements demanded of a precursor to an asteroid impact mitigation mission
- Evaluate potential mitigation concepts for a range of asteroid scenarios and characteristics
- Identify and define the mission phases
- Define the operational requirements of each phase

B.6.1 Requirements and Trade-off Analysis

A review of potential mitigation strategies and the NEAR (NASA), Hayabusa (JAXA), and Don Quijote (ESA) missions found that the minimum characteristics a precursor rendezvous mission needs to obtain en situ from an asteroid are; orbital trajectory, spin rate and spin axes, mass, centre of mass, surface features, and internal structure. From these, and the mission requirements, the baseline payload was defined as; a transponding beacon (which is required to last for more that 20 years), an imager, seismology and radio transmission tomography (RTT) equipment, and an intelligent AOCS (for discovering the mass to a high accuracy). Any other data that can be gathered would enhance the scientific return. As well as being a potential threat to Earth, most minor planetary bodies are thought to have been preserved in the state they formed (ISAS), hence their exploration could answer questions relating to the formation of the solar system.

The mitigating thrust should be aligned along the COM-engine vector, and parallel to the velocity vector, for an efficient manoeuvre. The internal structure will determine what type of mitigation strategy to use. Ideally, a single strategy that could be applied to any asteroid type and time frame would be beneficial. Figure B.10 illustrates the ΔV requirements given a specific mitigation date for the asteroid 99942 Apophis. Depending on the time before a potential collision, two scenarios transpire. For a long and close approach, ΔVs of the order of 10^{-7} m s^{-1} and 1 m s^{-1} respectively, are required.

B.6.2 Mitigation

A quantitative trade-off analysis was conducted on the mitigation concepts. These included using SPOM (Solar Powered Orbital Mechanics), nuclear explosives, conventional rockets, gravity tractors, and projectiles, to alter the asteroid trajectory. The more far fetched techniques were not considered as they can not be easily implemented using current technologies. Figure B.11 shows the results of this analysis. It compares the ΔV normalised with respect to launch mass (as if it were a payload leaving Earth), to the ΔV each method could deliver. (The SPOM and Electric Engine calculations assumed an effective thrust over a one year period). It was concluded that the best method of deflection for the close approach scenario is the use of a nuclear detonation, near the asteroid surface, acting in a direction perpendicular to the direction of motion (assuming impact would occur regardless of a force parallel or anti-parallel to the direction of motion). An electric engine, delivering a low thrust over a longer period of time, would be best suited for all types of long approach bodies. For the purposes of the PRIMA mission, a $\Delta\omega$ (change in angular velocity) can be demonstrated if the thrust is directed about the asteroids spin axis. A change of the order of one part in 10^5 should suffice in detectable using a star tracker. Hence, a ΔV can be

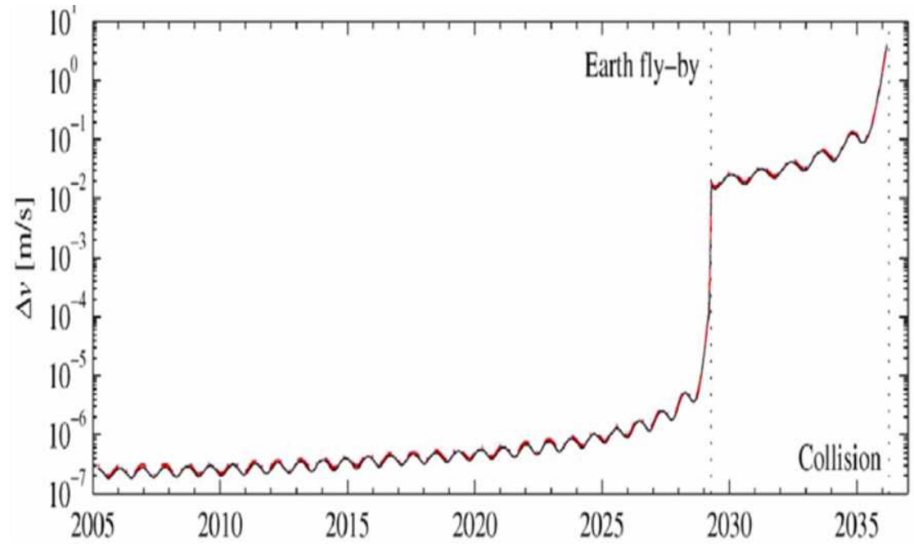


Figure B.10: Optimal velocity change required for Apophis before and after its 2029 close approach with Earth (Kahle, Hahne and Kuhrt, 2006). Two concepts were chosen to tackle the close and long approach scenarios.

imparted without the risk of perturbing its major orbital elements, which could turn Apophis into a more threatening asteroid. This manoeuvre could be attempted in 2013 at the end of the science phase, or in 2014 when Apophis comes within 0.5 AU of Earth again.

B.6.3 Operations

The mission in brief is thus; in 2012, PRIMA will be launched from Kourou directly into an Earth escape trajectory using a Soyuz launch vehicle with Fregat upper stage. Figure B.12 shows the top level mission timeline. The phases are outlined in Table A1.

Table B.7: Top level Phases with minimum personnel included. Running times and rough phase times are shown. Note that Mission, Operations, and AOCS Engineers are present at each phase.

Phase	Event	Running time days	Duration days	Personnel
1	Launch	0	-	Mission, Launcher
2	Transfer Orbit	286	286	Propulsion, Navigation
3	Rendezvous	291	5	Propulsion, Payload
4	Imaging	296	5	AOCS, Payload
5	Deploy Lander/Probes	296	1	Payload (Orbiter / Lander)
6	RTT/Seismology	325	17-31	Payload (Orbiter / Lander)
7	Mitigation Demonstration	325+	7+	Mitigation, Payload

After a transfer orbit time of approximately nine months, the craft will navigate towards Apophis, enter into a random orbit, and conduct scientific experiments. Surface mapping, and obtaining the spin, mass, and orbit characteristics, will be done with the Orbiter over a proposed 10-day period. The Lander will then be deployed to a pre-selected location and initiate its transponder, thus satisfying the primary objective. Over the subsequent weeks, RTT will be performed which will determine the internal structure to a 30 m resolution. (It is assumed asteroid fragments of 30 m or less pose as no threat to Earth (Gritzner et al., 2006)). Seismology probes will then be deployed to regions of geological interest, and a mortar on the Orbiter will deliver explosive charges to the surface. This will determine the internal elasticity of the asteroid, and whether it is a solid rock, or a conglomeration of smaller bodies. Upon completion of the science, the Orbiter

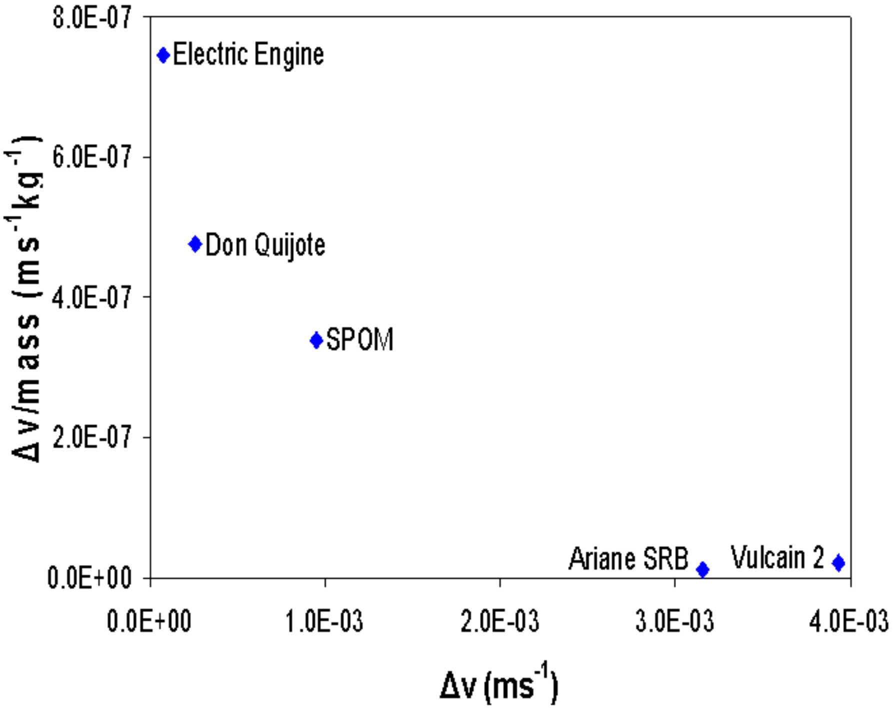


Figure B.11: Graph relating the ΔV per unit mass to the ΔV for each concept. The nuclear option is not included because it is orders of magnitude greater than the other concepts.

will land in a suitable area. A decision on whether or not to conduct a mitigation demonstration will then be made by the operators. Unforeseen circumstances may dictate that Phase 7 is not carried out; a high risk of turning Apophis into a more threatening body, for example. If and when Phase 7 takes place, the Orbiter will use its electric engine to de-spin the asteroid.

A 2013 was selected because Apophis will be within 0.5 AU of Earth for a number of months. This small distance eases the communication link constraint. Other constraints included continuous power for the electric engine during transfer, and a constant nadir pointing payload during orbit.

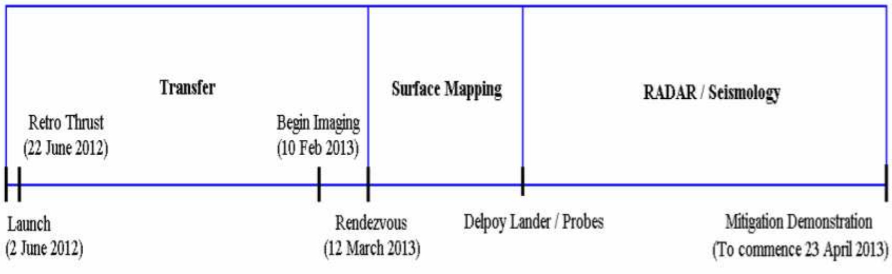


Figure B.12: Top level timeline.

B.7 Executive Summary: Mitigation mission, Gunish Sharma

Millions of asteroids and comets reportedly orbit in the solar system. Some of these Objects cross the Earths orbit and sometimes have the probability of intercepting. These NEOs differ in size and velocities greatly. Collisions have known to have occurred ever since the formation of our planet and responsible for injecting elements into the atmosphere integral for existence of life. Widespread alterations in Earths surface, and biological ecosystem over millions of years have been attributed to this phenomenon.

The threat has only recently been acknowledged and has been realized that the shocking scenario of impact collision with Earth from a celestial object isnt science fiction. This has resulted in surveying skies for potential hazards using advanced technology telescopes, so as to detect and monitor any NEO approaching threateningly close.

Impacts represent a significant risk to mankind. Humans however are the only species with the intelligence and technical prowess; with the capability to mitigate the consequences of such impacts.

Unfortunately, we are at a disadvantage because not enough information is available about these objects and this poses a serious risk. With improved knowledge of these eccentric and unpredictable members of the solar system, we can predict and analyse their characteristic behaviour and thus develop competent strategies for planetary protection. This was discussed in sections 1 and 2 of the report and concluded that for developing an optimum mitigation strategy, asteroid survey, selection and threat assessment are necessary. Also, maximum knowledge about their characteristics is a priority.

Various mitigation proposals are formulated and designed based on these very requirements and each and every characteristic of the NEO can influence the choice of mitigation option. Options like nuclear deflection, fragmentation, thrust push seem realistic and possible according to current technological condition although more innovative options are fascinatingly clever and promising.

Other issues of concern such as organizational needs, political and international co operation for a global unison to the problem are also instrumental equally in mitigation designs. So are disaster management, public communication and trust. It is recommended to take steps at the administrative level to formulate organizations such as the UNO with international participation to discuss issues and take swift, responsible decisions for the welfare of humanity.

B.8 Executive Summary: PRIMA: Launch and Trajectory, Jules Spencer-Jones

Asteroid 99942 (Apophis) is considered the most likely known object to impact the Earth. So that its orbit can be modelled more accurately, the PRIMA mission proposes landing a transponder on Apophis that will enable the asteroid to be tracked to a significantly higher accuracy than is possible with current methods. The PRIMA spacecraft will also carry out detailed scientific analysis of the asteroid so that likelihood of success of a possible mitigation mission is increased.

This report primarily investigates the launch vehicle to be used, the trajectory to and orbit around Apophis. The effect of PRIMA on the orbit of Apophis is also investigated.

B.8.1 Launch

As with any space mission, the cost involved in launching the spacecraft is a significant proportion of the entire budget. Therefore, minimising the cost of the launcher is required as well as achieving the necessary orbit. For the PRIMA mission the Soyuz 2 launch vehicle was selected. This was due to its good value, good reliability, extensive heritage and appropriate payload capacity for the PRIMA mission (see Figure B.13). PRIMA will launch from Kourou.

The newest version of the Soyuz launcher is expected to be the first version of Soyuz to be operated outside of the old USSR. Starsem is on schedule to start launching the Soyuz from Kourou in French Guiana by the end of 2008. This will give the Soyuz an extra advantage over launching from Baikonur or Plesetsk in that Kourou is closer to the equator so the launcher will gain more speed during take-off due to the fact that the equatorial regions are moving faster.

B.8.2 Trajectory

PRIMA will launch from Kourou in June 2012 and spend approximately nine and a half months in transfer to Apophis, arriving in March 2013. There are several factors that define this launch timing. As with any mission, a realistic amount of time is necessary before launch in which the mission is designed in detail and manufactured. It is assumed that the minimum time that a spacecraft such as this could be produced in is approximately three years. This gives the earliest year of launch as 2010. Also as this is a precursory mission it is vital that enough time be left for a mitigation mission if required. As the need for a mitigation mission will depend on the results of the precursor mission, enough time needs to be left for the development and production of the mitigation mission after the results are gathered from the precursor. It is assumed that although it would be a technically complex mission with very little heritage, the increase in funding and support, possibly on an international scale, would, if necessary, vastly reduce the time limit of producing such a mission. Any mitigation mission to prevent a collision in 2036 should occur before the 2029 close approach. After the close approach in 2029, the $Delta$V requirements become significantly larger to alter Apophis orbit by the same amount. The optimum launch windows occur every seven or eight years, which means the best opportunity to launch is in 2012.

The trajectory was then optimised to require the least total C3. This optimised trajectory can be seen in Figure B.14. As PRIMA will be using an electric engine, this trajectory will change when a low thrust propagator is used to model the transfer.

B.8.3 Orbit around Apophis

PRIMA will orbit around Apophis for several months after the rendezvous. During this time a number of imaging techniques will sweep the surface of Apophis and a lander with the transponder will land on Apophis. A number of seismic probes and charges will also conduct some seismological imaging of the interior of the asteroid.

Orbiting a body as small as Apophis, the spacecraft is subject to a number of quite severe perturbations. The non-spherical asteroid creates a non-spherical gravitational field. This interacts with the spacecraft which is also experience a large disturbance from the solar radiation pressure. These two perturbations could easily cause PRIMA to crash into the surface or to escape into heliocentric orbit without the attitude system. The electric engine is likely to be far more powerful

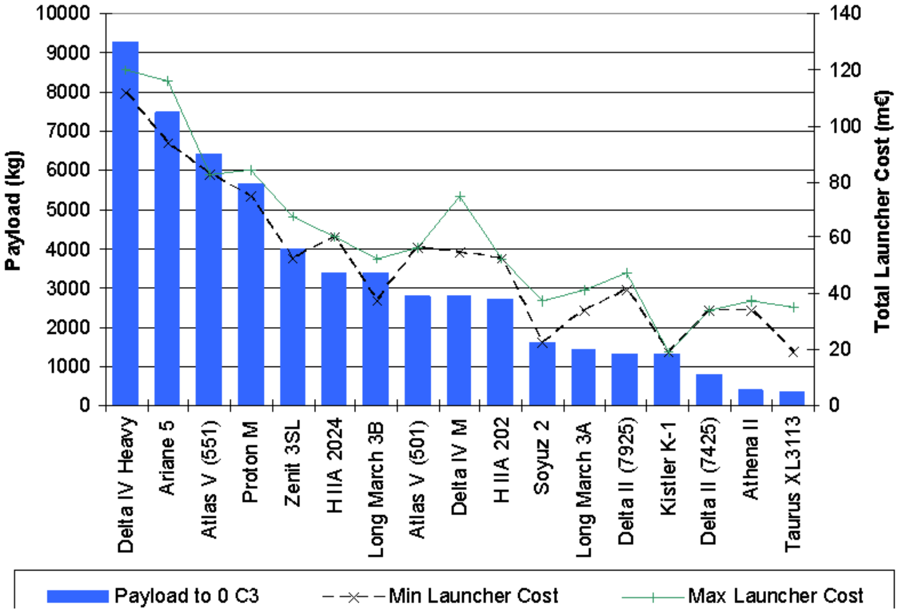


Figure B.13: Selection of Launch Vehicles Considered.

than either the gravitational attraction of Apophis or the solar radiation pressure and so will be able to control the spacecraft.

B.8.4 PRIMA's Effect on Apophis

As Apophis is such a small mass, compared to most planetary bodies that spacecraft have visited, the forces that PRIMA applies on Apophis during landing and the seismic detonations are enough to perturb the orbit. As Apophis is already in a threatening orbit, it is necessary to limit the sum of these forces so a collision is not caused. Therefore, careful planning of where the forces act on Apophis is required. With some thought, the forces can be used to cancel each other out, creating little or no change in the orbit of Apophis. The mitigation demonstration is designed not to effect the orbit of Apophis.

A MATLAB propagator was created to investigate these effects, and was found to be reliable. The complexity needed to accurately model the orbit of Apophis for a long period of time was not developed. The gravitational attraction of other planetary bodies would be required.

B.8.5 Conclusions

The Soyuz launcher was selected so as to achieve the desired trajectory and payload but at a lower cost offered by most of the launchers of this size. The Soyuz allows large departure C3s so that if required, a different trajectory to Apophis or a different asteroid can be achieved. The trajectory to Apophis has been optimised for an impulsive engine, however, the low thrust trajectory still has to be calculated and optimised.

Further study into the effects of the orbit around Apophis and Apophis orbit could be conducted. By increasing the accuracy of the MATLAB propagator, the close approaches of Apophis and the Earth could be modelled and a true sense of the effect of PRIMAs perturbations would be gained.

Although more work is necessary for the continuation of the PRIMA mission, it is believed that the feasibility issues have been answered.

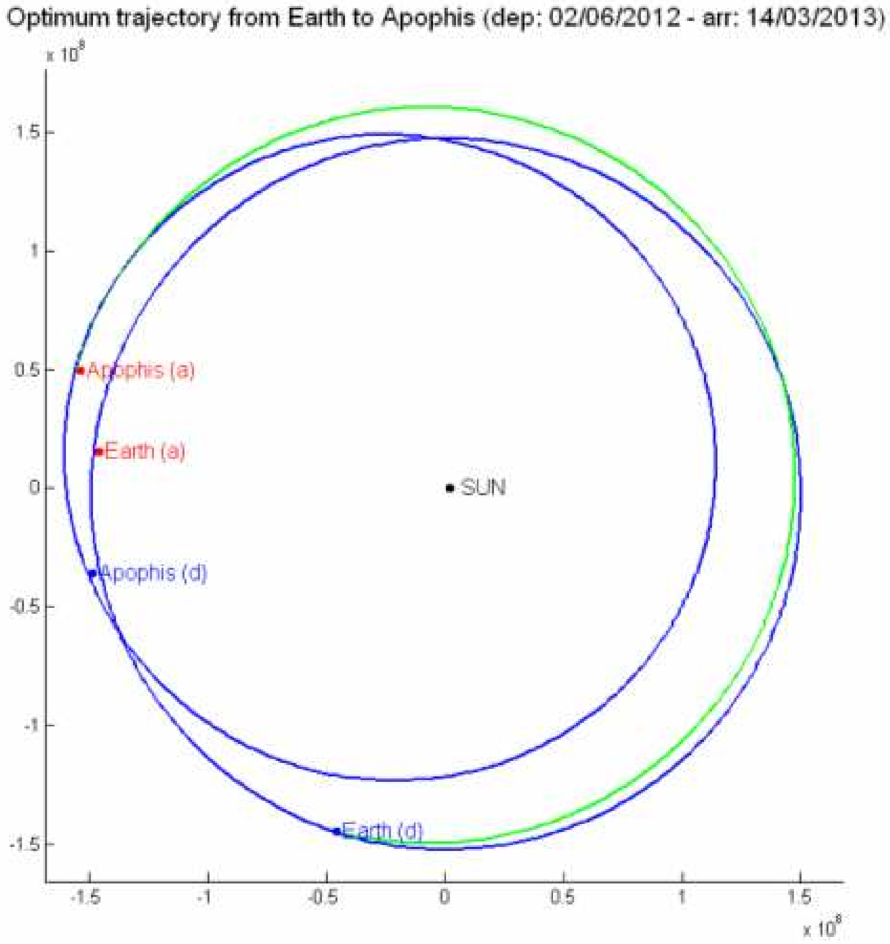


Figure B.14: The Impulsive Trajectory to Apophis.