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Investigation of the approaching and landing scenario of a probe on  
asteroid Apophis during its closed encounter in 2029

Cranfield University  
MSc in Astronautics and Space engineering

MSc  
Academic Year: 2023 - 2024

Supervisor: Dr. Marta Ceccaroni  
Associate Supervisor: Dr. Tra-Mi Ho  
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This thesis is submitted in partial fulfilment of the requirements for  
the degree of MSc in Astronautics and Space engineering

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- the thesis submitted has not been previously submitted to this university or any other.
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- that all quotations and references have been duly acknowledged according to the requirements of academic research.

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## **Abstract**

In 2029, an asteroid called Apophis is going to perform a flyby of Earth, coming 10 times closer than the Moon, inside geostationary orbit, where most of our communication satellites are placed. This will be an unprecedented opportunity to study materials and structures of asteroids, understand the Solar System and the early stages of planetary formation. To achieve this, Apossum mission is being designed, in order to bring more information to the field. In this paper, the whole mission scenario is studied in detail in order to assess the feasibility of it. Here is included the separation phase, the cruise towards Apophis, and the subsequent landing and return phases. The central focus of the report is the detailed landing scenario, which includes an extensive study on the densities of Apophis and a comparison of several control techniques to land successfully on the surface of Apophis. The results will provide an insight on the possible techniques to land and the associated density scenario.

The lessons learned from this mission would enhance the understanding in small-body landings, creating more opportunities for future missions to explore such celestial objects, thus providing the possibility of studying these asteroids and implementing control techniques in order to perform precise landing missions.

Keywords:

Asteroid Landing, Space Exploration, Advanced Control Techniques, Apophis, Densities.

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## List of Abbreviations

AOCS	Attitude and Orbit Control System
COM	Centre of Mass
DV	Delta-v
GEO	Geostationary orbit
GNC	Guidance, Navigation, and Control
PD	Proportional-Derivative
PID	Proportional-Integral-Derivative
SRP	Solar Radiation pressure

# 1 Introduction

Asteroids are essential when it comes to understanding the solar system from its emerging stages. They are remains of early solar system stages and give valuable clues about the basic building blocks that made up a planet or other objects in the solar system. Asteroids are like time capsules, as they hold conditions from 4.5 billion years ago. Most asteroids are located in the Oort Cloud and the Kuiper Belt.

In the recent past years asteroid deflection and sampling have gained significant relevance in the scientific community driven by the information these objects hide in their surfaces to understand the building blocks of planets. This information includes their composition and formation processes and potential clues about the origins of life on Earth, as some essential elements for life may have been given by asteroids.

Furthermore, studying asteroids can help develop strategies to change their trajectories, thus preventing potential collisions with Earth.

NASA's OSIRIS-REx and JAXA's Hayabusa2 that have successfully demonstrated the ability to reach, study, and even return samples from asteroids. Another mission that have similar objectives, but to study the possibility to deviate one, was Dart, which impacted in an asteroid and was able to change the trajectory of it, setting a step towards a future in which humans are able to deviate asteroids and avoid collisions.

DLR decided to study Apophis asteroid, whose encounter with Earth will be in 2029, passing at a distance closer than geostationary orbit at its closest point(Specifically at 31800 km (NASA, 2021) ). To get an idea of how close this is, there are satellites orbiting Earth that perform their missions further away.

The mission APOSSUM, is a small spacecraft that will be launched on RAMSES, which is a spacecraft built by ESA (ESA, 2024). Apossum will be a spacecraft able to navigate from RAMSES towards the landing place, therefore it has solar panels and all the subsystems needed to survive in that hostile environment.

Moreover, to get samples, it has a sampling mechanism with a motor and brush to remove material from the surface of the asteroid and a container to store them.

The report contains the mission analysis part. Therefore, this study contributes to the scientific knowledge of asteroids, and also explores new technological frontiers in spacecraft navigation, control, and landing techniques. Specifically, a trade off will be done by trying PID, PD and bang-bang control techniques to see the feasibility of them and the most suitable one for the mission. Moreover, multiple modelling techniques are used to compute the perturbations and a comparison of the results obtained with each one of them.

Normally when landing on an asteroid, there are several factors to consider, like the density, size, lobes and location to land. To obtain these measurements and data, telescopes are used. They capture not only in the visible spectrum, but also is important to obtain observations in the infrared one in order to infer the presence of different minerals and compounds. It is well known that analysing the spectrum of the light these materials are studied since they absorb certain wavelengths. Moreover, infrared observations are used to determine the thermal properties of the asteroid as well as surface composition. These techniques are coupled with radar observations that mainly provide high resolution images and shape models of the asteroid. Depending on the asteroid and the observations, scientists can even differ craters boulders, and ridges. To model such irregularities, radar observations are needed. All this information is then used to choose the landing place or to perform a more detailed study of the gravitational potential. The radar observations used in this study are the ones taken by NASA in 2013 which led to the tetrahedral shape used of the asteroid (NASA, 2021), (3D Asteroid Catalogue, 2021)

Another type of observations that are commonly used are the photometric observations, which measure the brightness of the asteroid over time, help scientists understand its rotation period and axis, as well as surface variations.

## 1.1 Apossum unique opportunity

Apophis is a unique opportunity to study due to its size and the proximity at which it encounters Earth. It represents the closest encounter of an asteroid of this size in the recent years. Although other missions have already obtained samples from an asteroid, this time, the mission is different since the spacecraft is not designed to perform the whole mission from Earth and back, but rather, travel with ESA's spacecraft and then detach. This is a unique opportunity to get samples from an asteroid at a low delta-v costs due to the avoidance of the travel from Earth.



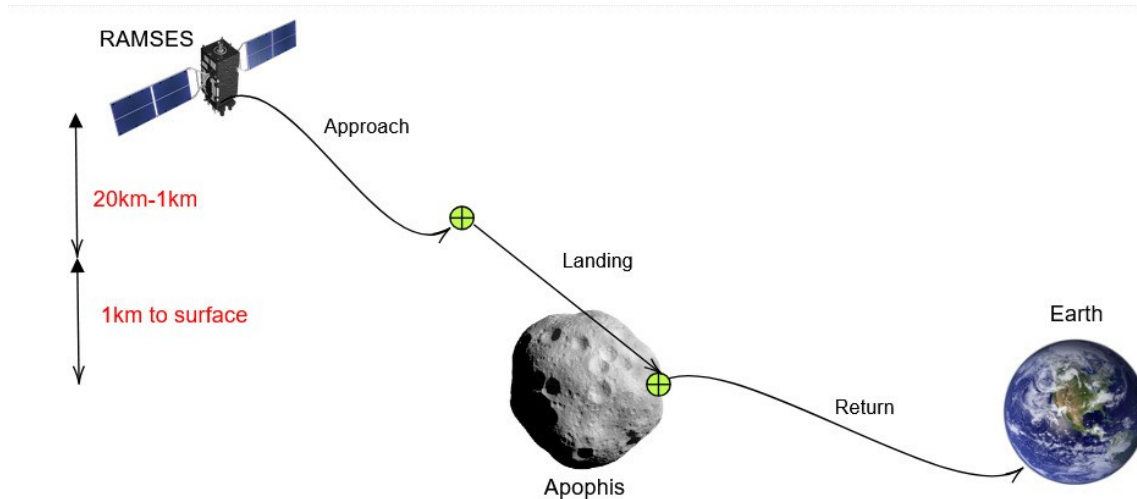
**Figure 1.1 Apossum Mission logo**

The mission that will be done by DLR is called Apopssum, the main objective is to get samples from the surface. To perform the mission, the spacecraft has a rotating mechanism and a vacuum container to get the samples. According to the report of other subsystems (DLR, 2024), the amount of material is expected to be 1 kg, 4 times more than (JAXA, 2022) mission performed in Itokawa. To achieve that objective, the spacecraft has the intention to approach the asteroid, land using the thrusters and return, the mission scenario will be explained in further sections.

As it can be seen, this mission fits into broader planetary defence and scientific research efforts.

## 1.2 Mission Scenario

As mentioned earlier the mission consists on getting samples from Apophis asteroid. To achieve this, the mission will be divided in 3 different phases.



**Figure 1.2 Overview of the mission to Apophis**

- The first one is determined by the detach of the spacecraft from RAMSES and approaching the asteroid (from 20 km to 1 km). In this study the software used was STK, assuming the asteroid is an ellipsoid. STK is a software that enables the user to compute the trajectories of spacecrafts given a scenario. In this case, the scenario was made by the solar system, the asteroid Apophis and Earth. Being the asteroid density constant and using the shape mentioned earlier.
- Moving to the second phase, this concerns the part of approaching the asteroid from 1 km above the surface to the target point. In this context the density and shape play an important role and so several scenarios are presented in order to be studied. In this section, the software used is Python and all the solutions are obtained through numerical methods. Different approaches will be followed and compared to have a wider view of the solutions available to land on an asteroid and to see the feasibility of using them in this mission.

- The third scenario involves the return of the spacecraft to the desired landing location on Earth. Similarly to the first scenario, STK will be used as software to see the viability of it. The spacecraft will leave the surface of the asteroid on a desired day in order to land on Australia on a specific place when needed. This location is such because it is on the opposite face of Earth with respect to Apophis, and so being able to study in detail with telescopes when the closes approach happens.

### **1.3 Densities studies and landing scenarios**

Several studies have been conducted in order to estimate the density of Apophis asteroid (G. Valvano, 2021). The range of possible densities is wide and so the mass of the asteroid. In this study several cases have been addressed in order to have a deeper understanding of the possible scenario that the spacecraft may face in its arrival.

Moreover, there are several ways to model the interaction of the asteroid with the spacecraft and different ways to model its mass and density. In this study, two modelling techniques are presented (Spherical harmonics and tetrahedral). The most suitable among them, is chosen to study the possible orbit perturbations when more than one density is taken into account, and for the landing scenario.

Finally, taking these results into consideration, several control techniques are studied and compared to see the feasibility of the mission and advantages and disadvantages of each one of them.

## 2 Mission objectives

The close flyby of asteroid (99942) Apophis on the late evening of Friday, April 13th, 2029 when it will pass within 32,000 km of Earth as a naked-eye object of 3rd magnitude, presents a unique scientific and strategic and science communications opportunity for asteroid research and planetary defence in particular. This event has prompted NASA to revise its OSIRIS-APEX (OSIRIS-REx' Extended Mission to Asteroid Apophis) mission to fly by Apophis after its closest approach, while ESA is currently studying the RAMSES mission for a flyby before Apophis's closest approach to Earth.

RAMSES is currently studied as a close derivative of the HERA mission, due to the tight schedule towards Apophis. Among RAMSES' main scientific objectives are observations of the tidal and magnetospheric effects on the Near-Earth Asteroid (NEA) during this close flyby, by providing 'before', 'during', and 'after' observations from the same platform and instruments.

A lander with suitable instruments would be ideally used to provide ground information to have a deeper understanding of the asteroid. This approximation, will lead to a sample return and therefore a more insight in the asteroid composition. Moreover, landing with the proper instruments, helps in the determination of the internal composition of the asteroid, it is still unknown and difficult to measure with only telescopes or radar observations.

This landing may only require additional delta-v, of the order of  $\sim 5\text{m/s}$  compared to a mission in which the spacecraft just goes to the vicinity and comes back. As it will be studied, this delta-v is as expected and therefore, makes the mission undeniably attractive from the Scientific view.

In this report, a verification of the amount of delta-v is given and a possible scenario in terms of density is explained in order to give approaches to a successful mission (land on the surface and get samples) and go back to Earth in the most efficient and convenient way.

Therefore, in this report the landing scenario will be assessed and the objective is to give an approximation of the delta-v needed to fully accomplish the multiple

phases of the mission. Moreover this is complimented with the estimation of the time to perform those manoeuvres. All the calculations are performed to satisfy the requirements written by other subsystems.

On the other hand, in this study, the feasibility of the methods to perform the simulations is assessed in order to get a wider view of the solutions and techniques used and see which one is more suitable for this mission.

Given this interest by the scientific community and the space agencies (NASA, ESA, DLR), Apophis brings opportunities to study it in detail and this mission will help to understand better the landing scenario, and demonstrate its feasibility.

Finally, I would like to add that the intention of this study is to be published in as a Journal paper for future missions.

### 3 State of Art

The study of asteroids and the missions related to their study, has advanced significantly, particularly with the discovery of Earth-Crossing Near-Earth Objects (NEOs). The existence of these objects was proven in 1932 with the discovery of Apollo by Karl Reinmuth at Heidelberg (ESA, 2019). This set a milestone in the history of Astronomy and open the possibility to study them with more detail and its trajectories. They can be hazardous for humanity, if one asteroid with certain dimensions collides with Earth, it can cause severe damages, even extinct all plants and animals.

In recent years, and due to the advancement of observational techniques and instrumentation, asteroids have been tracked. Thus, there are several space agencies like ESA (ESA, 2024), or NASA that have created a public dataset with all the asteroid observations and their corresponding Keplerian elements. Due to this deep study in asteroids, scientists can predict the collision or not of these celestial bodies.

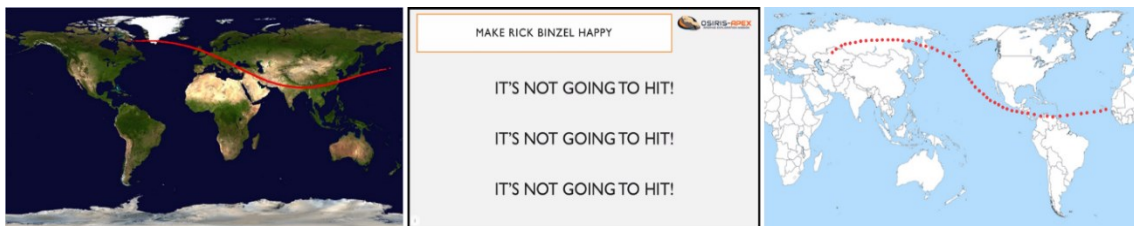
Knowing these object in detail has 2 main implications.

- The first one, and most important is because due to multiple studies (NewScientist, 2022), (Lawler, 2023), asteroids have been main characters in the history of life at Earth. The best example is the crater that an asteroid left in the peninsula of Yucatan 66 million years ago. This asteroid was enormous and was the cause of the extinction of 75% of animals and plants. The impact itself created several tsunamis and afterwards, a permanent winter, therefore knowing the trajectories and composition can help humanity to design strategies to deviate them and avoid the impact.
- On the other hand, the study of asteroids has been proved to be a key aspect when studying the early stages of the solar system. They are considered as “time capsules” since in their composition and shape. (Universal institutions, 2019).

Therefore, there have been multiple missions to asteroids like Dart whose aim was to impact on the surface of an asteroid and study the feasibility of deviating its orbit (NASA, 2021). Moreover, another mission called Hayabusa had a similar aim to the one studied in this report, its goal is to get samples from the asteroid Itokawa that had a close encounter (32,000 kilometres. Closer than GEO) with Earth and scientists from JAXA send the mission to get advantage of this opportunity (JAXA, 2022)

### 3.1 Discovery History of Apophis

Apophis was discovered in 2004. During that time, this asteroid observation, led to the first recognized case of a potentially hazardous asteroid (PHA) with an approximate impact probability of 1%. Nevertheless, after a deeper study, the risk of impact was virtually retired by the end of 2004.



**Figure 3.1 Ground track of Apophis (Wikipedia, 2024)**

Once discovered, and due to this potential impact, telescopes from all places around the world started to study it with more detail. To do so, astronomers used multiple observational techniques. Among them, the most common ones were observational with normal light and infrared and radar observations to refine its shape and characteristics. Once this data was gathered, the potential trajectory was computed. Since this object is perturbed by many celestial bodies, the trajectory has some errors and it is not precisely known.

This error in the trajectory of an asteroid is called uncertainty and is due to the interaction of it with the gravitational field of other celestial bodies in the solar system and with other asteroids. Moreover, there are also relevant perturbations due to Yarkovsky effect which arises from the heat that it emits after being radiated by solar light.

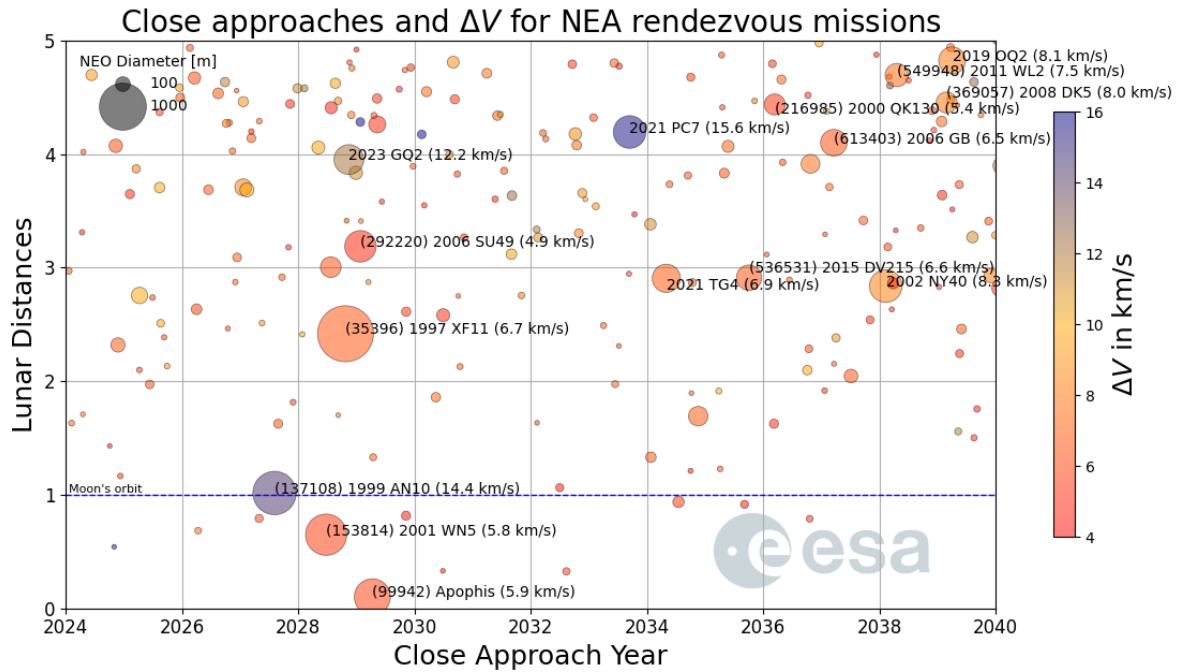
In the later years from its discovery, there were still relevant studies to know better its shape (NASA, 2021) (G. Valvano, 2021) .To achieve this, radar observations are used. There have been 2 relevant radar observations, one occur in 2013 and 2021, both done by NASA. Among them, and due to the time of this report being done, the shape considered is the one obtained using the 2013 set of information. Nevertheless, it is still a relevant shape according to recent studies on the asteroid that use it (NASA, 2021) (G. Valvano, 2021).

Once the shape is better known, the uncertainties of the trajectory can be reduced. These include the orbiting around Sun and the landing trajectories.

### **3.2 Significance of Obtaining Samples from Apophis**

As mentioned earlier, obtaining samples from asteroid is crucial to the scientific community in order to understand better the early stages of the Solar System and to study the possibility of deviate its trajectories to avoid an impact on Earth that can cause great damages.

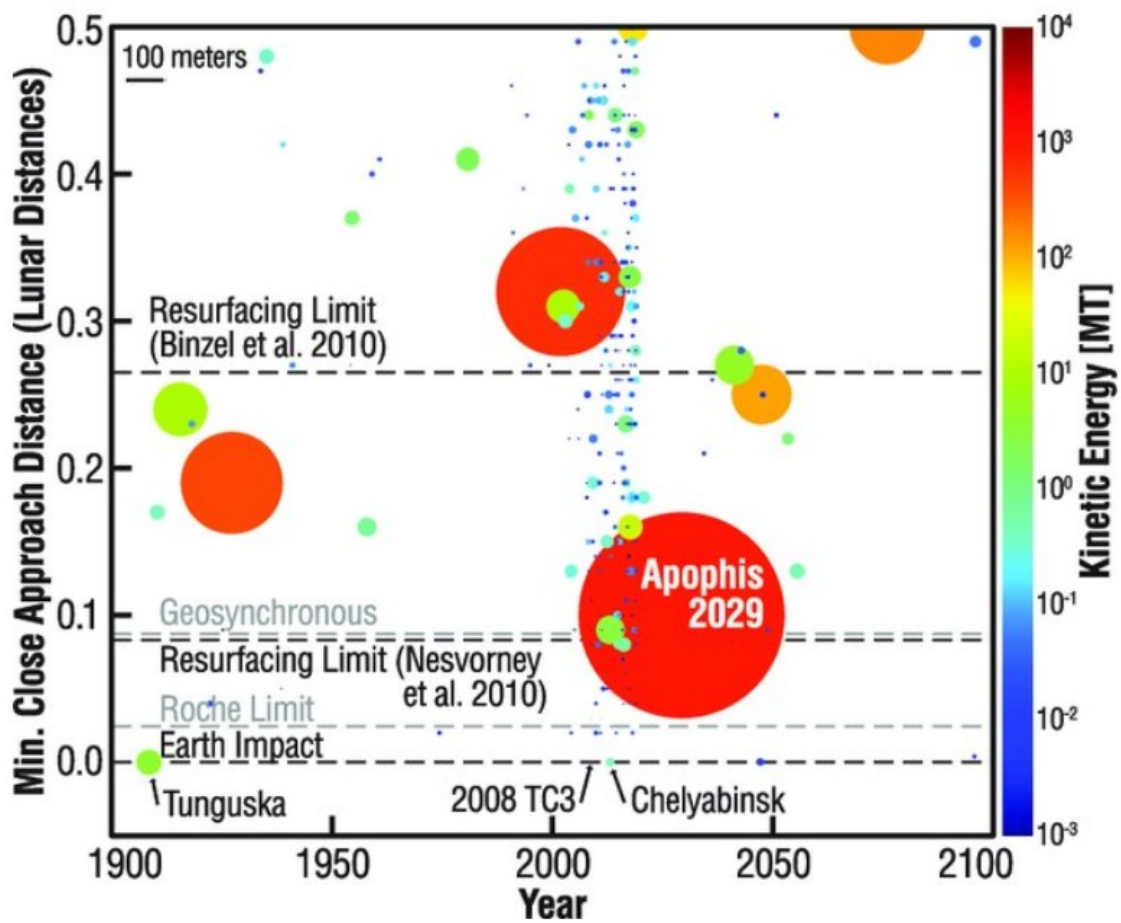
Since the discovery of NEO, several studies have been done to study the feasibility of studying an asteroid more in detail, therefore by going to its vicinities. (ESA, 2023)



**Figure 3.2 Close approaches and  $\Delta V$  for NEA missions (ESA, 2023)**

Figure 3.2 shows the result of this study done by ESA. The feasibility relies on more aspects than the delta-v, nevertheless, it is an important one to see how much fuel is needed to reach the asteroid's vicinity. This is crucial to get an estimation of the size of the spacecraft and of the propulsion system. Moreover, as shown in Figure 3.2, the asteroid with relevant mass and size that passes through Earth the closest is Apophis, making it a unique opportunity to study.

This study is supported by another one than by NASA were Apophis is considered as a "rare event" due to this close distance at which it does the fly-by. (Daniella N. Della Giustina, 2023).



**Figure 3.3 Impacts of asteroids and closes approach distances of asteroids (Daniella N. Della Giustina, 2023)**

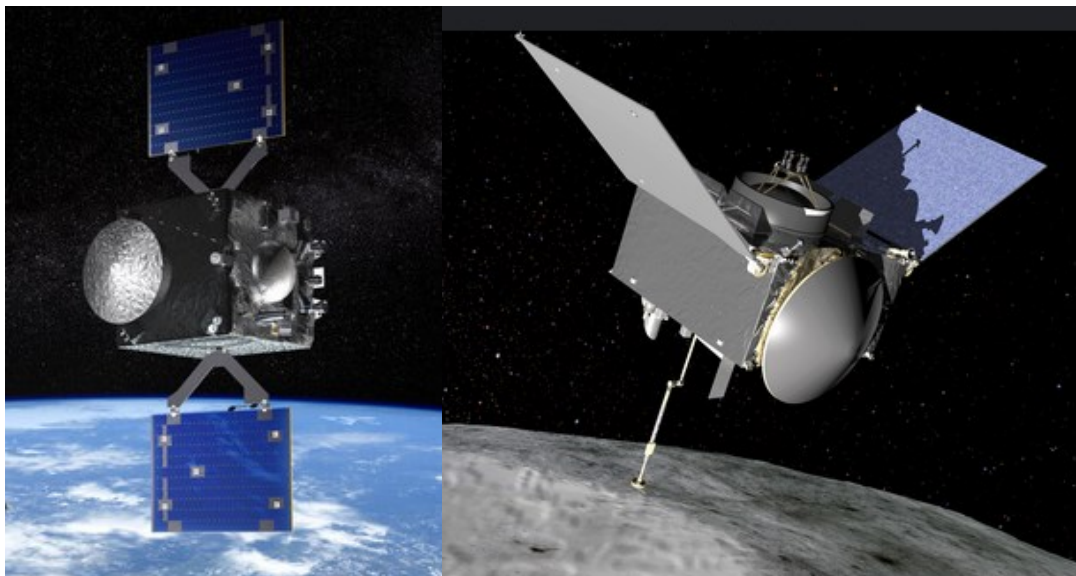
Figure 3.3 is the result of this NASA study and shows the relationship between the kinetic energy of the asteroids and the minimum distance to the centre of the Earth. Moreover, in the figure is shown the year at which the closest approach happens. Other asteroids are mentioned but the distance is greater and so the kinetic energy, making them less dangerous for Earth. Apophis is within the boundary set by the resurfacing limit which according to (Yaeji Kim, 2023) sets the minimum distance at which an asteroid can pass near Earth and still cause some damages.

For all of these reasons, Apophis asteroid is a unique opportunity to get samples and study possible strategies for Planetary defence. Moreover, as the orbit of it

is already predict, it is known that it will pass near Earth in 2036 and the results of the mission of 2029 like this one can be compared.

### 3.3 Current mission to study Apophis

As seen previously, the fly-by of Apophis is an extraordinary event, therefore there are several companies interested in its study. These missions commonly are directed by a “Prime” company that opens slots to fly with them until the asteroid. In this mission, OHB is the prime the spacecraft from ESA called RAMSES, which has slots in it to bring to space other missions as the APOSSUM or MASCOT from DLR are.



**Figure 3.4 Photos of OSIRIS-REx and RAMSES (Wiechern, 2023), (Romanos, 2024)**

Other relevant mission is NASA's OSIRIS-REx Mission from NASA to study its structure and composition (NASA, 2024). It differs from RAMSES in the launcher, in this case Falcon 9 is used, which has the advantage of lowering the costs since it is reusable.

### 3.4 Technological Challenges in Sampling from Apophis

Landing on an asteroid is a challenge for a spacecraft from the mission point of view due to the fact that two trajectories have to converge in one point and as

seen before, the kinetic energy is high and so the velocity of the asteroid. Moreover, when arriving to the vicinity of it, the asteroid must be thoroughly studied in order to get an approximation of the gravitational field around and so the possible forces that the spacecraft will encounter.

### **3.4.1 Low gravitational scenario**

The first problem that the spacecraft will face is the low gravitational field, this makes the landing more complex since thrusters have to correct the trajectory and land on the surface. Moreover, the velocity of landing must not surpass the limit imposed by the requirements of the mission and the maximum area of target is also a requirement.

As mentioned before, the studied made on Apophis have not yet provided a good approximation of the interior of the asteroid and so, the density in the landing place have to be studied when arriving to the vicinities. This assessment is crucial for the mission since it can happen that the landing location is on a porous region making the mission unsuccessful. The reason of this is that there is a need on a rigid surface in order to properly support the spacecraft. Otherwise the collection of samples and staying there would undergo a complication because more propellant will be needed in order to stabilize, therefore increasing the risk of the mission.

### **3.4.2 Sampling mechanisms**

On the other hand, there are also complications in terms of the sampling mechanism. The mechanism must minimize the disturbances to Apophis trajectory during sampling and upon arrival.

Moreover, the sampling mechanism has the following parts for a successful mission. They are mentioned to have a more in depth of the challenges.

- **Brush Wheel Mechanism (BWM):** The mechanism is responsible for collecting the micro-rocks from the surface. It is equipped with motors and brush that rotates to get samples from different materials and introduce them in the tube that connects with the tank

- **Sampling Containment System (SCS):** The SCS is the component that stores the collected samples.

As one can deduce, the main challenges of this sampling mechanism come from the uncertainty in the material of the surface combined with the micro-gravity environment which makes difficult the retention of the rocks in the container. Moreover, if the material is too hard, the brushers may only be able to extract dust from Apophis.

### **3.4.3 Communication issues**

Apossum is a small spacecraft that is not able to communicate with ground directly, therefore it uses RAMSES communication system as support. The problem of this approach relies on the tumbling behaviour of the asteroid. This means that for some periods of time, the communication link is unavailable and therefore, the sampling mission has to be autonomous since if control is required, is it impossible to do it successfully.

### **3.4.4 Radiation exposure**

This is not crucial for the landing scenario but rather for the return from the asteroid to Australia. This is important to be computed using the available software (in this case STK and Python) to size the radiators of the mission.

## **3.5 Modelling techniques for Asteroid Characterization**

There are several techniques when modelling an asteroid. The first step is to obtain a good model shape of the asteroid, which is achieved by using radar observations. Although it is an accurate method, it has to be combined with other observational techniques like the visual one or the infrared.

Gathering all these information the space agencies are able to reconstruct a shape model that matches most of the observations. In the case of Apophis, and due to the fact that the periodic approach to Earth occurs every 7 years, there are 2 main models to use, the tetrahedral one used in this study and another used in (Daniella N. Della Giustina, 2023). The choice for the model use in this study is explained in further sections.

Once the model is well characterized, the mass must be added in order to obtain a gravitational field needed to compute the perturbations that a spacecraft will encounter in the vicinities of the asteroid. This analysis is done in depth for the landing scenario in this study. However, for other missions, it is also relevant to obtain it if the spacecraft will be orbiting the asteroid or other celestial body.

### **3.5.1 Spherical Harmonics**

Spherical harmonics are a mathematical tool that originate from Laplace's equation in the spherical domains. They are used in astrodynamics to model the shape

of the celestial bodies and compute their gravitational field with more insight. Normally, celestial bodies do not have a perfect spherical or ellipsoidal shape, but rather a more complex one. Due to the nature of these mathematical functions (orthogonal ones), every function on the surface of a sphere can be expressed as a sum of spherical harmonics (Wikipedia, 2024).

Moreover, this method is used for great celestial bodies like Earth to compute the perturbations that the satellites may encounter in its orbit. Another notable application in the industry is its successful use in the detailed characterization of Bennu, particularly regarding its shape and gravitational field (Blažej, 2021).

The main advantage of this approach resides on the simplicity. The computational cost is directly proportional to the degree of harmonics used. Therefore, for an asteroid whose shape is regular, the number of harmonics will not be high and accurate results can be obtained at a lower computational cost (high meaning more than 15 degrees). Furthermore, this is a method proven in several scenarios as mentioned earlier and therefore there are libraries and resources online that facilitate their integration in the mission.

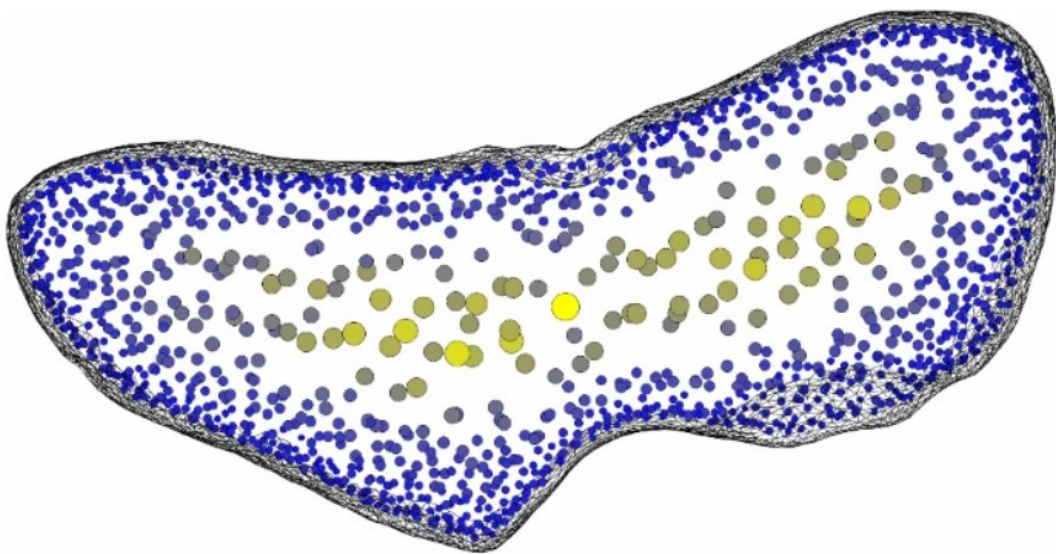
On the other hand, this method is not suitable for complex shapes where a greater degree has to be used to get a reliable result. Therefore, this method is more suitable for characterizing a celestial body like Earth or Mars.

### 3.5.2 Mascon

Mascon method is a pivotal tool for asteroid mass characterization, it is useful to compute the gravitational field and have a deeper understanding of their internal mass distribution (Jason Pearl, 2016).

The approach is based on the process on fulfilling the shape of the asteroid with point masses and therefore being able to represent complex density and mass distribution. These methods have been proved to improve the classical ones like Spherical harmonics, according to (Jason Pearl, 2016).

Nevertheless, this method has some disadvantages that must be accounted for. The computational complexity increases exponentially when dealing with asteroid with great size or complex shapes. This happens because the number of point masses raises and therefore the value of each of them. Moreover, the results depend greatly on previous results to have a better estimation of the accuracy (Paul, 2015).



**Figure 3.5 Example of a MASCON distribution to a random asteroid (Pearl, 2022)**

Furthermore, according to recent studies, the algorithm can be improved by combining spherical harmonics and mascon (Patrick, 2019).

### **3.5.3 Tetrahedral method**

This method is the one used in this study. It is based on dividing the whole volume of the asteroid in tetrahedral and enables the user to obtain a detailed result, which is crucial in order to compute the gravitational potential and perturbations that the spacecraft will encounter in the landing scenario.

As mentioned, the whole volume is dividing in tetrahedrals using the vertices of the shape, in this case (NASA, 2021) (3D Asteroid Catalogue, 2021). Once the vertex are known, a reference point is needed to build the tetrahedrals, depending on the shape, one or more will be needed (the reason of choosing a larger number of references is explained in further sections).

Due to the similarity of the shape model to an ellipsoid, it was the most suitable model to perform the computation, using as reference point the origin of the cartesian coordinates.

Although this method is really accurate and fulfils the whole volume providing reliable results, it is not suitable for all the asteroids shapes. The reason is because if the shape is really complex with branches on the sides, the model will lack on the volume computed and therefore the mass can be less or more than the real one making the result less accurate.

On the other hand, this method is computationally efficient, due to the fact that the process to a numerical integration method but in a volume, therefore it is efficient. Additionally, due to its simplicity, it can be adapted to other shapes and optimized in case of a complex shape that needs multiple reference points.

## **3.6 Control Techniques Applicable to Asteroid Missions**

Control techniques are an important tool when dealing with a landing mission in a scenario where several forces disturb the trajectory of the spacecraft. In this case, the control techniques were applied to the case of a small spacecraft trying to land on a specific location on the surface of an asteroid. Without this mathematical techniques, landing would be impossible since the gravitational field would not provide sufficient stability for a smooth and safe landing.

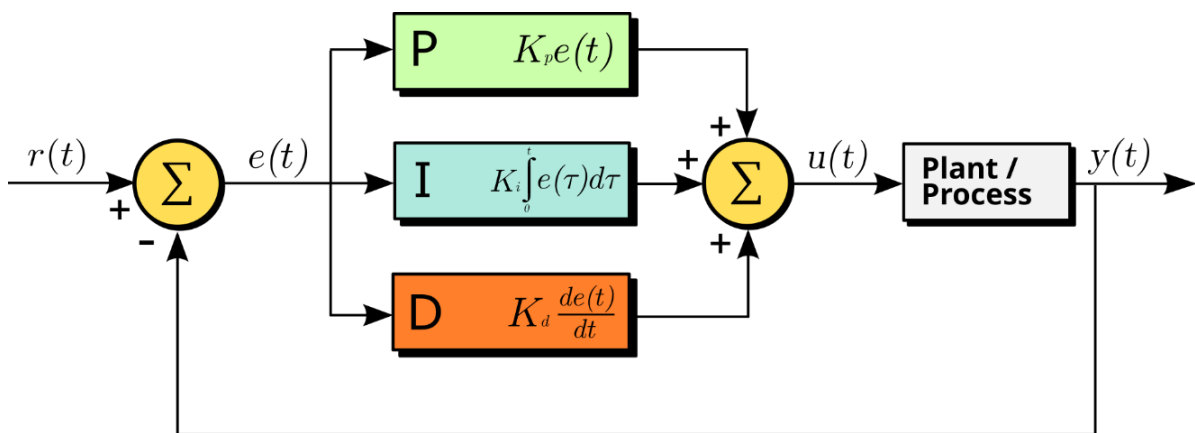
Moreover, these techniques are also really valuable in this type of scenarios as well as in rendezvous strategies because even if the spacecraft encounters a scenario where multiple forces are trying to deviate it from the expected path, the control manoeuvre is able to correct it and perform a straight approach so keeping contact with the destination.

Among all the techniques available, those that are most suitable and relevant for these type of missions, are explained in this section.

### 3.6.1 PD, PI or PID Control

It is a simple approach to the problem and very convenient when dealing with problems that involve rendezvous or landing on a specific location. This control techniques are also applied to AOCS and GNC subsystems.

The PID is the most generic case where the controller uses three control variables of proportional, integral and derivative influence on the controller output to apply accurate and optimal control (Wikipedia, 2023)

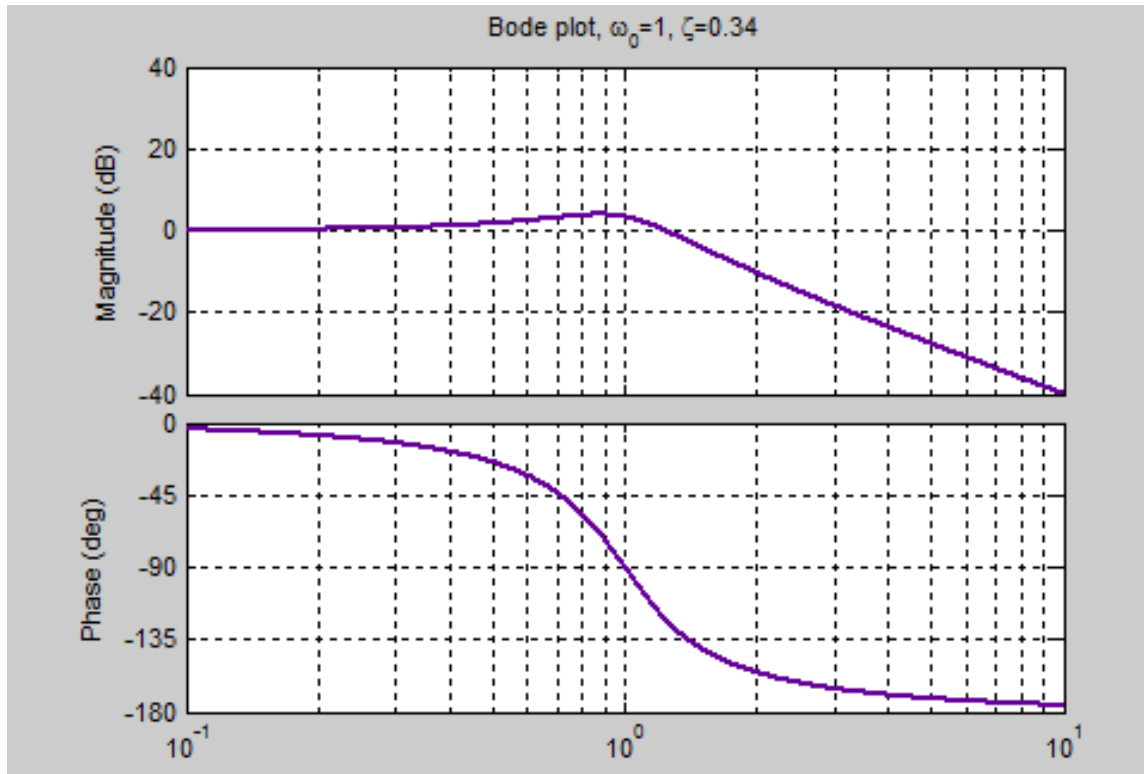


**Figure 3.6** PID loop diagram (Wikipedia, 2023)

Figure 3.6, shows the typical diagram of a PID control loop diagram. P is the proportional gain, I the integral one and D the derivative. If a PD control is used, only the derivative box will appear in the diagram.

The advantages of this method reside on the fine tuning that is able to obtain more accurate results. Moreover, this control technique, enables the user to

refine the results by modifying the poles and gains of the loop and therefore obtaining better bode plots.



**Figure 3.7 Bode plots example (Cheever, 2022)**

Figure 3.7 shows an example of a Bode plot, which is defined as an instrumental representation of the response of the system. In the case studied in this report, the Bode plot would display different magnitudes (velocity and position), but the appearance remains similar. (Cheever, 2022)

These methods are commonly used in the industry due to its easy implementation and the number of libraries and resources available. MATLAB, has Simulink, where these plots can be generated and fine tuned. Simulink is the software used by space industries for control techniques and to verify the possible manoeuvres that a satellite can perform . On the other hand, Python has many libraries to assist with the implementation. Moreover, the methods are robust, flexible and its accuracy can be further improved as mentioned earlier. (Softinery, 2024)

### **3.6.2 Bang-Bang Control**

This technique is simpler than PID control loop, it bases the strategy in a loop control where the thrust switches between maximum value and 0 thrust. The advantage of this control technique resides on the simplicity of the algorithm, it is close to an if else condition but taking into account in each time step the error.

For simple scenarios, where the spacecraft encounters a uniform gravitational field and the target's tolerance is wide, Bang-bang control techniques remains as a good option to consider. Moreover, another advantage that this method has, is the time saving. Since maximum thrust is used, the spacecraft takes less time to reach the target location. (Control Systems, 2021)

Therefore, this method is suitable for those missions in which the time of travel is a strict requirement, and the fuel spent and accuracy is not a driver for it. Nevertheless, in this study, this alternative will be studied in case the difference of fuel is not great and if it meets the requirements of the accuracy. (Kun, 2023).

### **3.6.3 Advanced Autonomous Control Algorithms**

Advanced Autonomous Control Algorithms are the next step in control strategy, they are used in industries like robotics, autonomous vehicles and aerospace. These techniques, go beyond the other methods presented, the accuracy they provide is higher but so the computational cost. The high computational cost comes from the ability to perform real time decision making and adaptive behaviour to respond to external perturbations or deviations that the hardware (satellite, spacecraft, robot or car) may encounter.

In the space field they can be used for the close rendezvous to dock 2 spacecrafts. The most famous scenario suitable for this is the docking strategy that a module can follow to dock to the ISS.

Moreover, in the recent years the use of artificial intelligence is being studied to be implemented in these kind of algorithms. This makes them even more computationally expensive and therefore a more complex hardware to use them for a deep space mission like the one presented in this report. Nevertheless, this

type of algorithms are too complex for the requirements of this mission since the target tolerance is of 3 meters and the communication link does not allow these complex strategies.

## 4 Methodology

In this section, the model used and the software tools to obtain all the results are explained.

### 4.1 Choice on the language for the simulations

The choice of selecting the programming language is crucial to obtain accurate results in an efficient way. Moreover, depending on the choice, the algorithms may be exported to other in a more easy or efficient way. For example, MATLAB is not an open source software and although it achieves good results and has many sources to do the job, it is not as flexible or has the number of libraries and webs to consult as Python. This is mainly because the MATLAB license can cost up to 2150 euros (Trustradius, 2024) for a standard license whereas Python is open-source.

Moreover, for the studied developed, Python is more suitable since it has the following libraries available that can help comparing results and boosting the time to achieve others.

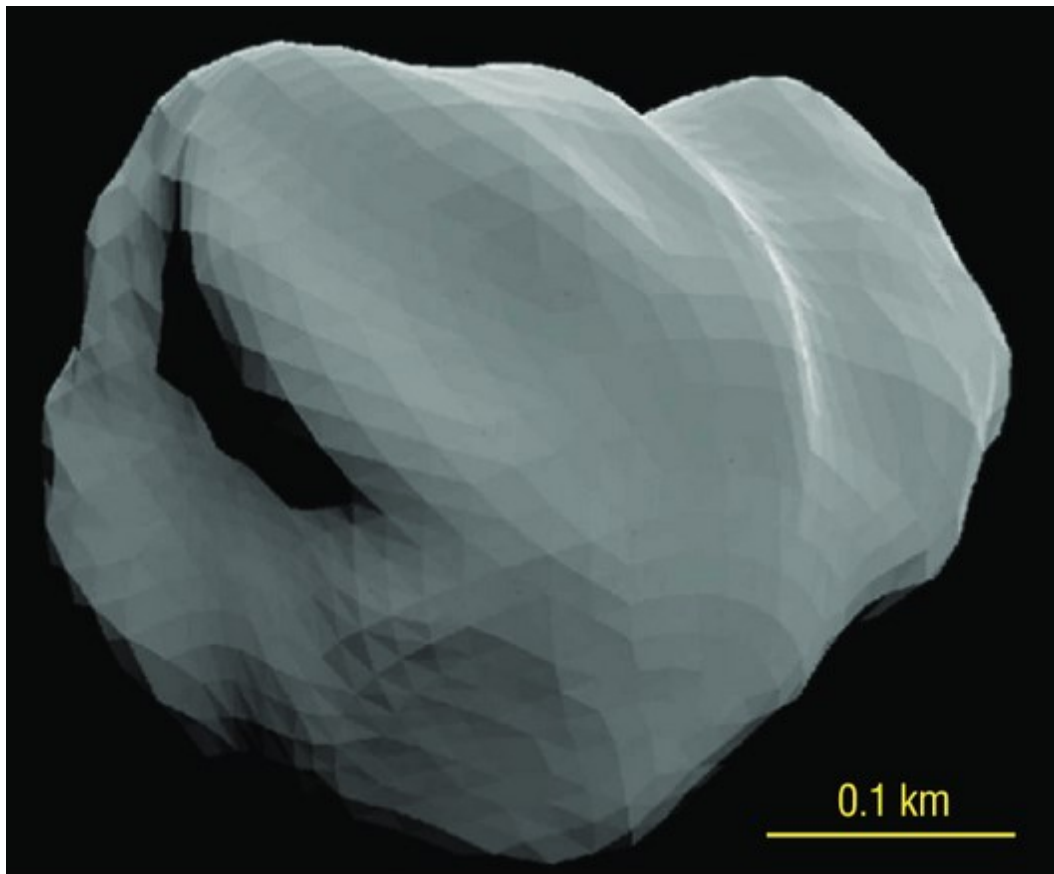
- Open3D: is a library used for 3D data processing and visualization. In this study it was used to handle the meshes and points of the shape of the asteroid in order to use them for the tetrahedral method or spherical harmonics. ( Open3D, 2024)
- NumPy: Is a fundamental library for numerical methods in Python. In the case studied, it was used for processing the data and to use numerical methods for integration and therefore obtain the orbits
- SciPy: This library was very useful to compare the results obtained numerically of the spherical harmonics and to ensure the accuracy of them is the one needed. The library imported was `special.sph_harm`
- Matplotlib: is a library used for data visualization. The plots shown in this report were obtained using this library. Moreover, a customization was done by importing also colours form it. (Matplotlib development team, 2024)

- Control: this library is useful when designing control systems, specifically the ones mentioned in earlier sections. (python-control.org, 2023)

By using these Python libraries, the study was able to leverage a flexible and powerful codes that can be implemented in further studies. Moreover, due to the choice in Python, all the code implemented can be adapted to other missions and asteroids by changing just few parameters.

## 4.2 Model Choice

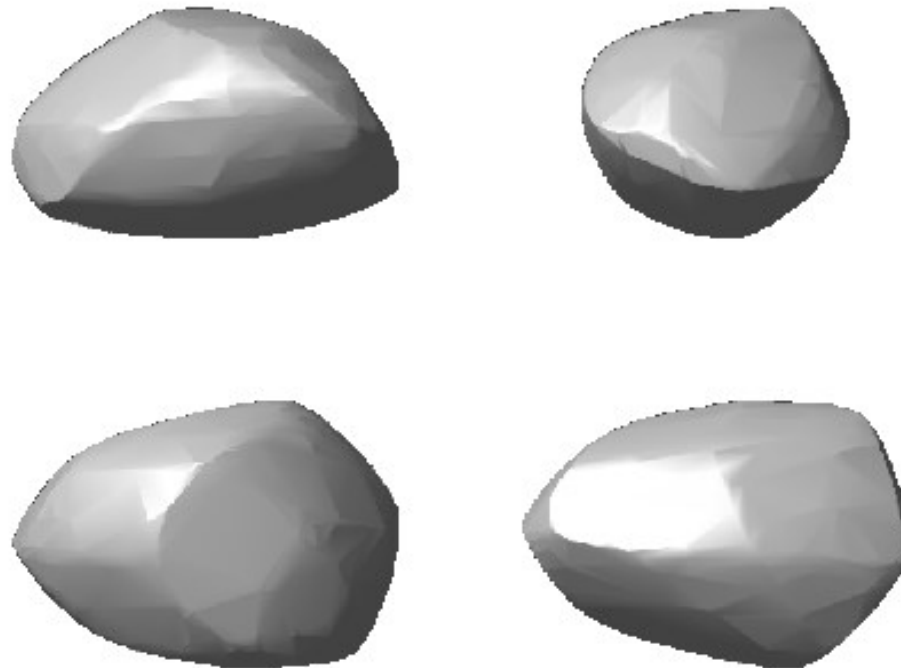
The differences between both models are based on the uncertainty of the middle part of the asteroid. The tetrahedral model is closer to an ellipsoid whereas the other has 2 lobes connected.



**Figure 4.1 Alternative model of Apophis (Daniella N. Della Giustina, 2023)**

Figure 4.1 shows a representation of the alternative model of Apophis asteroid, as described earlier, it has 2 lobes. The advantage of the model used compared to this one, is that it was being modelled with the radar observations from NASA

and it is published . Moreover, the model used has already been studied in detail and the shape and vertices do not have any issue they are fixed, the only need is the rescaling from the size that was published to the actual size of the asteroid.



**Figure 4.2 Model used in this study (Ji, 2017)**

As shown in Figure 4.2, the model is different from the other presented before, as the shape is closer to an ellipsoid and it is also modelled using NASA observations. Nevertheless, it has to be mentioned that there are no big differences from one model to the other since the study considers different density scenarios and the distances from the beginning of the landing scenario are of the order of kilometres.

### **4.3 Rescaling**

As mentioned earlier, the model used in this study required a rescaling. The rescaling must be performed keeping the characteristics and shape of the asteroid.

The procedure involves enlarging the dimensions of all the points and obtain the same shape but to the correspondent size. This, was accomplished using MeshLab which is an open source software used in design and suitable for this case since it reads the meshes and the resultant shape is exactly in proportion to the original one.

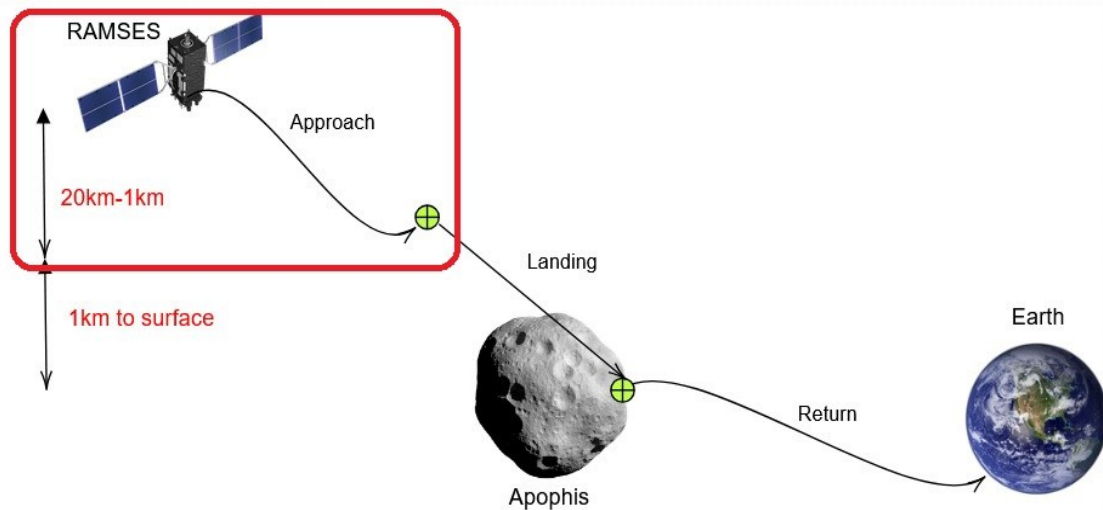
#### **4.4 Modelling and control techniques**

In this study, tetrahedral method and spherical harmonics are used and its feasibility is evaluated to be used for the final control landing scenario.

Moreover, the control techniques used are the most suitable for this mission: PD due to the simplicity and the appropriateness since the variables that play an important role are position and velocity, and Bang-bang, due to its ease in reaching the target location and its low computational cost.

## 5 Phase 1, detaching from Ramses

This scenario covers the mission time from the detach from RAMSES until the spacecraft arrives at 1 Km above the surface.



**Figure 5.1 Phase 1 of the mission**

The main objective of this first part of the mission is getting at 1 km height with respect to the centre of the asteroid from the worst case scenario given by ESA which is 20 km. Nevertheless, to go there, multiple options were considered.

- Going with Ramses: This is the main option for DLR since the host spacecraft will be from ESA and so it is easier to work with due to the fact that is a European company.
- DLR performing the whole navigation path from Earth to the encounter: This means that the spacecraft will be inserted in orbit and the whole navigation process until the nearby of Apophis has to be done by Apossum itself. This approach has many disadvantages since the structure itself has to be modified, this means that for example the propulsion system would need to be amplified with more thrusters and a bigger propellant tank for the whole journey. Moreover, the thermal and power subsystems will need to be changed since the spacecraft would remain longer times in deep space. For all of this reasons plus the fact

that it will be bigger, heavier, more expansive and more complex, this option was discarded.

- Going with NASA: It is a similar approach than going with RAMSES, but this time in another mission. The advantages and disadvantages are almost the same, nevertheless, the communication with ESA is better since it is a European agency.

Once the host spacecraft is known, the mission is adapted to their schedule. According to ESA (ESA, 2024), the launch year is 2028 so the mission has to be ready by then. Moreover, the arrival at Apophis will occur during March 2029. This approach will be different for RAMSES and DLR.

The objective is to detach from RAMSES spacecraft before the Science mission starts. This Science mission is the name that the phase during which RAMSES studies the asteroid has. During this time, ESA's spacecraft starts performing hyperbolic trajectories in the nearby of the asteroid to get a deeper understanding of its shape and materials. Furthermore, and using gravimeters, they are able to study the density more in detail. Therefore, in this phase, using STK, the trajectory from RAMSES to 1 km above the surface is computed (to obtain the delta-v needed and the time to perform the manoeuvre)

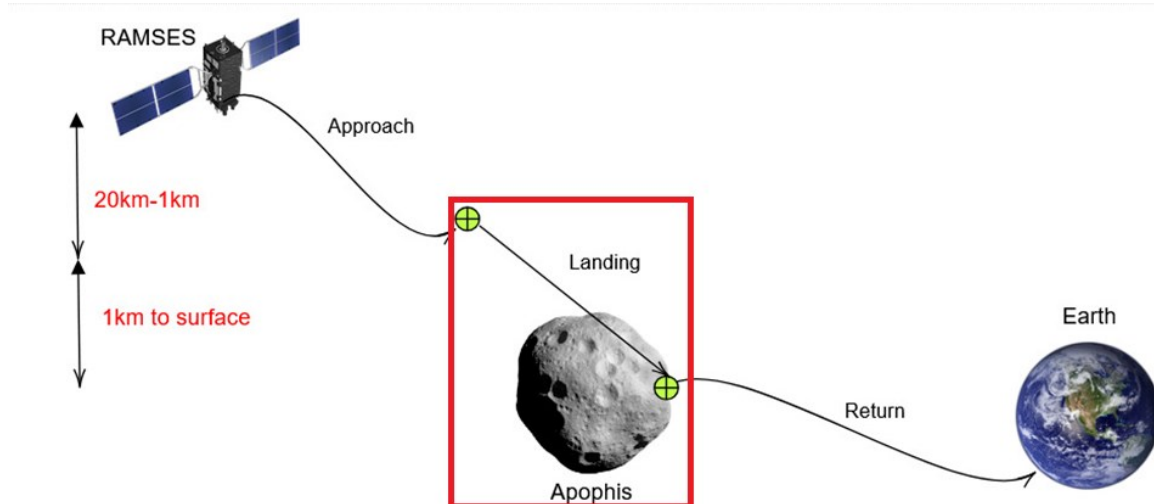
The checkpoint is at 1 km from the surface of the asteroid since the objective is to perform a navigation first and then check for possible problems in the surface of the asteroid that may lead to a failure in landing. Since the landing location is not selected before, the spacecraft must remain time at a checkpoint to see the feasibility.

Once the DLR's spacecraft detaches from the host, it will approach Apophis in a straight line. To compute the  $\Delta V$  and the time of transfer, STK software was used. Under this conditions, the asteroid is assumed as a ellipsoid with constant density and mass of  $6.1 \cdot 10^{10}$  kg. As it will be discussed in further sections, this approximation still leads to good results since 20 km and 1 km are distances far away to get any perturbations due to differences in densities inside the asteroid.

Once the simulation is done, the result obtained was 1.7 m/s to arrive at the checkpoint using the thrusters. To achieve that, the aim is not to be thrusting and correcting all the time but rather to change the orientation of the spacecraft towards the asteroid (detected by the cameras) and thrust in that direction. Since the distance is 20 Km no correction is needed, and was proved with the simulation in STK, for this phase of the mission.

## 6 Phase 2. Landing Scenario

In this section the second part of the mission is addressed and so the main part of this study.

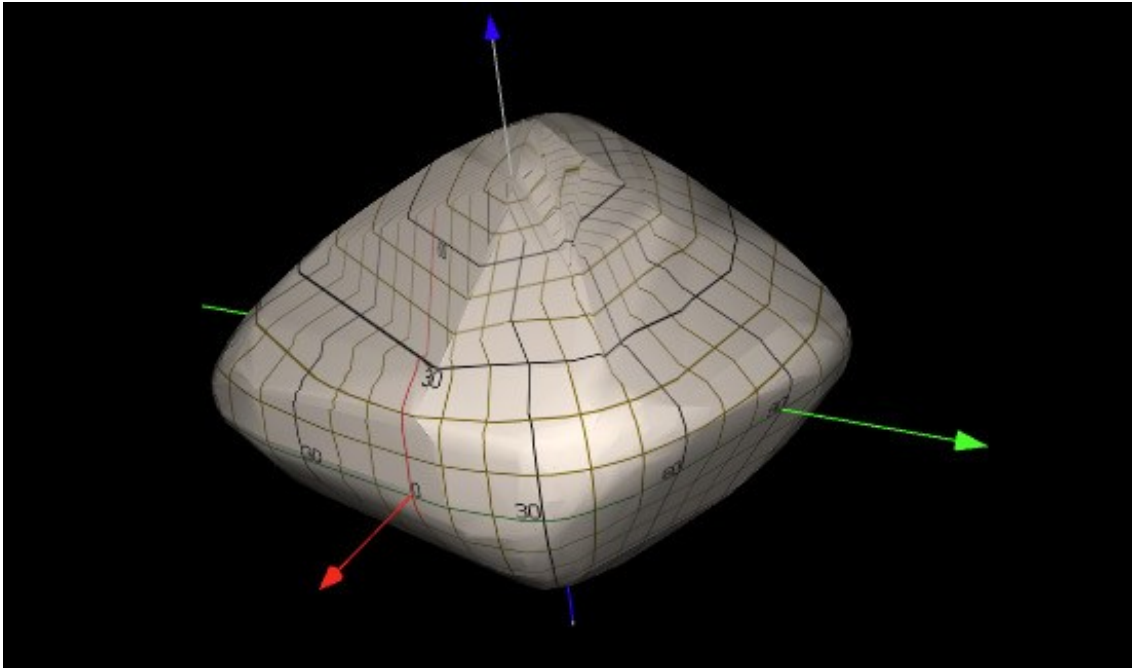


**Figure 6.1 Phase 2 of the mission, landing**

Several Python codes were developed in order to study the landing approach and the possible trajectories and perturbations that the spacecraft will encounter. Moreover, from this section on, the model of Apophis will be the one done by NASA with their own radar observations of 2013 (NASA, 2021).

The Apophis shape model was rescaled using MeshLab, a software whose main objective is to edit meshes in order to enable them for a later work (Paolo Cignoni, 2008) (MESHLAB, 2024). These works are from the engineering point of view and from others like art or architecture. Nevertheless, it satisfied the requirement of rescaling the model accurately and that was the reason to be used.

The first step was rescaling the reconstructed model in line with the asteroid's known physical dimensions, so the simulations would be more realistic for the APOSSUM mission (DLR's spacecraft). This rescaled mesh is used as the geometric model for further gravitational and landing dynamics and control simulations, explain in later sections.



**Figure 6.2 Model used (3D Asteroid Catalogue, 2021)**

Variable	Dimension [m]
x axis	450
y axis	370
z axis	170

**Table 6.1 Dimensions of the asteroid Apophis (M., 2024)**

As can be seen, the physical characteristics of the asteroid are close to those of an ellipsoid, making the initial approach for the first part of the mission a good approximation. Moreover, the overall mass, has not yet been computed accurately. This is due to the challenges associated with accurately approximating the mass, density, and their respective distributions based on the measurements available. Nevertheless, based on a study of 2021 (G. Valvano, 2021) in which several densities are tried and the characteristics of it studied, resulting in a total mass of  $2.1 \cdot 10^{10}$  to  $6 \cdot 10^{10}$  kg.

## 6.1 Constant density scenario

In this subsection, the constant density approach to modelling the asteroid Apophis for the APOSSUM mission is explained in detail. For a first approach to the problem, constant density is applied to the whole volume of the asteroid. This is done to provide a simplified scenario to the one that the spacecraft will face when the landing takes place. Moreover, a constant density approach is useful to verify that the process that will be used for the complex scenario works properly and as expected.

Finally, by comparing this approach to the variable density model use in further sections, the implications of some of the assumptions in terms of density will be shown and therefore conclusions can be made for future missions whose objective is to land on an asteroid.

The model used is a shape model and therefore it has planes and vertices that form the asteroid shape. Therefore, the model has no mass or density properties and they have to be computed. This, can be done either by Spherical harmonics or tetrahedral method. Both techniques are going to be explained, their strengths are highlighted, to see which one is more suitable for the mission

### 6.1.1 Mesh Processing and Area Calculation

The model is imported to the code and the geometric properties of it are obtained. Since the model is based on vertices and planes, the vertices locations are going to be key for the whole method. First, Heron's formula (Britannica, 2024) is used for all the triangular facets of the mesh, since it is important for an accurate distribution of mass over the asteroid's surface assuming a constant density.

$$Area = \sqrt{s(s-a)(s-b)(s-c)}$$

(6-1)

Where:

- a, b and c are the sides of the triangle
- s is  $(a+b+c)/2$

This is done to compute all the triangles' areas that are in the shape model and are going to be used in further calculations.

### 6.1.2 Spherical Harmonics for Gravitational Field Representation

Once the model is well characterized (all the triangles and vertices are located and the area obtained), the spherical harmonics are computed. These are series of orthogonal functions defined on the surface of the sphere to solve problems which involve Laplace's equations in Spherical coordinates. They are used to compute the imperfections of an object and to model it. This approach is convenient from the computational point of view but also from the analytical one since they are able to give results in a short period of time while keeping the accuracy in them.

$$Y_n^m(\theta, \phi) = \sqrt{\frac{(2n+1)(n-m)!}{4\pi(n+m)!}} P_n^m(\cos\theta) e^{im\phi}$$

(6-2)

Where  $P_n^m$  are the associated Legendre polynomials and  $e^{im\phi}$  represents the complex exponential function, essential for incorporating azimuthal symmetry.

$$Y_n^m(\theta, \phi) = -\frac{GM}{r} \left( 1 + \sum_{n=1}^{\infty} \left(\frac{R}{r}\right)^n \sum_{m=-n}^n C_{nm} Y_n^m(\theta, \phi) \right)$$

(6-3)

where:

- $r$  is the radial distance
- $\theta$  and  $\phi$  are the polar and azimuthal angles respectively
- $G$  is the gravitational constant
- $M$  is the total mass of the object
- $R$  is the reference radius of the object which is 185m
- $C_{nm}$  are the coefficients of the spherical harmonics terms

- $Y_n^m(\theta, \phi)$  are the spherical harmonics functions.

In this case, the maximum degree of harmonics used was 20. According to (O. Jamet, 2010) normally between 20 and 25 could be used to model an asteroid with this characteristics so I used 20 since the change in detail is minimum (the differences using both number of degrees is less than 1% (GASKELL, 2010), (O. Jamet, 2010) )and is more computationally efficient.

After applying previous equation, the spherical harmonics  $Y_n^m$  are decomposed by separating the azimuthal dependency into real components. Knowing that  $Y_n^m = P_n^m(\cos\theta)e^{im\phi}$ , and knowing that the exponential term can be separated unto real and imaginary part. This allows to compute only the real gravitational potential which is the responsible for the perturbations that the spacecraft will encounter.

Once the harmonics are computed, the potential can be obtained using the equation 6-4.

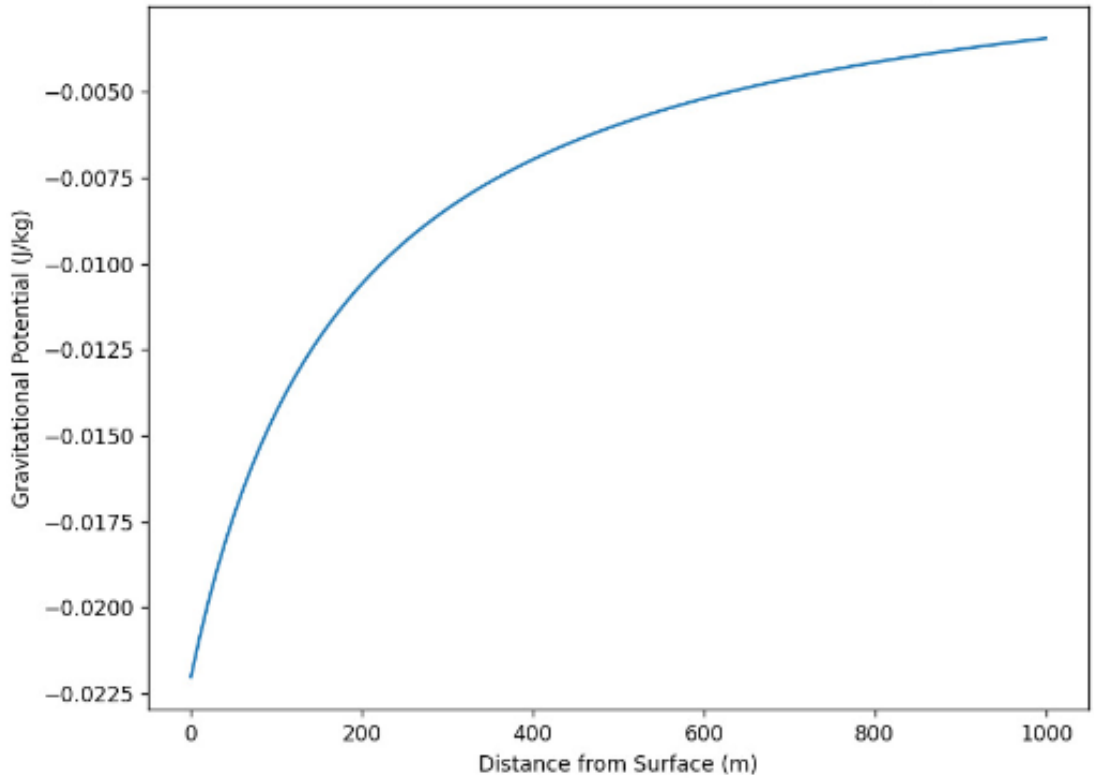
$$\mathbf{V}(\mathbf{r}, \theta, \phi) = -\frac{GM}{r} \left( 1 + \sum_{n=1}^{\infty} \left(\frac{R}{r}\right)^n \sum_{m=-n}^n P_n^m(\cos\theta) (C_{nm}\cos(m\phi) + S_{nm}\sin(m\phi)) \right)$$

**(6-4)**

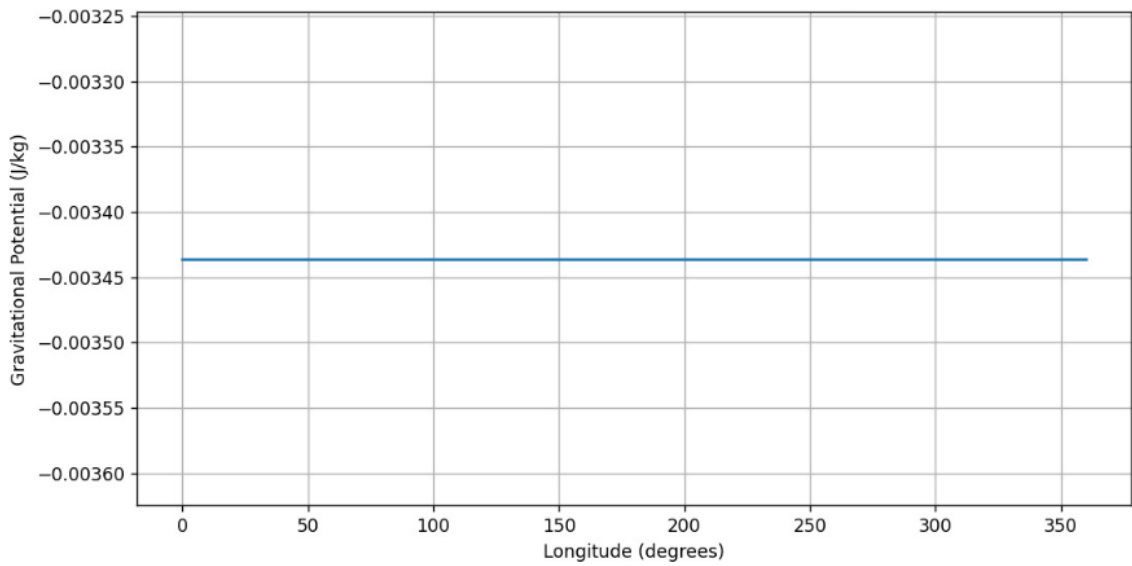
where:

- V is the gravitational potential,
- R is the reference radius, which is considered to be the mean radius of the asteroid.
- $P_n^m(\cos\theta)$  are the associated Legendre polynomials,
- $C_{nm}$  and  $S_{nm}$  are the coefficients of the spherical harmonic terms.

Now in order to test if it was correct or not, the centre of mass was computed and the potential expected at 1 km away from the surface giving the results shown in Figure 6.3.



**Figure 6.3 Gravitational Potential from Surface to 1 Km away**



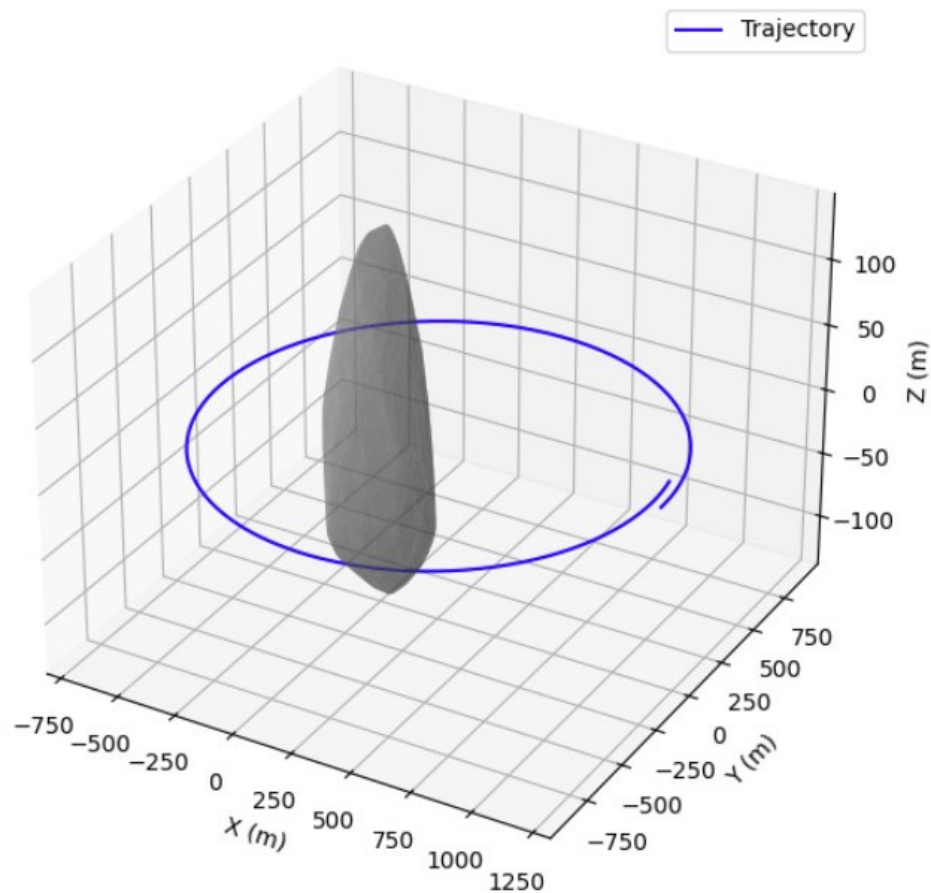
**Figure 6.4 Gravitational Potential at 1 Km from the Surface along the Equator**

As it can be seen the potential is almost constant and its value is very closed to the theoretical one given by  $\frac{GM}{r}$  so seems reasonable (with  $6.1 \cdot 10^{10}$  kg). Choosing a random height, the gravitational potential matches the theoretical one. The use of 20 harmonics instead of 1 is due to the increase in precision and to account for the non-spherical shape of the asteroid. Furthermore, the 20 harmonics do not play an important role when measuring at 1 km from the surface but for a landing scenario it is important to have a well characterized asteroid.

Moreover, one may notice that the potential is really constant, this is due to the location of the centre of mass, which is shifted few meters from the origin, according to the simulation, less than 1 meter.

Once the potential is well known and computed, the computation of the trajectory can be obtained. To do so, basically the force is computed knowing that  $F = -\frac{dU}{dr}$ . With that in mind, a dynamics function is created and using Runge-Kutta 45 method, the trajectory is computed.

The trajectory is computed for the simplest case, so only gravitational perturbation. To do so, the general formula of circular orbital velocity is used  $v = \sqrt{\frac{\mu}{r}}$  with  $\mu$  being  $G \cdot M$ ,  $M$  being  $6.1 \cdot 10^{10}$  kg



**Figure 6.5 Trajectory around Apophis model**

As one may notice, the result is pretty accurate to the theoretical one, so making this approach reliable for further studies.

Once the gravitational attraction was modelled, the other main perturbation that the spacecraft will suffer is included and is the SRP (Solar Radiation Pressure). In order to model it, the spacecraft dimensions must be included. From the CEF study, the mass of Apossum is 100 kg and the cross-sectional area is 0.2205 m<sup>2</sup> (in this case worst case scenario was assumed and so always facing to the Sun in such a way that the area is maximum).

The SRP formula is computed assuming 1 AU from Sun and constant.

$$\vec{a}_{SRP} = \frac{P_{SRP} A_{SRP}}{m_{s/c}} \vec{s}$$

**(6-5)**

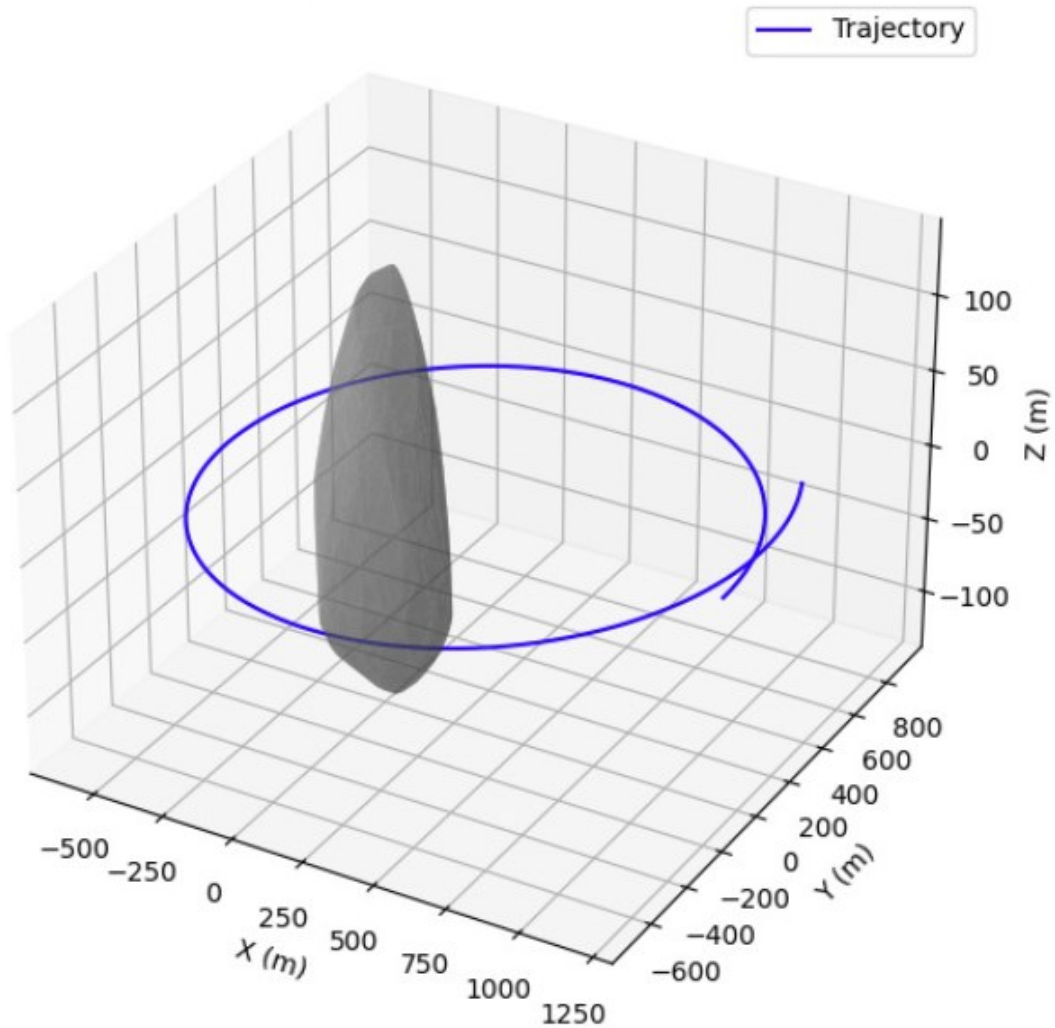
Where:

- $a_{SRP}$  is the acceleration due to radiation pressure
- $P_{SRP}$  is the solar radiation pressure at 1 AU (Astronomical Unit) in  $N/m^2$
- $A_{SRP}$  is the cross-sectional area of the spacecraft affected by the solar radiation in  $m^2$
- $m_{s/c}$  is the mass of the spacecraft in kg
- $\vec{s}$  is the unit vector from the spacecraft towards the Sun, assuming the Sun's influence is along the positive x-axis.

It has to be mentioned that some assumptions were made, PSRP was assumed to be constant since it is very close to 1 AU and the value does not vary much as one can see in (Ha, 2010). Moreover, the direction of the pressure was along the x-axis, this is such since it has to be worst case scenario and still the position of release from Ramses is unknown.

With all those factors taking into account and including them in the dynamics function, the trajectory once again with the same initial conditions as before is computed.

### Trajectory around Apophis with Model



**Figure 6.6 Trajectory around Apophis with SRP**

It can be seen in Figure.6.6 that the orbit has changed and it is shifted towards right so the SRP was correctly included. the variation is not much, but enough to take it into account from the control attitude point of view.

As one may have noticed, this part is not what is expected in real life since the density it is very uncommon to be uniform. So, the study will be focused more on the non- constant density scenario from now on but keeping in mind this results in order to verification and make sure further results are reliable. This is such since the base has to be correct since for more complex approaches, the distinction between a correct orbit and an incorrect one is difficult to distinguish.

Although these calculations are not the result of using the configuration of the real scenario, a deeper understanding of the techniques use nowadays are obtained and so, verifying the results obtained in further sections.

Besides, these results are important for confirming the robustness of the models and control algorithms used. They will form a basis on which any future improvements and refinements are made, thus making future missions more precise and reliable.

## 6.2 Tetrahedral method for modelling

This is an alternative method to the classical spherical harmonics. In this case the orthogonal functions are not used and the method tries to mesh all the interior of the asteroid to compute its properties and perturbations that will cause in the vicinities.

With the study made before, the trajectories are computed. This is done not only to verify the calculations are correct but also to further studies for the landing scenario.

Firstly and before computing the trajectories, the centre of mass is obtained using equation 6-6

$$\vec{r}_{cm} = \frac{\sum_{i=1}^n m_i \vec{r}_i}{\sum_{i=1}^n m_i}$$

(6-6)

Where

- $m_i$  is the mass of the i-th tetrahedral element of the asteroid
- $\vec{r}_i$  is the position vector of the i-th mass element with respect to the coordinate centre.

Once the centre of mass is computed, the actual method is implemented. the whole volume of the model is divided in tetrahedral elements (using the mesh) using 3 vertices and one middle point chosen to be in the centre of the asteroid

$$m = \rho \cdot V$$

(6-7)

where  $\rho$  is the density used and  $V$  the volume of the tetrahedral obtained with the 3 points in the surface and the reference one. Once the mass is obtained, it is divided in the 3 points of the surface of the asteroid to try to recreate the same perturbation created by the corresponding volume.

Once the mass is computed, the gravitational force exerted by all the mass elements is obtained in each time step and so equations 6-7 and 6-8 are used

$$\overrightarrow{a_{grav}} = -G \sum_{i=1}^n \frac{m_i(\vec{x} - \vec{r}_i)}{|\vec{x} - \vec{r}_i|^3}$$

(6-8)

- $\overrightarrow{a_{grav}}$  is the total gravitational acceleration exerted on the spacecraft by every mass element used in the asteroid.
- $G$  is the gravitational constant whose value is  $6.674 \times 10^{-11}$  is  $\text{m}^3 \text{kg}^{-1} \text{s}^{-2}$
- $n$  is the total number of mass elements. In that way with the sum, the force accounts for every mass element used.
- $X$  is the position of the asteroid.
- $|\vec{x} - \vec{r}_i|$  is the length of the vector difference between the spacecraft's position and the  $i$ -th mass element's position. This represents the distance between the spacecraft and the  $i$ -th mass element.

As one may have noticed, equation 6-8 corresponds to Newton's law of gravitational force, but in this occasion, it is exerted by several mass elements, which is why it is expressed as a sum.

Once this gravitational force is obtained the differential equation is used in order to compute the trajectories. This time it accounts not only for the perturbations due to the irregularities on the shape of the asteroid but also the solar radiation pressure.

$$\ddot{r} = a_{grav} + a_{SRP}$$

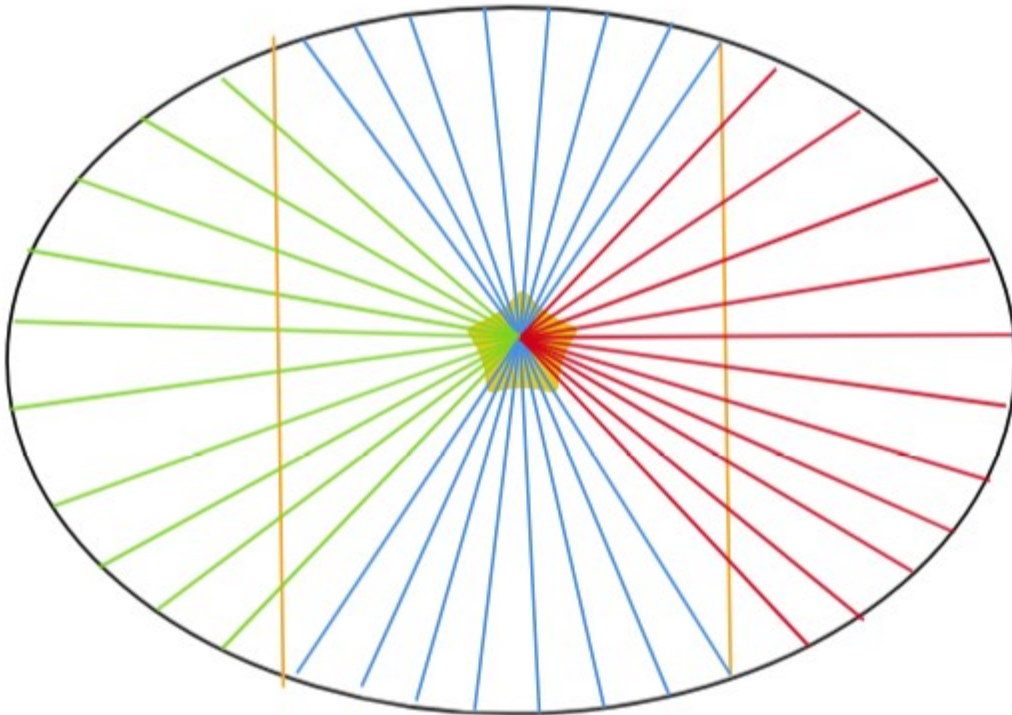
**(6-9)**

To obtain them there are several numerical methods available to choose from. In this occasion, the one chosen is Runge-Kutta. This choice comes from the fact that Runge-Kutta method provides a good balance between accuracy and efficiency in computational terms. This is particularly important for this kind of simulations, where small errors can be accumulated in each time step leading to bigger errors in the trajectory and so the Delta-v needed for the mission.

Specifically, the RK45 algorithm is used. This means that during the integration an adaptative step size is used which means it can adjust the step size dynamically based on the estimated error at each step. Furthermore, RK-45 is more stable than other lower-order methods and can handle non-linearities such as those that may arise in this kind of problems where gravitational interactions from many mass elements play a role.

### **6.3 Possible Incoherences using tetrahedral method**

This modelling technique is suitable for this asteroid shape since it is very similar to an ellipsoid. The reason is that, for all the vertices in the shape of the asteroid, a common point is used, this is the centre of the whole asteroid. To have a clearer view of the modelling procedure, Figure 6.7 is shown, where the procedure that this technique uses is explained visually.



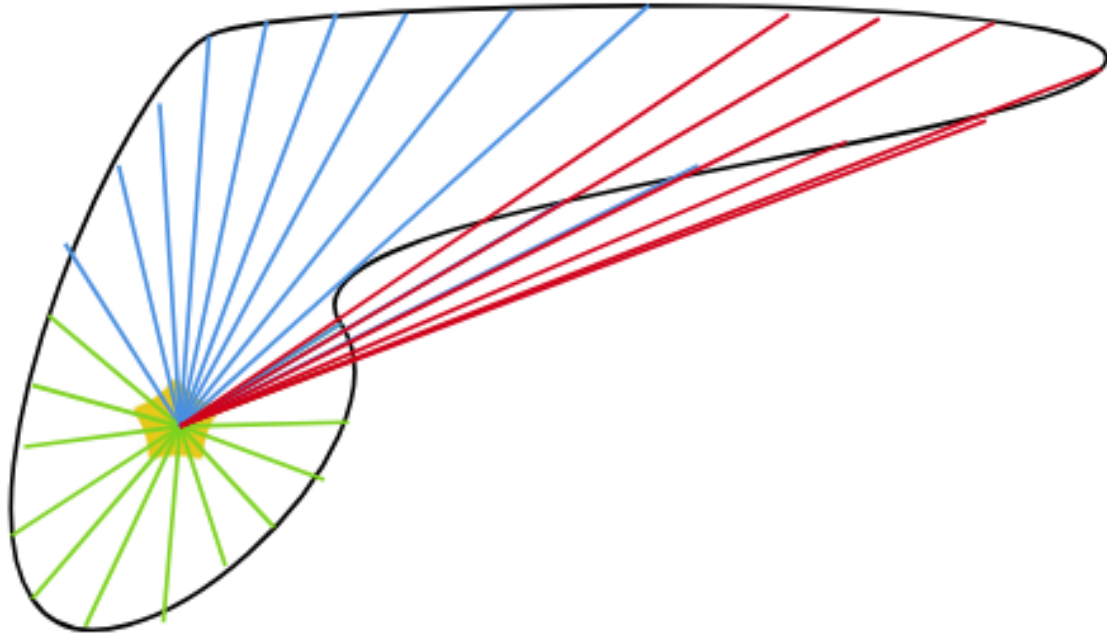
**Figure 6.7 Schematic graph of the modelling procedure**

Figure 6.7 is a schematic representation in 2D of the procedure followed to compute the overall mass of the asteroid. In this case for a deeper understanding since it reflects better how some areas may not be well covered, therefore, 3 densities were used but is the same for 1 density.

The orange lines delimit the areas with different densities and the star is the geometric centre of the asteroid. The colours used for each density area are the same as the ones used in the code, as explained in Figure 6.7 .As it can be noticed, the whole area is covered with the triangles and so the mass will be consistent if this modelling technique is used. The same will happen if the shape is in 3D, to understand this better, the same shape rotated  $360^\circ$  has to be pictured and so, the whole 3D space will be modelled.

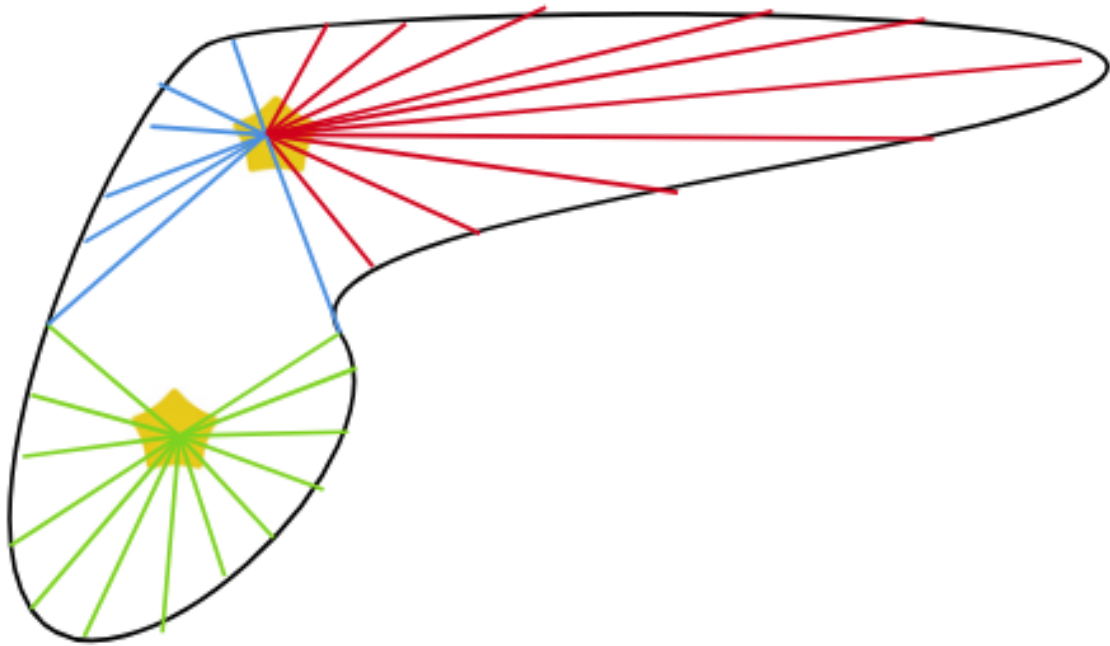
On the other hand and when dealing with more complex asteroid shapes, the procedure may need to be changed, the reason is that some areas may not be covered if the shape is very irregular or that some of the line from the mass

element towards the centre exits the asteroid and so the volume of the tetrahedral is not well computed.



**Figure 6.8 First impossibility found using a random shape of an asteroid**

Figure 6.8, represents a complex shape (not a real asteroid shape) in which the method described before is not suitable. As it can be seen, there are edges of the possible tetrahedral (in this case triangles since the shape is in 2D), that will be outside the figure. Therefore, the total volume computed will be bigger than the real case and so multiplying by the density, the resultant mass is also greater and therefore the centre of mass may be shifted to another location.



**Figure 6.9 Second impossibility found using a random shape of an asteroid**

A possible way to solve this problem, could be using more than one reference points as it is shown in Figure 6.9 being represented with the golden star. Nevertheless, this does not solve completely the problem since there are holes between the stars that are not taken into account.

As a result, the whole volume is less than reality and so the mass. Therefore this is not feasible for very complex shapes. Although, there are other possible refinements that can improve the results like using more reference points or placing them in other locations within the shape of the asteroid.

This method can be thought of as a numeric method for integration but taking reference points to obtain the result. On the other hand, it has to be mentioned that there are other numeric methods to obtain the desired result like MASCONE.

#### **6.4 Constant density scenario using tetrahedral method**

In some studies about Spherical harmonics (Takahashi, 2014), a divergence in the results appear when trying to model a small celestial body, as in this case.

Therefore, to ensure that previous results were correct and that can be applied to other Apophis missions, tetrahedral method was used.

In this case the density was set to 3.2 g/cm<sup>3</sup> which is within the expected limits found in (G. Valvano, 2021). Therefore, to compare, the gravitational potential is computed using equation 6-10

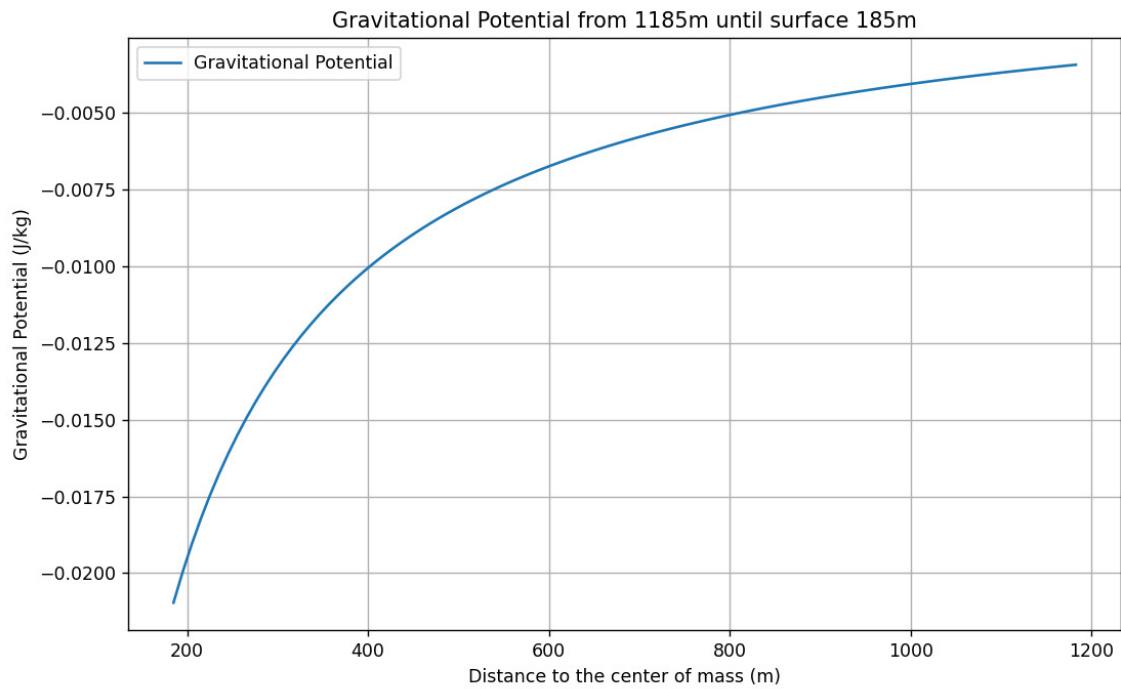
$$V(r) = - \sum_{i=1}^N \frac{G \cdot m_i}{|r - r_i|}$$

**(6-10)**

Where:

- $V(r)$  is the gravitational potential at the point  $r$
- $G$  is the gravitational constant ( $6.67 \times 10^{-11}$ )
- $m_i$  is the mass of the  $i$ -th tetrahedral element.
- $r_i$  is the distance to the  $i$ -th tetrahedral element

Therefore the potential can be obtained and it is shown in figure 6.10



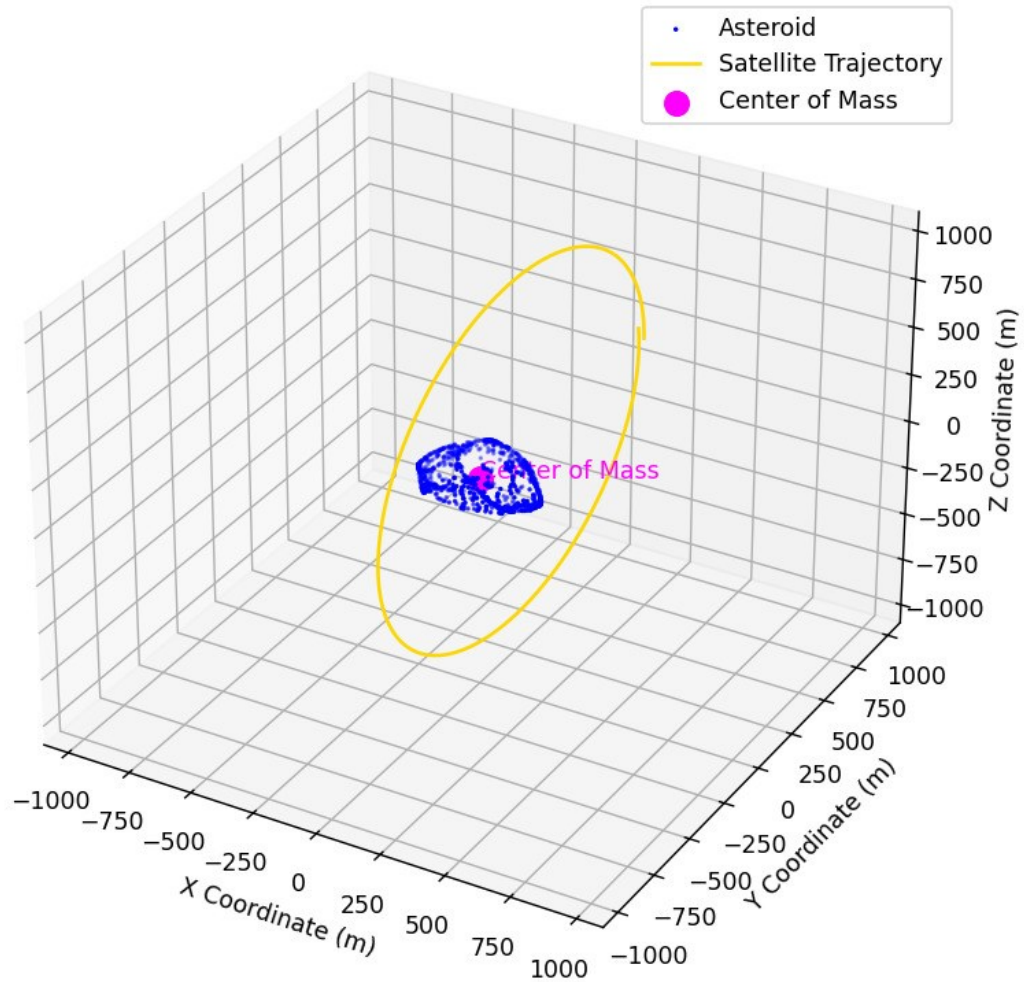
**Figure 6.10 gravitational potential for constant density scenario using tetrahedral method**

As it can be seen in figure 6.10, the gravitational potential values are very similar to the ones

obtained using spherical harmonics. Therefore it can be said that in this case the premise set before is not fulfilled since it does not diverge. Moreover, the values are identical, therefore reliable since they have been computed with 2 different methods and with the theoretical.

On the other hand, and to fully understand that the divergence does not occur in this case using spherical harmonics, the trajectories for this same scenario are obtained.

Center of Mass: [-6.81523682e-06 4.28016246e-06 -3.23602125e-08]



**Figure 6.11 Orbital trajectory around the asteroid using tetrahedral method for constant density scenario**

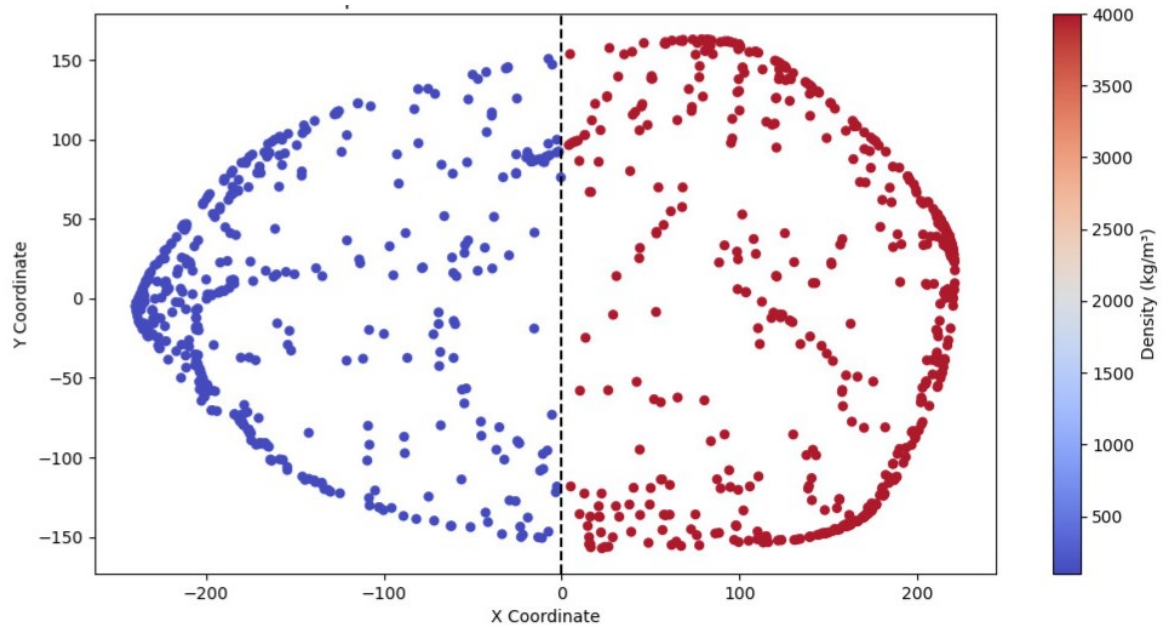
Figure 6.11 shows the orbital path of the spacecraft around the asteroid Apophis. In this case the total mass resultant using this density was the same as for the spherical harmonics. Moreover, the centre of mass is placed in the centre of the asteroid as it can be seen with shifts of the order of  $10^{-6}$  which is close to 0. Furthermore, the orbital period of this trajectory is the same as the one used in earlier sections for the alternative method (25 hours). Therefore the final trajectory will only vary in small details, since it looks identical one to another.

Once these figures are shown, it can be said that the proof of non-divergence of spherical harmonics has been completed.

## 6.5 Density study

This section examines density variation possibility which corresponds to a more plausible scenario for the mission.

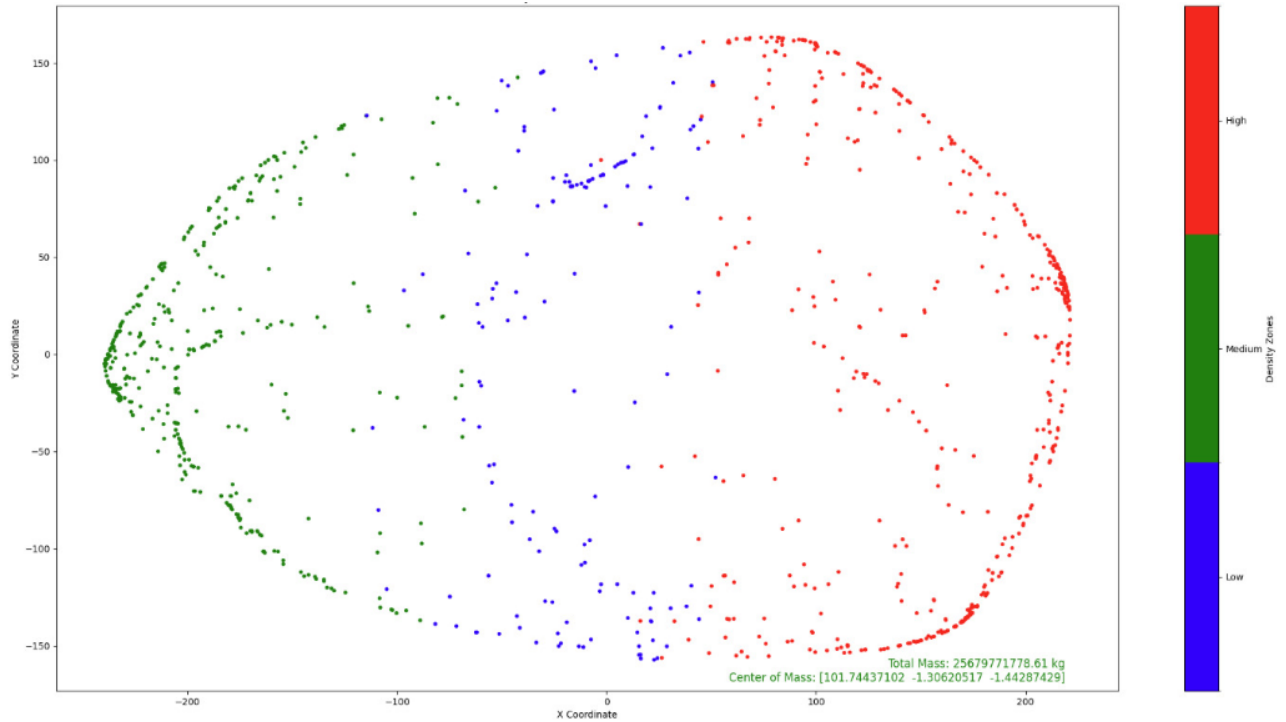
The first possibility was the one of the famous asteroid Oumuamua, this one has a specific density distribution in which there was a very dense part and another very light. By applying this knowledge (the density distribution with 2 lobes), derived from the findings on Oumuamua, to Apophis asteroid, and varying the density to be in accordance with the radar observations, the following distribution is obtained.



**Figure 6.12 Visual Representation of Mass Distribution on the Asteroid**

The densities used are in accordance with the radar observations (NASA, 2021) (M. Brozović<sup>1</sup>, 2022) and the distribution is within the expected values so in this case  $1000 \text{ kg/m}^3$  and  $4000 \text{ kg/m}^3$ .

Another scenario considers the presence of two dense lobes with a less dense region in between as seen in Figure 6.12



**Figure 6.13 Density Distribution of the Asteroid**

As shown, the densities selected were once again in accordance with the observations, so using densities of 3200, 1200 and 200  $\text{kg/m}^3$ . This is a reliable distribution to consider in the study since according to studies as [] (G. Valvano, 2021), most asteroids, and in particular those of irregular shape and the bilobate, are known to have bimodal density. This refers to large areas where the densities differ considerably in such bodies, normally pointing to differences in composition. Having two lobes of high density would set the asteroid to have probably formed from two different bodies that collided at high enough speed to fuse together, quite plausible for an asteroid belt setting.

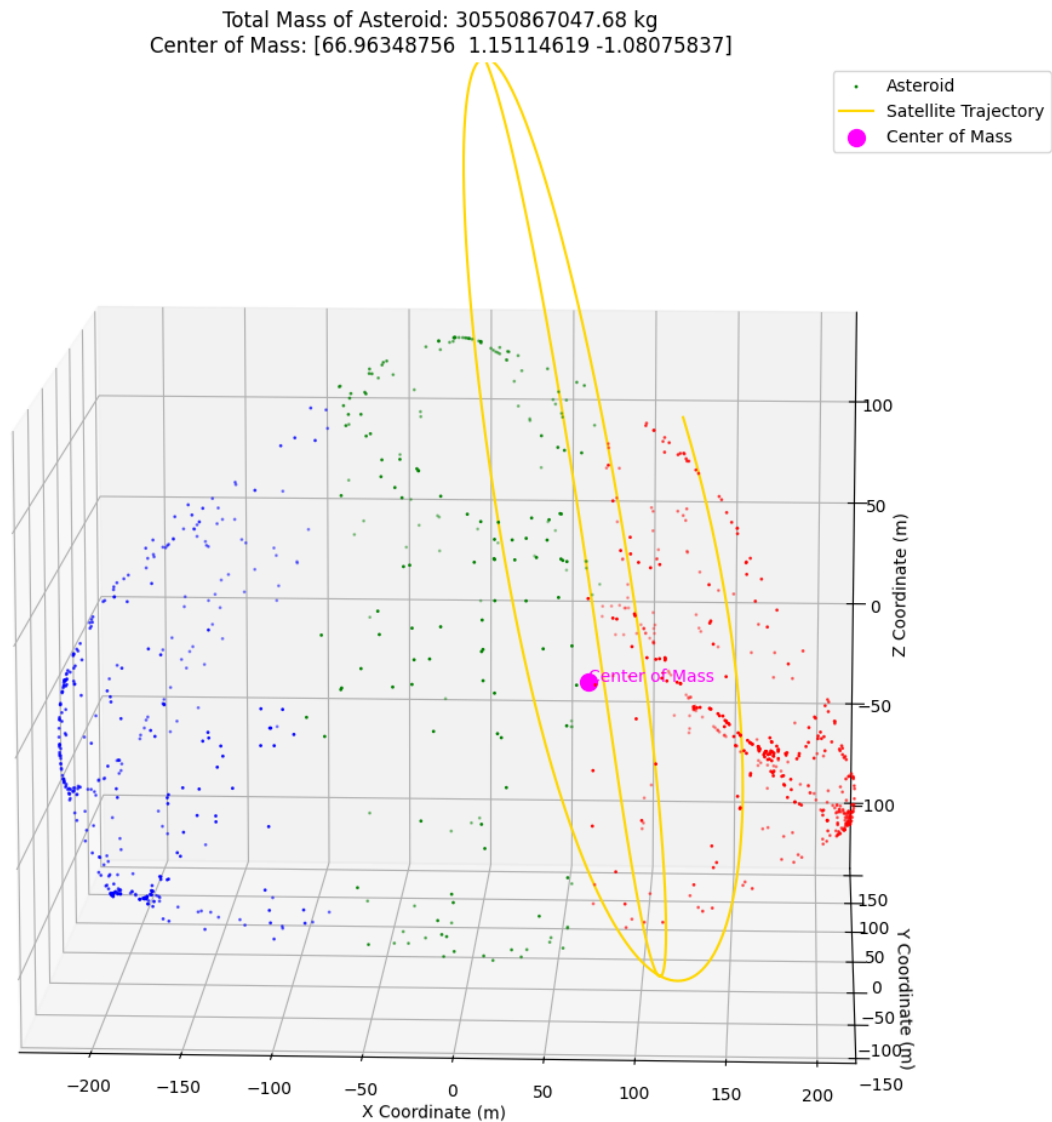
The chosen values are within the expected values and reflect realistic values for asteroid materials. The higher density regions may represent metal rich areas while the lower dense areas could correspond to porous regions where wholes can appear in reality.

Moreover, this asteroid composition leads to a realistic total mass which is  $3 \cdot 10^{10}$  kg. And it is within the expected mass of the asteroid according to recent studies (G. Valvano, 2021).

## **6.6 Trajectories**

In this subsection, the trajectories of the spacecraft around the asteroid are computed. Specifically for the scenario shown in Figure 6.14 where 3 densities were used emulating the appearance of 2 denser lobes.

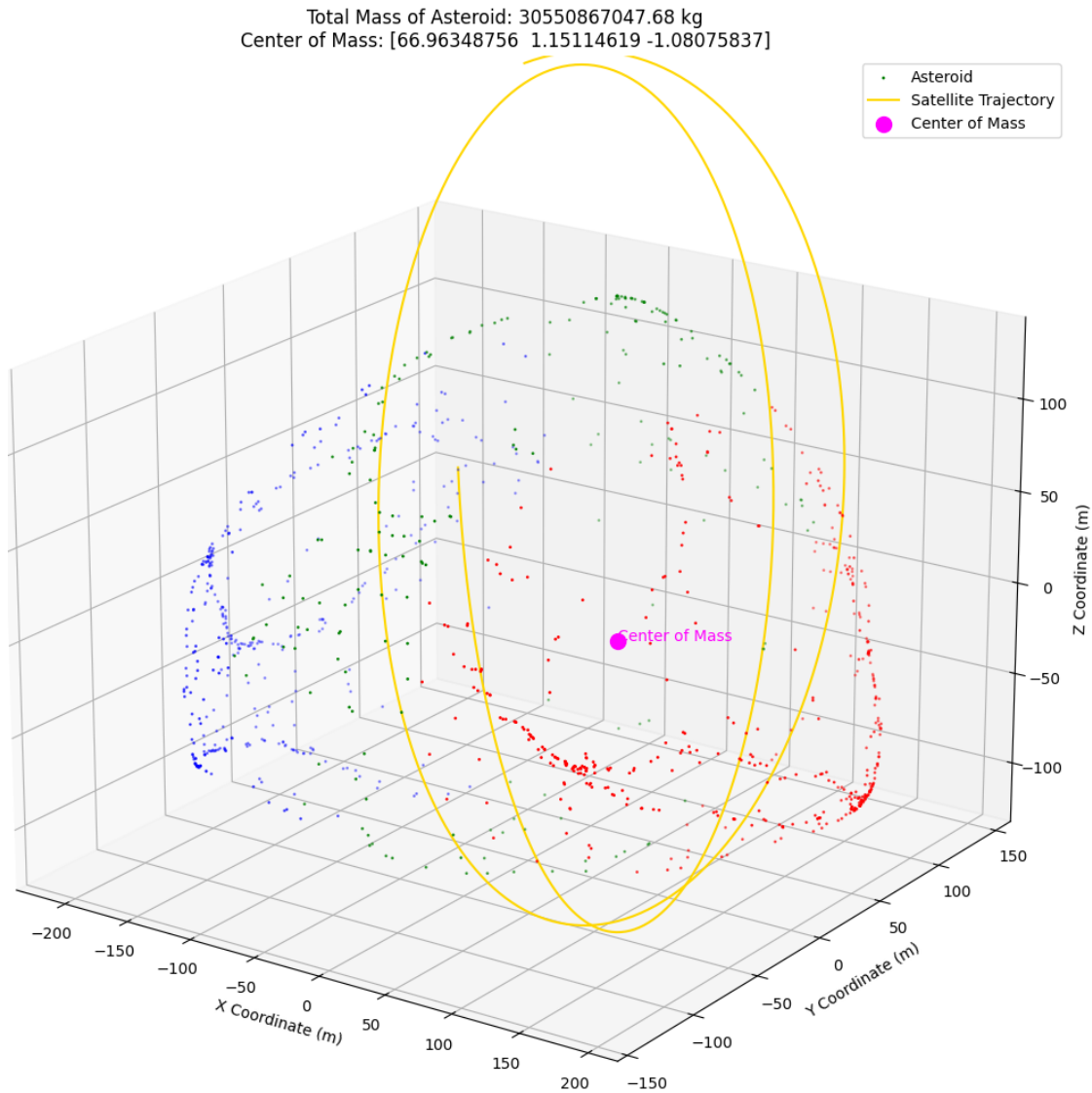
To compute them, the numerical equation 6-9 has to be solved, in this case the classical Runge-kutta method was used for its accuracy and computational cost.



**Figure 6.14 Spacecraft's trajectory using 3 densities in the model**

Once the numerical problem is solved, the trajectories shown in Figure 6.14 and Figure 6.15 are obtained. There are 3 different colours used when plot the mass elements, this is done in order to differentiate better the 3 densities used and which mass element was chosen to have which density. The red ones correspond to the regions with higher density ( $3200 \text{ kg/m}^3$ ), the green points to medium density ( $1200 \text{ kg/m}^3$ ) and finally blue points with the low density ones ( $200 \text{ kg/m}^3$ ). The points are mass points.

This density distribution is in accordance with the location of the centre of mass and explains the deviation in the trajectory to the right hand side of the plot where the total mass is bigger.



**Figure 6.15 Lateral view of the trajectory around Apophis perturbed**

Furthermore, the total mass is within the expected range for an asteroid of this characteristics (G. Valvano, 2021) and specifically is approximately  $3.1 \cdot 10^{10}$  kg .Since the shape of the asteroid is irregular, and several densities are used, the gravitational potential will be affected, being more complex than expected for an ellipsoid.

Moreover, the spacecraft was set at 300 m height from its surface with an initial velocity computed using the approximation shown in equation 6-11

$$v = \sqrt{\frac{GM}{r}}$$

**(6-11)**

Where  $M$  is the mass of the asteroid and  $r$  the position of the spacecraft. Using this and setting an initial direction, the trajectory was computed. The orbit seems to be stable and it shows how the gravitational field of the asteroid has captured the spacecraft and is attracted to the centre of mass. Without this density distribution, the orbit would not be tilted to the location of the centre of mass where the gravitational forces are higher but rather stayed straight as shown in previous section with the constant density scenario.

Furthermore, this simulation corresponds to a 7 hours trajectory. This duration will not happen in reality since the main goal of the mission is to get samples from the asteroid. Nevertheless, it is a good example and another verification step before using control techniques to land on specific location in the surface.

Additionally, the inclusion of SRP effects are already included and have contributed to the irregularities on the trajectory. As mentioned for the simplest case with constant density, this influence was assumed to be only in one specific direction and constant.

Moreover, it should be noted that for all these shown trajectories, the tumbling behaviour of Apophis was also taken into account. To achieve this, a rotational matrix was introduced in the code. According to (H., 2022), the asteroid exhibits a tumbling behaviour given by the rotation on one of its principal axis and influenced by the rotation about others. In this scenario, both are tacked. According to (Wikipedia, s.f.) and (H., 2022), the asteroid rotates about one axis every 30.4 hours, 27.38 and every 263 hours about the others, resulting in the tumbling behaviour.

The rotational matrices are assumed to be with respect to each axis of the asteroid as shown in to (Wikipedia, s.f.) and (H., 2022). Therefore the rotational matrices used are shown.

**Rotational matrix around z-axis:** This rotational matrix accounts for the period of 30.56 hours. The angle  $\theta$  corresponds to the amount of angle displaced by time step. The amount is done by the total time divided by the number of timesteps considered, in this case  $5.721 \cdot 10^{-4}$  radians per timestep due to the fact that it runs for 7 hours and the time step is 2 seconds. ( $w=2\pi/T$ ), where T is the period.

$$R_z(\theta) = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(6-12)

**Rotational matrix about y-axis:** This rotational matrix accounts for the period of 27.38 hours. In this case the amount of case  $1.274 \cdot 10^{-4}$  radians per time step.

$$R_y(\theta) = \begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{pmatrix}$$

(6-13)

**Rotational matrix about x-axis:** This rotational matrix accounts for the period of 263 hours . case  $1.332 \cdot 10^{-5}$  radians per time step.

$$R_x(\theta) = \begin{pmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{pmatrix}$$

(6-14)

**Combined rotational matrix:** Is the resultant rotational matrix that accounts for the tumbling behaviour of the asteroid

$$R_{total}(\theta) = R_z(\theta) \cdot R_y(\theta) \cdot R_x(\theta)$$

(6-15)

To account for the displacement of the asteroid during landing, the rotation matrix is applied every time step. Therefore the procedure followed was computing the rotational matrix and apply the corresponding space variation to every point at

each time step during numerical integration. This results in an accurate result since every mass point of the asteroid is in the right place and influences the spacecraft as it should. This approach is equal to setting different scenarios for the spacecraft and the asteroid every time step but taking into account previous results for position and velocity.

In future sections the control technique scenario will be addressed using this modelling methods. The procedure to compute the new location of the points every time step is also kept but this time, the number of radians will vary as it depends on the total time it takes for the spacecraft to land.

## **7 Mechanisms and control techniques to land on the surface**

Successful landing on the asteroid is a key aspect of the mission. Several requirements need to be fulfilled since the spacecraft cannot perform a rough landing and the trajectory has to follow some restrictions (DLR, 2024) (Shyam Bhaskaran),

Asteroids with their complex shapes and irregularities create a dynamic and often unstable landing scenario. Thus, it means to navigate under this conditions (complex gravitational field and with the influence of the solar radiation pressure), the spacecraft will need some techniques and manoeuvres to compensate them to ensure a safe and accurate descent (following a straight line and landing within 3 meters from the target location). This section will focus on presenting the possible strategies and algorithms that can be applied to this complex case.

To address this problem, navigation algorithms are used. These algorithms utilize the data obtained from the sensors of the spacecraft to update the spacecraft's position, velocity, height, attitude and solar vector. Using the control mechanisms, they can correct all the misalignments or travel to the desired destination. They also provide immediate corrections in response to unexpected changes in the gravitational field or surface conditions.

As mentioned before, they are based on algorithms but they use data from sensors like star trackers, Thermal and visual cameras or spectrometers. In this case, the most important ones are the cameras and the star trackers to keep on record the landing location and the orientation of the spacecraft. This is such because the sampling process is going to be the main objective. Specifically the sensors used are:

- Sun Sensor. Helps the determination of the spacecraft orientation towards the Sun.
- Navigation camera. To capture images of the asteroid and help to make the decision of the landing location or aborting the landing manoeuvre if some problem raises in the surface.

- Altimeter. Measures the altitude of the spacecraft above the asteroid's surface, providing critical data for landing.
- Star tracker. Using the position of the stars is able to determine the precise orientation of the spacecraft.
- Inertial Measurement Unit: It is composed of 3 accelerometers, 3 gyroscopes. Provides acceleration and rotation rates.

To compensate for all the possible perturbations, thrusters are used. In this case the spacecraft will use 1 N Thruster and their properties will be referenced in this section.

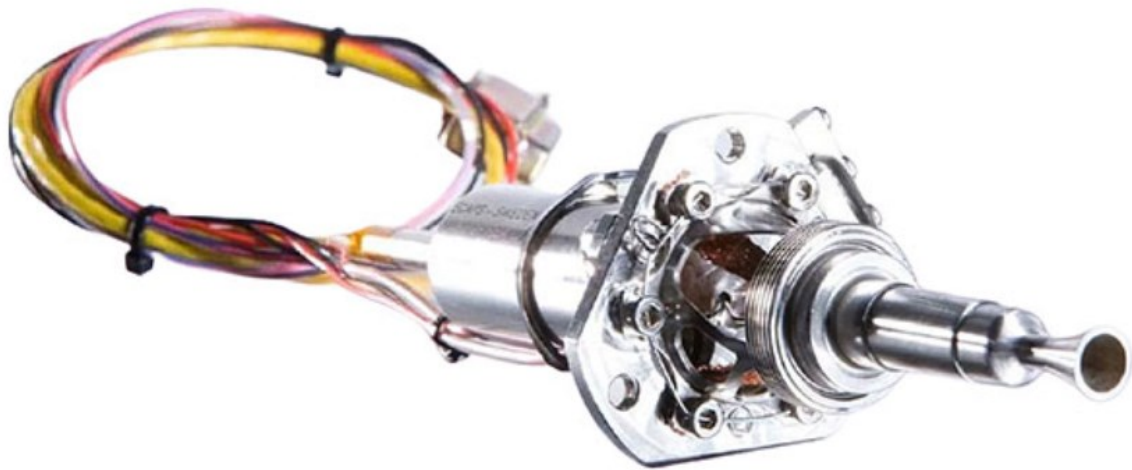


Figure 7.1 Propulsion thruster of the mission (SATNOW, 2024)

Thruster details	
Part Number	1N HPGP
Name	1N HPGP Thrusters for Small Satellites
Thrust	0.25 to 1 N

Thruster Mass	0.38 Kg
Specific Impulse	204 to 231 Sec
Propellant	LMP-103S

**Table 7.1 Thruster characteristics and performance (SATNOW, 2024)**

As seen in Figure 7.1. and Table 7.1. The thruster is able to give a range of thrusts and so they will be used in the simulation. Moreover, it is perfectly suitable for this landing scenario since the corrections needed are small and the spacecraft is light (100 Kg of weight) and small to be attached to RAMSES.

Furthermore, the use of LMP-103S reflects a consideration for environmental impact. This propellant is less hazardous, which reduces associated costs and improves safety.

## 7.1 Control techniques

Once the model has been verified, the landing scenario can be studied in detail. Normally the most efficient manoeuvre would be computed by trial and error to use the gravitational potential in the favour of the spacecraft and so orbit it as it lands in a curve trajectory.

However, this mission is different, since Apossum spacecraft must communicate with RAMSES. Therefore, a control loop technique has to be used. In this case, there was no preference on the landing location so a random point was selected.

For this mission 2 control techniques were chosen: PD (Proportional-Derivative control), due to the importance of velocity and position, which suits with this technique, and bang-bang Control due to its simplicity and advantage of arriving to the target location in a short period of time.

PD is a control technique in which the control input is based on both the current error and its rate (derivative). In this mission, the desired velocity change using a proportional term and the current velocity, which acts as a derivative term.

$$\Delta V = K_p \cdot \overrightarrow{e(t)} - \vec{v}$$

(7-1)

Where:

- $K_p$ . Is the proportional gain.
- $\overrightarrow{e(t)}$  is the error vector. This is the difference between the current and the desired position.
- $\vec{v}$  is the current velocity (which is used as the derivative of the position)

Moreover, it has to be mentioned that for this calculations a maximum  $\Delta v$  and a minimum one were set. These values were computed using Newton's equation and the corresponding thrust of the engine explained before.

$$\Delta V = \frac{T \cdot \Delta t}{m_{sc}}$$

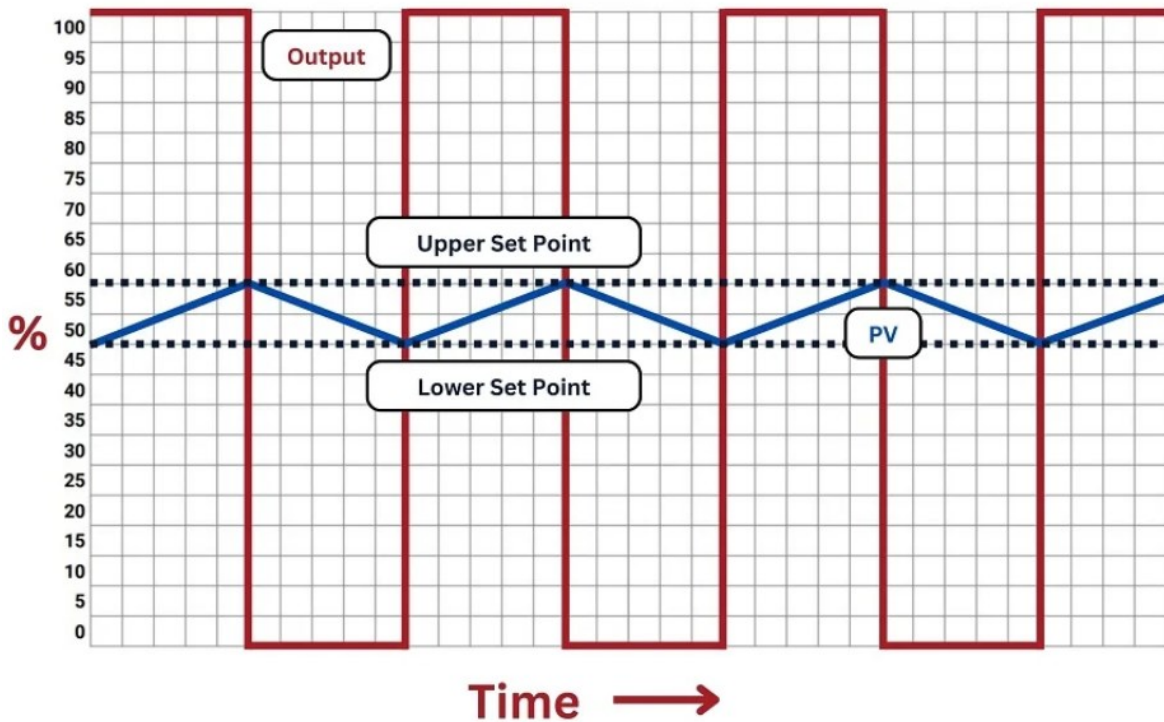
(7-2)

Where:

- $T$  is the thrust
- $\Delta t$  is the time step
- $m_{sc}$  is the mass of the spacecraft

The time step plays an important role in this scenario. Depending on the minimum time available for the engine and the chosen one, the thrust occurs every less or more time and so the fuel consumption of the spacecraft may rise. It will be shown later the relation between these variables to optimize the landing scenario.

On the other hand, Bang-bang control technique is a simpler strategy. In this occasion, the engine thrust is not modular, instead it switches between the maximum and 0 thrust.



**Table 7.2 Bang-bang control technique (Control Systems, 2021)**

As shown in Figure 7.2, Bang- bang control technique bases the strategy on getting the maximum thrust as output when it is switched on. This type of manoeuvres is very suitable for missions in which the trajectory is simple and does not need many small corrections.

On the other hand, it is not a good option when dealing when rendezvous trajectories since the corrections are made more often and the variations have to be very precise without abrupt changes. An example of a not suitable mission can be the approaching and docking of 2 spacecrafts (a capsule of astronauts and the ISS).

The direction of thrust is obtained by using the unit vector error. This vector is obtained by normalizing the error vector to get the direction in which the spacecraft needs to move as shown in equation 7-3.

$$\overline{e(t)} = target - position$$

(7-3)

On the other hand, and when dealing with the maximum or minimum thrust, equations 7-4 are used

$$\Delta V = \begin{cases} v_{max} & \text{if } \overrightarrow{e(t)} > 0 \\ -v_{max} & \text{if } \overrightarrow{e(t)} < 0 \end{cases}$$

**(7-4)**

This shows the procedure followed by the algorithm to switch the direction of the thrust. If the error unit vector is greater than 0 means that the target is “ahead” and so the impulse must be done to reduce it, on the other hand, if the error unit vector is less than 0, the target is “behind” and therefore, the correction must be done to fix it.

Moreover, it has to be mentioned that for all these simulations, the rotation of the asteroid was taken into account. The asteroid has a period of 30.56 hours according to (R.). Therefore for all the following results, this rotation is included.

To include the rotation, a matrix to change coordinates is used. This matrix assumes that the rotation is perfect with the z-axis aligned with the geometric centre of the asteroid (0,0,0). The rotation of the asteroid is done by rotating each vertex the amount corresponded using the mentioned rotational matrix, therefore in each time step, the spacecraft is affected by the asteroid in the new position.

## **7.2 Comparison of the control techniques**

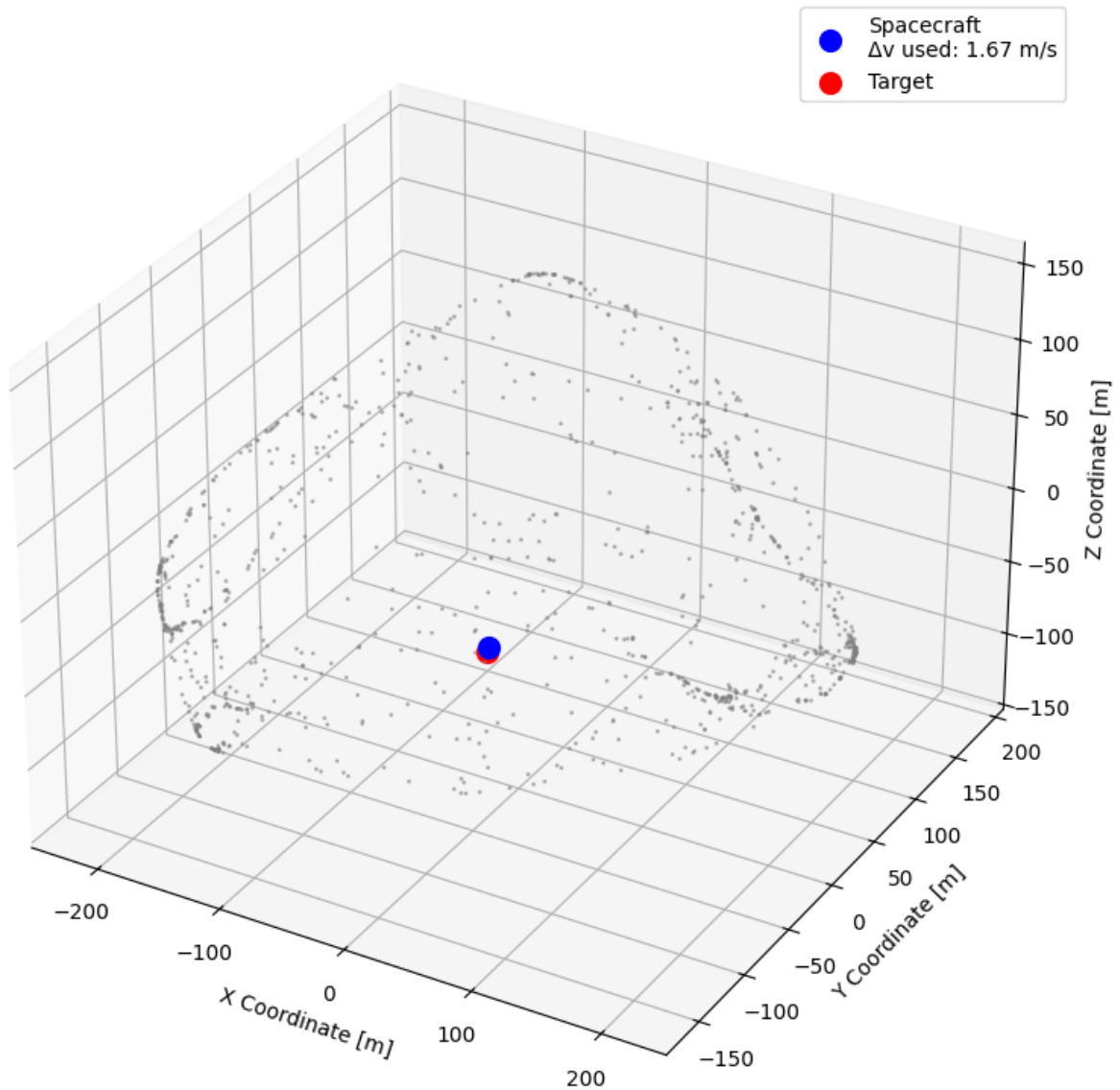
Both techniques mentioned earlier have merits to be suitable for the mission presented and therefore land successfully on the surface. Some strengths and weaknesses have been mentioned for both of them, nevertheless, in this case a real comparison will be done by setting an initial point and conditions and a final target on the surface of the asteroid.

The initial conditions were introduced as row vectors. Specifically, the initial position used is [100, 100, 1000] being the 3 components of the vector the axis

x, y, z. On the other hand, the target position is [50,-100,10], a point on the surface of the asteroid.

The initial and final locations are generic since the mission is still not developed enough to know where is going to be the place of arrival at 1 km height neither there is a preferable landing location since the properties of the asteroid are not well determined enough to get any conclusions. Nevertheless, these values are within the feasible landing scenario locations and so they are going to be used not only for comparison but also to have a better estimation of the delta-v budget needed to accomplish the mission.

Moreover, using the results mentioned in section 5.3, the initial condition is set to the spacecraft. The initial velocity is set to be [0,0,0.05] m/s, to be a good approximation to the theoretical one mentioned.



**Figure 7.2 Landing control scenario using PD control technique**

Figure 7.2 shows the simulation scenario set for the control techniques. The blue dot is the spacecraft with the cross-sectional area mentioned in previous sections and the red one is the target location at the surface of the asteroid.

In order to compare, the time towards the target is going to be measured as well as the delta-v used. Moreover, according to the requirements of the mission, the landing is considered a success if it lands within 3 meters from the target location. So this distance will be used, nevertheless, the accuracy can be improved but also the fuel consumption may rise.

Several trials were used with these techniques varying the variables inside each algorithm in order to achieve the best result possible. Ideally would be to land within the location as quickly as possible while still being smooth, keeping contact with RAMSES (going as close as possible to a straight line, avoiding any orbiting manoeuvre) and with the lowest delta-v possible.

### 7.2.1 Bang-bang

As mentioned before, this is a simpler technique than PD and switches between maximum and no thrust to land on the target. After several trials, it was proven that the precision is lower. While PD can land very precisely, Bang-bang needed some trials to land in the location set. The best trial obtained is shown in Figure 7.3

<b>dt</b>	1	<b>Dv</b>	3.66	<b>tolerance</b>	3
<b>Time</b>	450				
<b>Success</b>	Success				

Figure 7.3 Best Bang-bang result

As it can be seen, the tolerance was set to the minimum value required and the time spent by the spacecraft was 450 seconds, which it is fast when compared to the other technique used. Moreover the Dv, raises to 3.66 m/s.

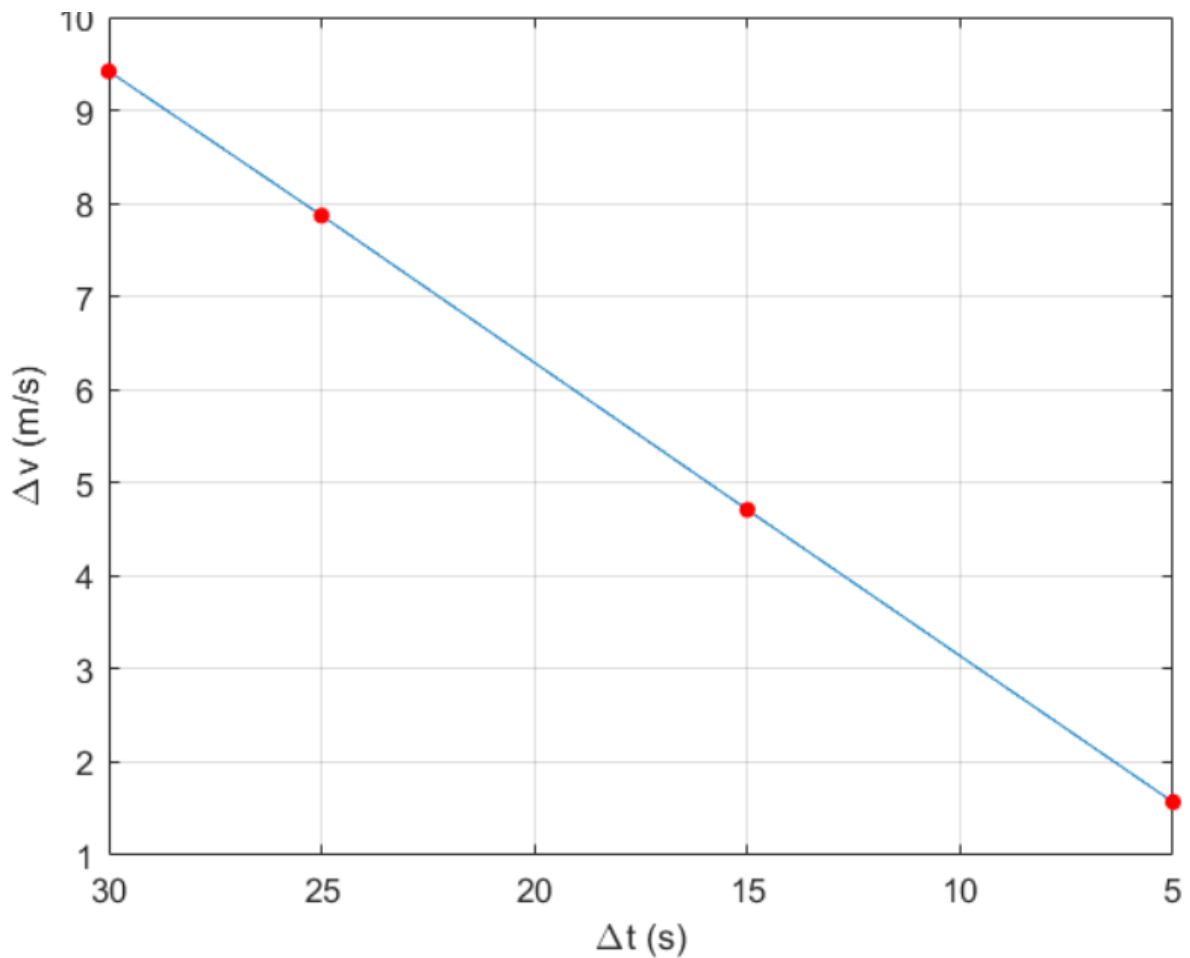
### 7.2.2 Proportional Derivative

<b>Kp</b>	0.0005	<b>dt</b>	5	<b>Dv</b>	1.57
<b>Time</b>	8140	<b>tolerance</b>	2		
<b>Success</b>	Success				

Figure 7.4 Best PD control landing

As it can be seen from Figure 7.4 , a  $K_p$  of 0.0005 was used, this value is not randomly chosen but rather optimized beforehand to get the best possible results.

Moreover, the tolerance was reduced to 2 meters. Although the requirement is 3 meters, a preferable option of 2 meters was selected to have some safety margin. Furthermore, the time step was raised to 5 seconds since this allowed to lower the fuel consumption and therefore the time needed increased to 8140 seconds.



**Figure 7.5 Relation between DV and time step**

This technique is more complex, and therefore the computational time required for each time step is higher. Nevertheless, the time of simulation is achieved successfully and multiple results were obtained.

On the other hand, Figure 7.5 shows the relationship between delta-v and time step ( $\Delta t$ ). It can be seen that  $\Delta t$  is inversely proportional to delta-v, that is why for the best result, the time step was minimized to save the maximum fuel possible.

### **7.2.3 Algorithm final decision**

As mentioned earlier, both techniques can be used in this mission, nevertheless, bang-bang control showed a less accurate landing and a higher fuel consumption.

The importance behind minimizing the delta-v or fuel consumption relies on the complexity of the mission. Apossum is not the main mission and so it has to fit in the constraints of the launcher and in RAMSES, therefore the space available has to be optimized as well as the weight. On the other hand, bang-bang control technique needs less time (450 against 8140 seconds) to land successfully on the target location. Although is much faster, in the requirements of the mission there were no restrictions on the landing time, therefore this does not count as an advantage.

For all these reasons, PD seems to be more suitable for this mission since there is no restriction on the landing time, therefore 8140 seconds are within the limits and there is a save in fuel consumption.

## **8 Phase 3. Return**

The return phase of the mission will be explained in this section. First, navigation to Earth will be described: from the launch at the landing location on Apophis to the actual landing on Earth for the recovery and completion of the sample mission.

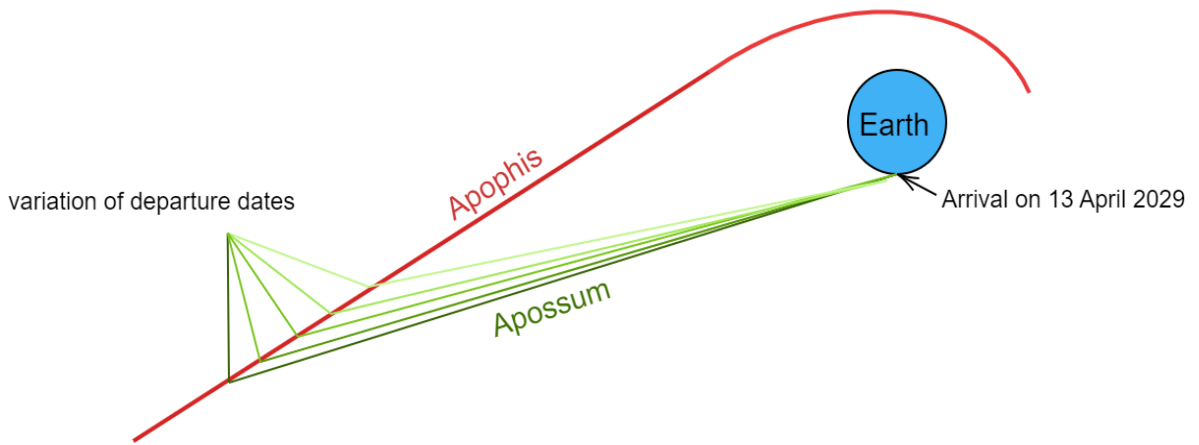
Finally, the Apophis departure involves the selection of the date to leave. Choosing the right date is significant as it assures a successful landing at the destination with minimal delta-v or fuel consumption. In addition to that, the destination location is such that DLR can collect the samples and not harm any urban area.

### **8.1 Landing location**

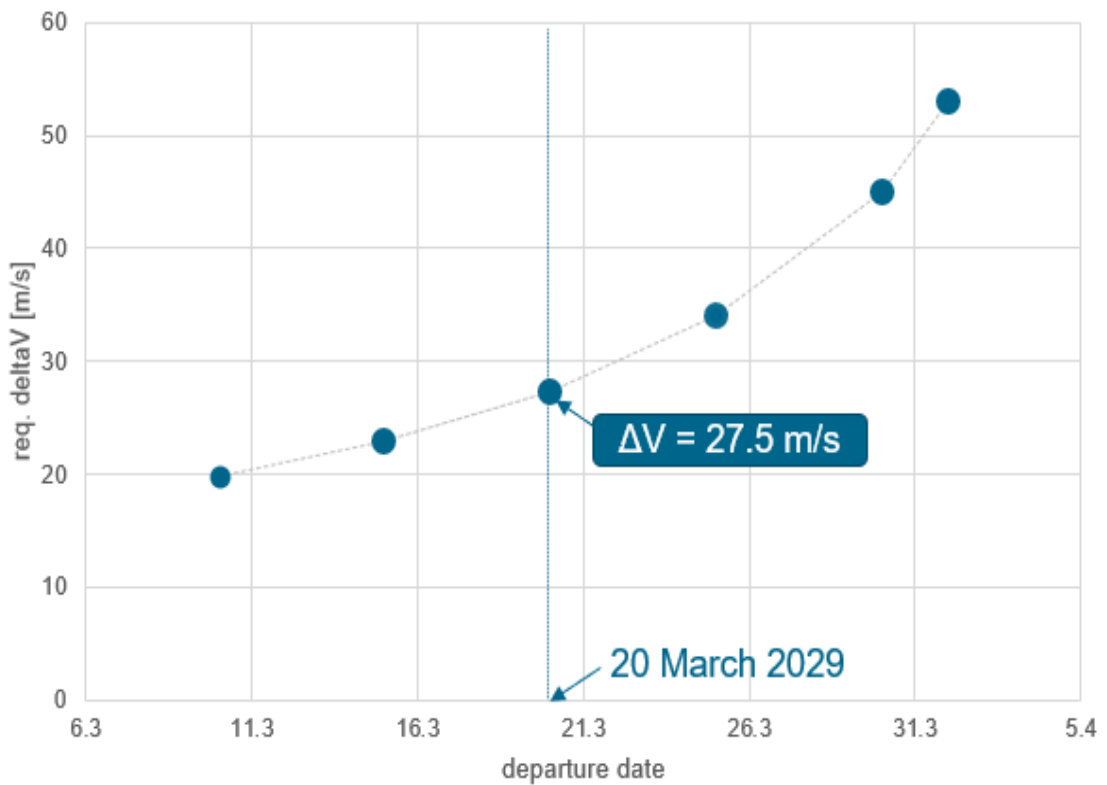
The chosen location to land on Earth was on the western part of Australia, on the desert, specifically in Woomera (Longitude  $-31^{\circ}$ , Latitude  $128^{\circ}$ ). As mentioned before, This location was selected due to its sparse population, which minimizes the risk to human life and property. Moreover, it must be taken into account that the asteroid has to be on the opposite site of Earth when landing for the telescopes to take the right pictures of it and avoid any possible interruption.

### **8.2 Departure date**

According to observations and studies (ESA, 2021), (J., 2010), the date in which the asteroid reaches the closest point to Earth is 13<sup>th</sup> of April of 2029. This closest point is at 31000 km from the surface. This will be taken into account to try to land that date varying the departure one.



**Figure 8.1 Variation scenario posed for the mission**



**Figure 8.2 Relationship between the required DV and the departure date**

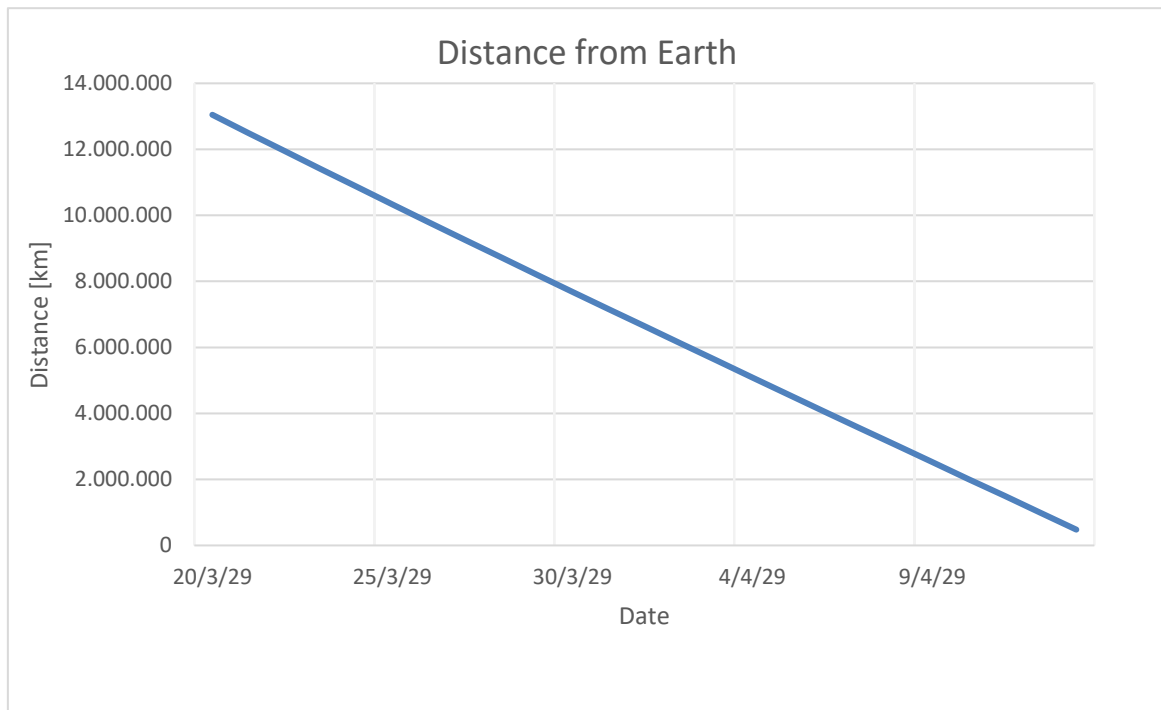
As it can be seen in Figure 8.1 and Figure 8.2, as the departure date gets closer to the closest approach, the needed delta-v to return increases. This is because

the trajectory needs a greater correction and acceleration to arrive on the same date. A trade off was made, taking this fact into account along with a requirement of the FPA (Flight path angle) that the spacecraft must have when approaching LEO ( $20^\circ$  or less).

This FPA requirement arises from the necessity of landing at the correct location on the surface and preventing the components from burning up.

Considering all this data and requirements into consideration, the departure date was chosen to be 20 of March or 2029. This is translated into a transfer time of 23 days of navigation time and 27.5 m/s of  $Dv$  needed. This  $Dv$  is within the expected values and the budget, making it a reliable result. Moreover, during that time communication is needed to be sure that the spacecraft is on the right path, and as it is shown there is no problem, but a further study is needed.

To ensure that the trajectory was computed correctly, Figure 8.3. is obtained directly from the locations of the spacecraft and Earth these days from the model of STK used.



**Figure 8.3 Evolution between the distance from Earth and Date**

As shown in Figure 8.3, the distance between the spacecraft and Earth is as expected from the trajectory overview, this is getting closer in a proportional way to the location. With this plot we can ensure that also numerically everything goes as planned and the landing is expected to be a success.

### 8.3 Landing on Australia (Woomera)

As mentioned before, the expected location is Australia, in Woomera (Longitude  $-31^\circ$ , Latitude  $128^\circ$ ). The simulation must accurately include this target location and compute the necessary Flight Path Angle (FPA) for a safe re-entry and landing.

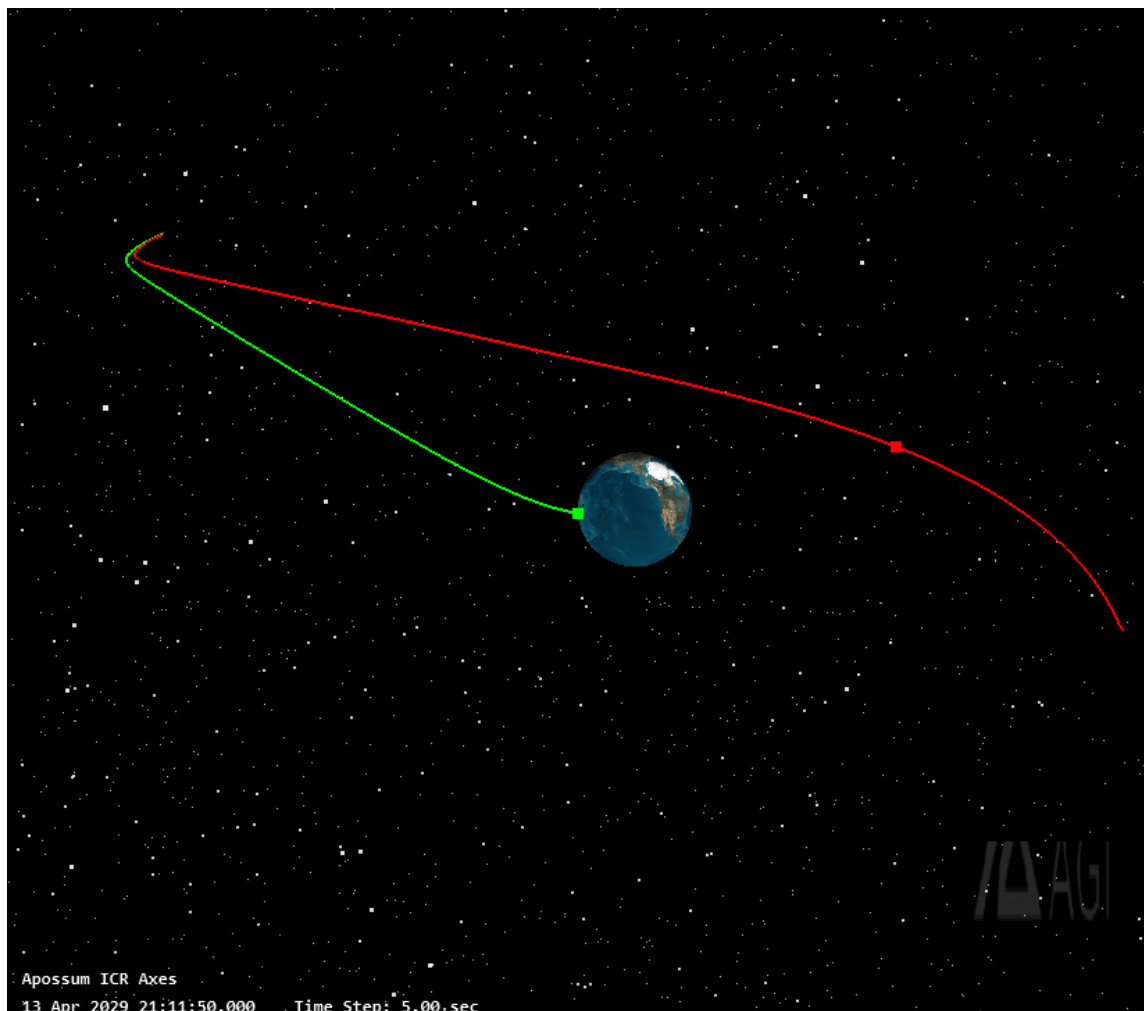
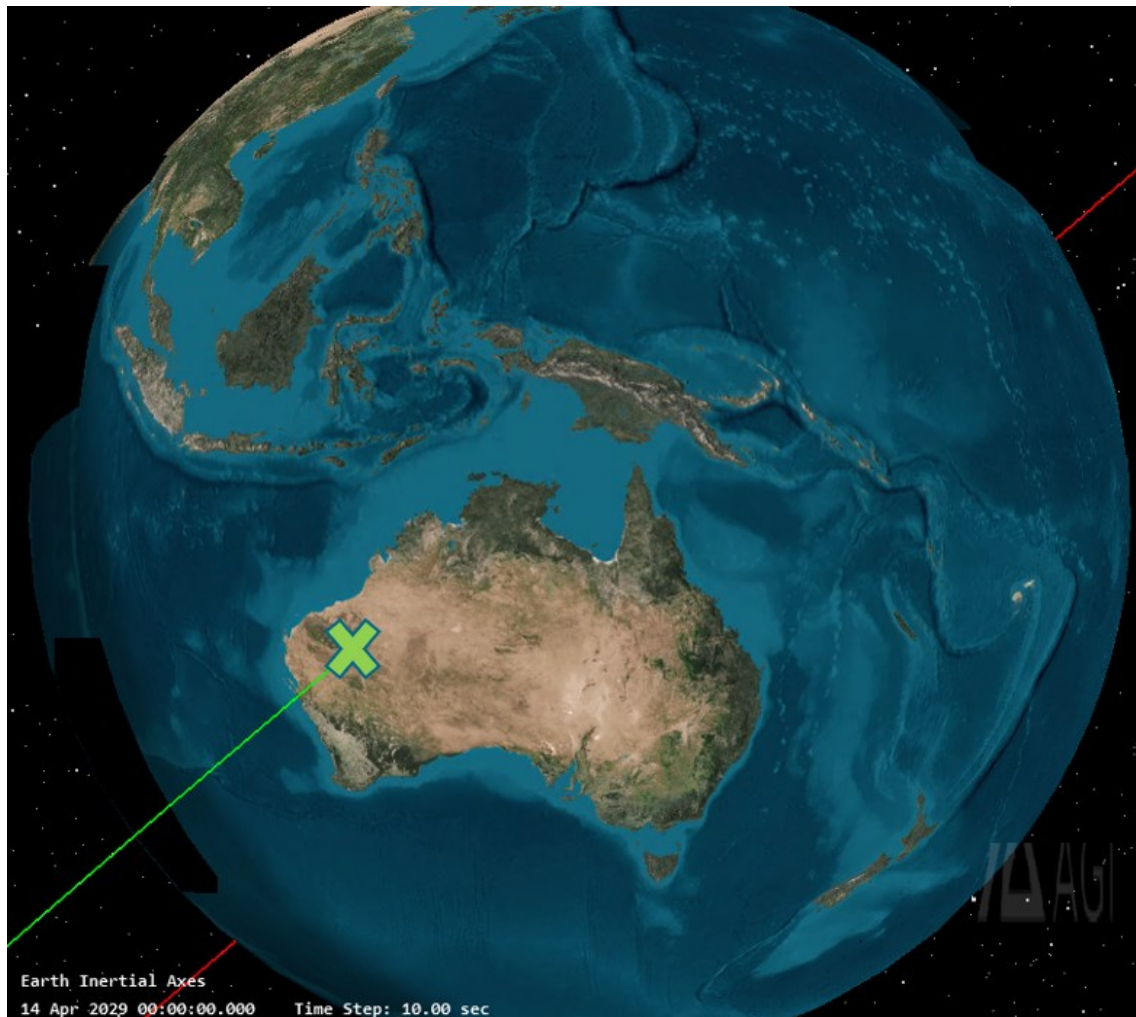


Figure 8.4 Picture of the returning scenario

Figure 8.4 shows the trajectory from Earth point of view of the spacecraft (green line) and Apophis (red trajectory). Moreover, the squares that are plotted are the locations of Apossum and Apophis on their respective lines. As it can be seen, when the spacecraft lands, the asteroid is on the opposite face of Earth, fulfilling the requirement of no affecting the observations from the telescopes.



**Figure 8.5 Landing point of Apossum**

In order to give a more accurate sight about the place of the location, figure 8.5 is shown: As it can be seen, it resulted in a successful simulation, since the landing location was inside the limits and also the flight path angle was computed and was equal to  $-20^\circ$  with a velocity of 12.4 km/s at an altitude of 200 km from the surface.

The success of the simulation relies on the fact that it matches exactly the design expectation, moreover, the numerical results are also reliable and fulfils the requirements from other subsystems.

The results are essential for propulsion to calculate the volume of the fuel tank, for configuration to know how much space to allocate for the fuel tank, and for communication to compute the link budget. That way, the spacecraft's specific location in this journey could be obtained and, consequently, one could know how much time it is possible to transmit and receive data. This underlines the importance of detailed analyses in trajectory and landing site in view of space missions.

## 9 Discussion of Results

The study was a success from the mission point of view and all the results were delivered to the other subsystems to have a deeper understanding of the possible scenario that the spacecraft may face upon arrival.

The results delivered were divided into the 3 phases of the spacecraft mission scenario in terms of delta-v, time and trajectory.

- **For the phase 1** where Apossum approaches the asteroid, 1.7 m/s were used. In this case, the results are accurate and the only possible errors can be numerical since the simulation was done using STK and its subroutines. These account for the interaction of the spacecraft with sun (SRP), with Earth and with the gravitational field of the asteroid.

On the other hand, some errors may come from the simplification of the asteroid to an ellipsoid. This was done due to the distance to the asteroid and its minimum impact on the results. For further studies, it is recommended to improve and implement the actual model.

- **Second phase.** The spacecraft tries to land on the asteroid, similarly to the previous case, there will be numerical errors, but this time, they are minimized.

In this case, the errors are not likely to come due to the use of numerical methods such as Runge-Kutta or PD control technique. In this occasion the error imposed to perform the simulation, was minimized, this time, it was of the order of  $10^{-10}$  whereas for the previous phase, the settings were left as default and therefore, the magnitude of the error was  $10^{-5}$ .

This treatment to the absolute and relative errors is done to avoid any possible divergence during simulation, specially, in orbit computation this is happens often due to the interaction of several point masses that may alter the results.

The errors in this occasion, may come from the modelling technique. Although, the approach followed (tetrahedral technique) is accurate, computationally efficient and suitable for this asteroid as the shape is close

to an ellipsoid, it comes at a cost when trying to model the interaction with the spacecraft. As explained before, this error does not affect the gravitational potential but it alters the trajectory.

The deviation is minimal but still has to be mentioned. The reason comes due to the approach that this method uses. Since the tetrahedral mass is divided into the three vertices on the surface of the asteroid, the exact location of the mass is shifted and therefore the gravitational pull that the spacecraft will encounter.

Moreover, when the tumbling behaviour is added, the exact shape can suffer small variations that sum with the previous errors, can result in bigger uncertainties. Nevertheless, for this study, this were taken into account and during all the simulation they were mitigated. Moreover, since the simulation time for the landing scenario was lower than any period of rotation of the asteroid, the effects of this shape variation are minimized. This was mentioned in order to be accounted in future research projects and studies of this asteroid.

Finally, the last error that should be mentioned is the presence of the YORP effect. This effect can alter the asteroid spin rate over time and therefore it must be accounted for long term missions in which the asteroid may stay orbiting without landing. Since this does not apply to this case, it was not accounted, nevertheless, it should have a small impact on the spin rates.

- **Third phase.** This corresponds to the return phase from the asteroid. As mentioned earlier, the software and approach used was similar to the Phase 1. Therefore, the inaccuracies are similar, the asteroid was modeled as an ellipsoid.

Nevertheless, the influence is minimal due to the presence of Earth's gravitational field compared to the asteroid one. Finally it should be mentioned that the atmospheric model used was the ISA density model (Ansys, 2023), therefore it is a good approximation to reality but it will not be exact, some minimal deviations can appear in reality.

As it can be noticed, although there are numerical errors, they are all mitigated and minimized in order to obtain the most accurate result possible.

## **10 Conclusions**

This study sets a step towards a future in which asteroid missions are easily reproducible. The reproducibility comes from the techniques and study developed in this report.

The mission's approach has demonstrated that tetrahedral method and spherical harmonics can be adapted to be used in future missions. The reason behind is that they rely on the input of few parameters like the shape model of the asteroid, and the density that the user wants to study.

Nevertheless, it should be noticed that some asteroid's shapes may be problematic for the tetrahedral method but alternatively, if orbiting is the main intention spherical harmonics can be used or assume the numerical error of the model.

### **10.1 Future studies**

This report is part of the mission study Apossum to get samples from Apophis asteroid and therefore its main intention is to deliver results to the rest of the subsystems to perform a successful mission. Nevertheless, several techniques were tried and compared as well as scenarios to study the feasibility. In future studies, these techniques can be generalized to other asteroids and see the fit of the results in those scenarios to ensure the feasibility of generalizing this to all asteroid missions.

As mentioned in the introduction this study will be published as a journal paper and therefore it will be available for all the scientific community to replicate the approach to other mission scenarios.

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# Appendices

## Appendix A Ethical approval letter



1 May 2024

Dear Mr Hernandez Megia ,

Reference: CURES/21810/2024

Project ID: 24979

Title: Investigation of the approaching and landing scenario of a probe on asteroid Apophis during its closed encounter in 2029

Thank you for your application to the Cranfield University Research Ethics System (CURES).

**We are pleased to inform you your CURES application, reference CURES/21810/2024 has been reviewed. You may now proceed with the research activities you have sought approval for.**

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

