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APOPHIS EXPRESS, A UNIQUE OPPORTUNITY FOR A HUMAN VISIT TO A NEO IN 2029

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ABSTRACT

This paper presents an original mission design that can be applied to any human visit to a NEO making a close approach to Earth with a reasonably low relative velocity.
The proposed mission scenario is an interception type. As such, it allows for a very short mission of only a few weeks. The crewed mission requires that a more traditional pathfinder mission be achieved in advance.
This mission scheme is considered in the case of the close approach of Apophis in April 2029.

I-INTRODUCTION

Among the few dozens of potentially hazardous asteroids (PHAs) recently discovered, Apophis is the only one for which a final encounter with the Earth within a few decades has not been definitely ruled out. Apophis, which has been discovered in 2004, is a 250 to 300 meter wide asteroid that will come back very close to the Earth on April 13, 2029.
In a way similar to a gravity assist maneuver that is currently used for a deep space probe, the gravitational pull of the Earth during its flyby will dramatically modify Apophis orbit around the Sun. The equivalent ΔV that will be provided by the Earth during this flyby is about 2.8 km/s. From a period of 323 days prior to the flyby, the orbital period of Apophis around the Sun will be increased by about a hundred days.
The present uncertainty on the perigee altitude of the Apophis swing-by is about 1,000 km, which corresponds to a 4-day span, between 417 and 421 days, for the subsequent orbital period. If this new period is commensurate to the 365.25 day period of the Earth, that is Apophis executing *m* revolutions around the Sun in *n* years (*m* and *n* being integers), Apophis can come back again very close to the Earth in 2036, 2037 or at a later date.
During its 2029 flyby, Apophis will be easily visible with the naked eye from the Earth (visual magnitude m_v around 3 at perigee), especially from Europe and West Africa and we can expect to precisely determine its geometry and thermal properties from ground based observations. However, the characterization of its interior cannot be achieved solely from ground based observations. Such a characterization is essential to prepare any future activity related to this asteroid.
A purely robotic mission can do a lot of job but obviously a manned mission would have a much higher interest.
Compared to an ‘ordinary’ crewed mission to a NEA (Near Earth Asteroid) the mission that is presented here presents two outstanding advantages:

- it is a short mission: only a few weeks will elapse between the launch and the end of the flight operations
- the distance to the Earth will not exceed significantly a million kilometers, 3 lunar distances.

II -THE 2029 FLYBY

The orbit of Apophis with respect to the Earth during its April 2029 flyby will be a hyperbolic trajectory, in a plane inclined at 140° over the Earth equator and a perigee altitude between 29,500 and 33,800 kilometers over the Atlantic Ocean (42.9°W, 29.0°N).

Apophis will cross the equatorial plane 80 minutes before reaching its perigee at an altitude close to 48,000 km. There is no risk of collision with any geostationary spacecraft, all of them being about 10,000 km lower.

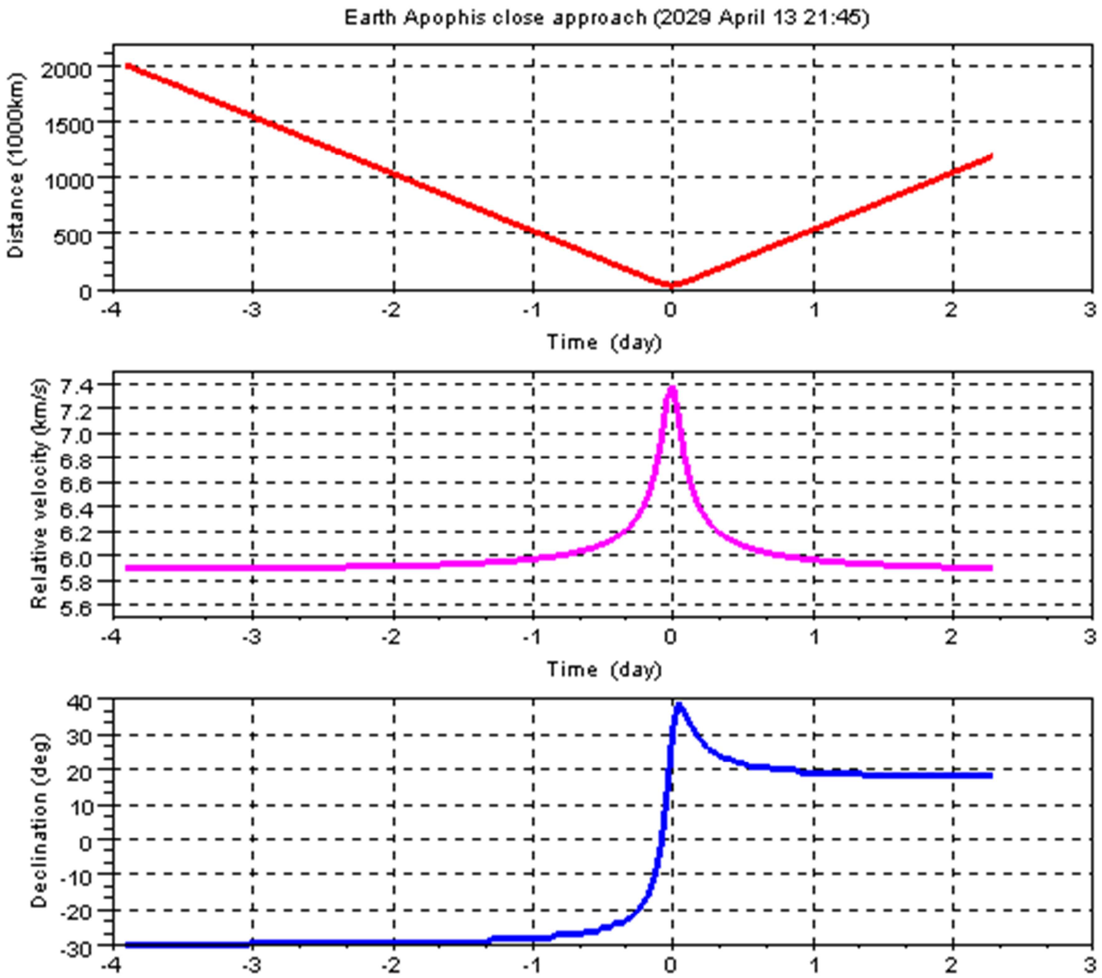


Fig.1 From top to bottom:

- distance to the Earth center in thousands of kilometers
- velocity relative to the Earth
- declination
- T=0 corresponds to April 13, 2029 2145 GMT – obtained from the Institut de Mécanique Céleste et Calcul des Ephémérides website (www.imcce.fr)

Its hyperbolic excess velocity on the incoming leg will be 5.86 km/s (~500,000 kilometers per day) with a declination close to -30°. The velocity at perigee will be 7.4 km/s. Apophis will spend only 2 hours at an

altitude below 40,000 km from the Earth surface. The 140° inclination means that the motion of Apophis with respect to the Earth will be retrograde (or counterclockwise). Apophis incoming leg will be in the Southern hemisphere so it will be an unreachable target for the Arecibo radar (located in Puerto Rico Island). The possibility of radar ranging from Goldstone a few weeks before the swing-by has still to be confirmed.
A pathfinder robotic mission is mandatory to pave the way and secure a fast human visit to Apophis in 2029.

III – PATHFINDER ROBOTIC MISSION

Earth-Apophis transfer

The objective of the mission is to softly land a set of scientific and operational devices to proceed with preliminary activities on the surface of Apophis and prepare the arrival of a human crew in April 2029.
At the latest, this mission has to be launched in May 2028, in order to reach the vicinity of Apophis in February 2029.
The Earth departure / Apophis arrival diagram in Fig. 2 shows the required Earth departure hyperbolic excess velocity. The green line corresponds to a launch in early May 2028 and an arrival on Apophis in early February 2029.
Fig. 3 depicts the velocity at the arrival on Apophis and Fig. 4 provides the total ΔV. One should keep in mind, however, that this total ΔV does not apply to the same mass: the Earth departure ΔV is provided by the launcher while the maneuver for canceling the arrival velocity with respect to Apophis is provided by the cruise module.

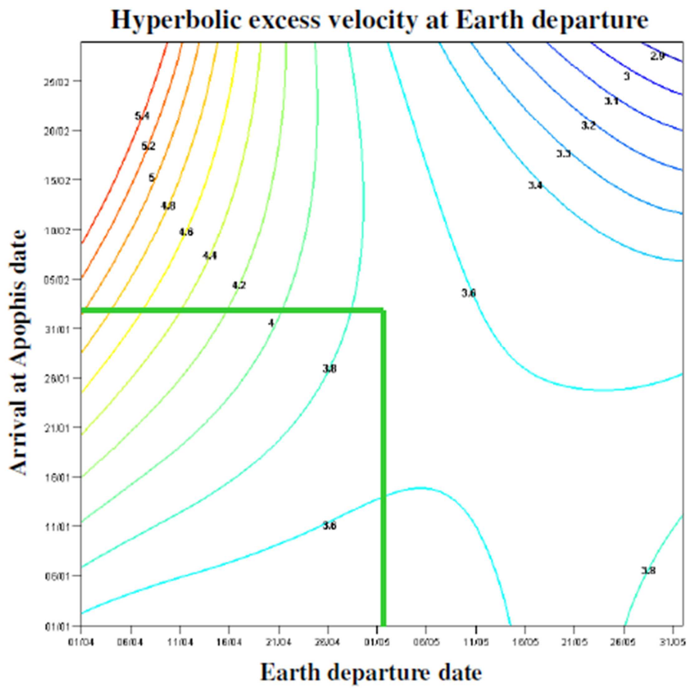


Fig. 2 Earth departure / Apophis arrival diagram for the 2028-2029 pathfinder reference mission. All the dates are in European format.

Departing from Earth on May 1, 2028 and arriving on Apopphis February 2, 2029 (green lines) requires 3.8 km/s departure velocity from the Earth (C_3=14.44). The arrival velocity to Apophis for that pair of dates is 1.6 km/s.
Other dates for launch/arrival on Apophis can be found in order to arrive earlier on Apophis and spend more time for preparing the visit of the crew.

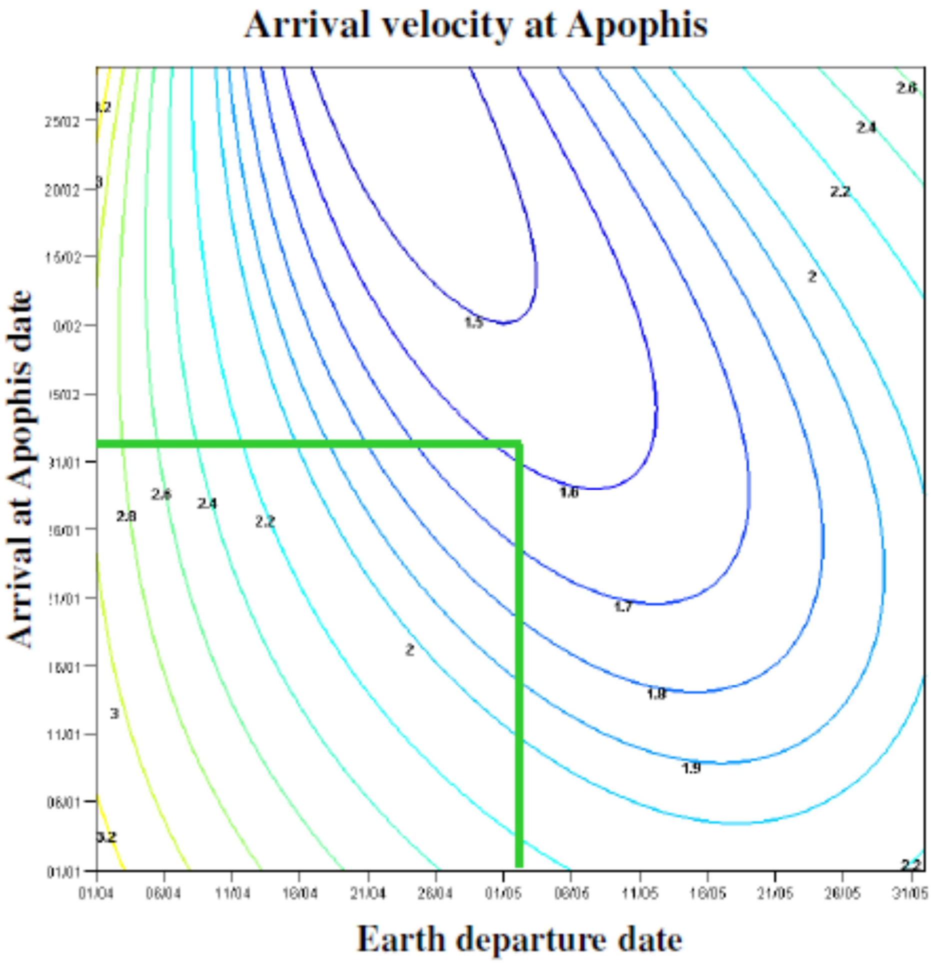


Fig. 3 Arrival velocity at Apophis

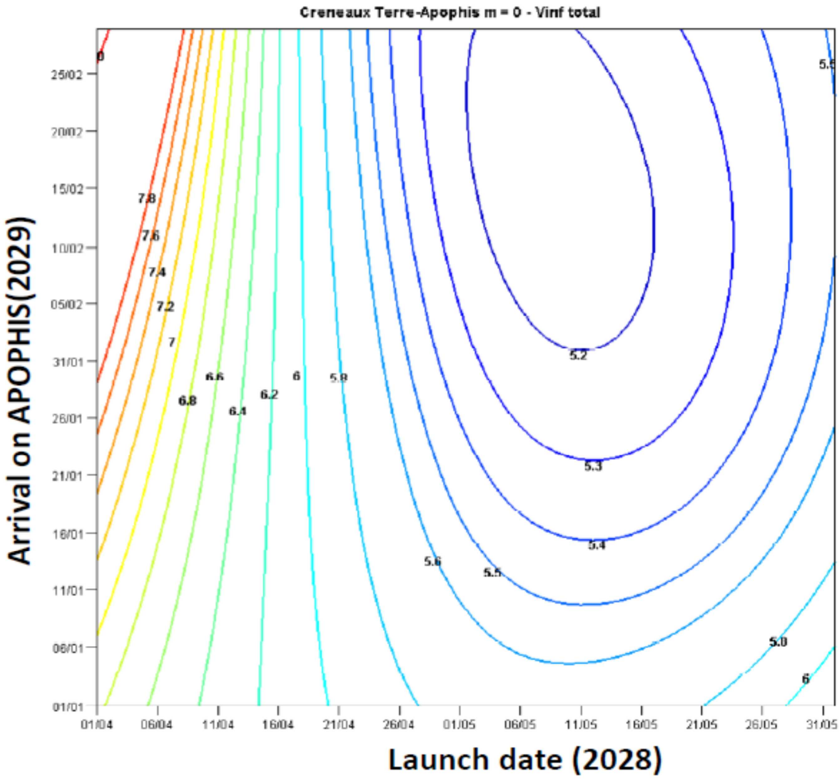


Fig. 4 Total ΔV

Scientific objectives

Near Earth objects represent a precious source of information as they represent a mixture of different population of small bodies containing fundamental issues on the origin and early evolution of the solar system.

The accretion mechanism plays a major role in the formation of the planets of the solar system. These small bodies are believed in fact to be the remnants of the swarm of planetesimals from which the planets were formed.

Monitoring the response of this asteroid to the gravitational constraints induced by its close approach to the Earth will permit to characterize its internal structure and thus to refine the accretion models.

A network of seismometers will be deployed at its surface to record the signals induced by the likely internal motions of the core of the asteroid under these natural gravitational constraints. Active seismology can also be envisioned. Such instruments are already prepared for lunar and martian missions.

Mitigation objectives

Depending the actual geometry of its 2029 pass close to the Earth, the orbit of Apophis around the Sun can be modified in such a way that further close flybys or even impacts with the Earth can occur in the decades to come. In particular, if the new orbit period is commensurable with the Earth period (365.25 days) then a new close encounter will occur *m* years after April 13, 2029, after Apophis has accomplished *n* revolutions around the Sun, *m* and *n* being integers. Long term extrapolation of the Apophis orbit beyond a few

decades will not be reliable as long as the most important non-gravitational perturbation, the Yarkovsky Effect, has not been fully characterized.
From the observations that have been gathered since the discovery in 2004 and that will be obtained during the next visibility periods (2012-2013, 2020-2021), we can expect an accurate determination of the Yarkovsky effect on the orbit of Apophis. But this determination will not be valid after the 2029 pass since the average distance of Apophis to the Sun will change significantly and consequently, the magnitude of the Yarkovsky effect due to its thermal origin.
It is of prime importance to use the 2029 opportunity to deliver at the surface of Apophis a reliable tracking system, similar to the laser reflectors that have been released on the Moon during the Apollo and Luna missions in the '70s. Such devices are passive and are still in use for measuring the Earth-Moon distance variation. At each future close approach of Apophis close to the Earth, laser ranging will allow to monitor its orbit and update the assessment of future risk impact.
In case an impact with the Earth cannot be prevented, a mitigation mission will have to be carried out. The knowledge of the internal structure will then be mandatory to model the behavior of Apophis during its atmospheric entry. If the conclusion is that the risk of doing nothing is too high for the planet, then a mitigation mission will have to be planned. Again the knowledge of the deep features of Apophis will be necessary for making the best choice.

Support to the human mission

The objectives of the mission concerning the preparation of the manned mission are to provide all the navigation and landing support that will be necessary for an accurate and safe landing of the crew module. A transponder system in connection with the Earth will allow to improve the ephemerides of Apophis to the required level of accuracy. A radio and or optical navigation system will be used for the guidance of the man tended module during the interception and close navigation phases.

The tools that will be needed by the crew to proceed with the scientific activities will also be delivered on Apophis by the pathfinder robotic mission.

IV – CREWED MISSION

The main particularity of the crewed mission is its duration. The crew will have to spend only a few weeks in space, which is more than the past lunar missions but by far less than any manned mission to Mars or even any NEA other than Apophis.

The basics of the mission is to head towards Apophis when it comes to the Earth by launching on a highly eccentric orbit, to accelerate from the apogee of this orbit to ensure a low velocity touch down on Apophis, to spend less than a day on its surface and then to come back to the Earth.

The assumptions that are made for this mission scenario are taken from a description of the Space Launch System available at www.nasa.gov/pdf/588413main_SLS_Web_final.pdf

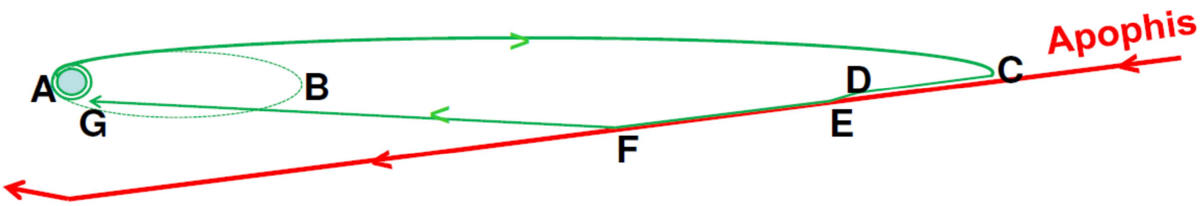
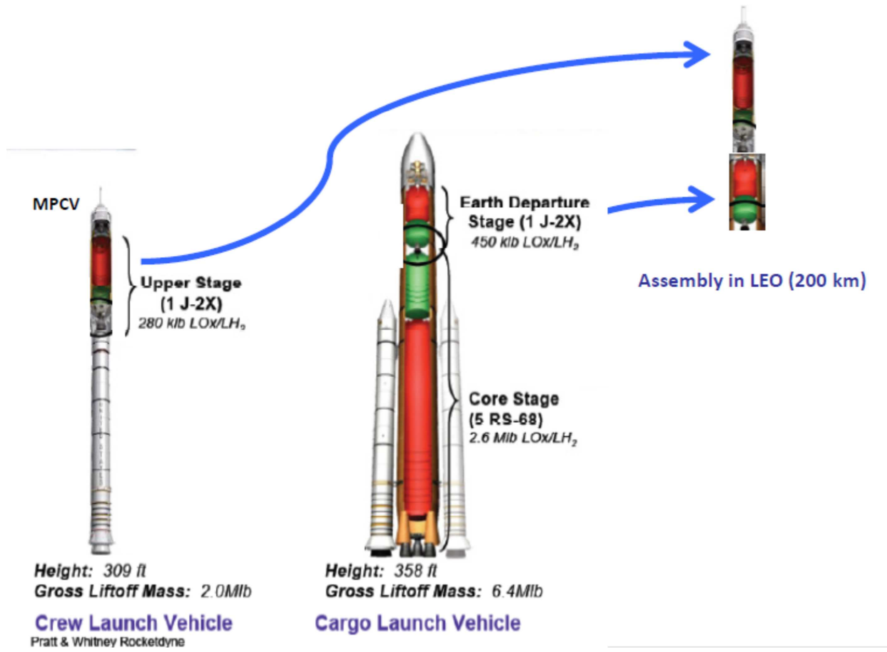


Fig. 5 Sequences of the crewed mission. The trajectory of Apophis is in red, the path of the crew in green

<u>IV.I Mission Overview</u>

At first, a Cargo Launch Vehicle is launched, placing the EDS (Earth Departure Stage) into a Low Earth Orbit. This takes place around mid-March 2029, one month before the Apophis pass.

A few days after, a Crew Launch Vehicle places on the same orbit the MPCV (Muti-Purpose Crew Vehicle). They rendezvous and link together.



Then the ignition of the EDS provides a ΔV of 3300 m/s that places the MPCV on a highly eccentric orbit of apogee around 1 Million kilometers. After its burn, the EDS is jettisoned, leaving in orbit the Crew Launch Vehicle Upper Stage carrying the MPCV.

It takes about three weeks for the crew to raise from LEO (A on Fig.5) to the apogee of this orbit (C).

At the apogee of this eccentric orbit, the MPCV is close to the natural path of Apophis. The MPCV velocity with respect to the Earth is very low, just a few tens of meter/second. Apophis is approaching with a velocity of 5900 m/s. The Upper Stage is then ignited and delivers a ΔV around 6000 m/s so that when Apophis catches up the MPCV, their relative velocity is only a few tens of m/s (D). The Upper Stage is then jettisoned and the close navigation phase can start. This phase ends when the crew module is at reach of the surface of Apophis (E).

The visit of one or two of the crew members can then begin. One can imagine two different scenarios, depending on the capacity of the MPCV to land on Apophis or not. If it is not expected to land, one astronaut has to stay onboard the Crew Module while his/her mates are walking and working on Apophis.
The Earth is approaching very rapidly (more than 6 km/s one day before the closest approach). The visiting astronaut(s) will have only less than one day to perform its scientific programme and, very likely, to accomplish some highly spectacular media duties.
One day before the closest approach, at the latest, everybody has to be in the Crew Module to get ready for the return to Earth (F). Two kinds of maneuver have to be performed then:

- a reorientation of the trajectory to provide an altitude change at perigee around 38,000 km (difference between the Apophis perigee altitude and the altitude of 125 km that is required for an atmospheric reentry),
- a braking maneuver so that the speed at 125 km be less than 12 km/s for a safe atmospheric reentry.

IV.II Main Characteristics of Each Phase

Earth departure (A-C)

The characteristics for the launches are taken from http://www.nasa.gov/pdf/214593main_Bouley(Lamm)2-26-08.pdf.
The engines that are used by the EDS and the Upper Stage are assumed to be of J-2X type with a Specific Impulse of 448s.
The mass of the Earth Departure Stage delivered by the Cargo Launch Vehicle is 115 metric tons (mT), of which 101 mT are the propellant and 14 mT the structure.
The mass of the MPCV and the Upper Stage placed into LEO by the Crew Launch Vehicle is 76 metric tons.
The ΔV that is required to go from LEO to an elliptical orbit of apogee around 1 Mkm is 3300 m/s.
This is delivered through the consumption of 115 metric tons of fuel from the EDS.
An interim orbit (B) can be used for reducing the gravitational losses of a single burn. The total amount of ΔV would not be changed but the total mission duration would be extended by a time corresponding to the period of this interim orbit..

Interception Trajectory (C-D)

The trajectory of Apophis is counter-clockwise while the eccentric orbit is clockwise. This means that the impulse to be delivered by the Upper Stage of the Crew Launch Vehicle to place the MPCV on an interception orbit is the sum of twice the velocity at apogee plus the relative velocity of the incoming Apophis. As a first approximation, a ΔV of 5900 m/s is considered. This corresponds to a fuel consumption of 56 mT. As soon as the burn has ended, the Upper Stage is jettisoned. The mass of the MPCV is 13 mT. Its trajectory is very close to the trajectory of Apophis which catches it up with a relative velocity of a few tens of m/s.

Landing on Apophis (D-E)

Within a few hours, the MPCV has to perform close navigation operations in order to safely deposit on the surface of Apophis one or two astronauts. The estimation of the fuel budget for that is of the order of 150m/s. The Specific Impulse of the Service module of the MPCV is 349 s.

Apophis spin rate is estimated to 30 hours from the available observations up to 2008. The determination of its dynamical and geometrical properties will improve with time and will be fully available from the pathfinder robotic mission. Two options can be envisioned: landing the Crew Module on the surface or hovering over the surface of Apophis and having one or two astronauts perform some sort of Extra Vehicular Activity on the surface. The criteria for the choice will be the information on Apophis characteristics, considerations about safety and the current international regulations about small body protection.

One day on Apophis (E-F)

This will be of course the most exciting part of the mission. It will take place on April 11, the anniversary day of the Gagarine space flight (in 1961). The dramatic intensity of this day will reach the magnitude of the first steps of Neil Armstrong on the Moon 60 years before. Obviously, the scientific part of the stay of one or two astronauts on Apophis will have to be reduced to a minimum, leaving an important role for media and communication constraints.

Walking and even working on an asteroid is much harder than walking on the Moon, due to the quasi absence of gravity. Special tools and equipments will be needed. This mission can be a unique opportunity for testing and qualifying them in the perspective of asteroid mining. All these devices will have been delivered by the pathfinder robotic mission.

Back to Earth (F-G)

Twenty four hours before the closest approach, Apophis velocity relative to the Earth is still under 6 km/s, its distance to the Earth being 500,000 km. After leaving Apophis, a trajectory correction is performed in order to lower the perigee altitude from 32,000 km (Apophis natural trajectory) to 125 km where the atmospheric reentry will begin. This trajectory steering maneuver should be combined with a braking maneuver in order to reduce the natural velocity at this altitude (12.6 km/s) to a more ‘comfortable’ velocity under 12 km/s. A second braking maneuver can be performed a few hours before the reentry to decrease a second time the reentry velocity of the Crew Module and/or to accurately target the landing area.

The total fuel budget for the Service Modulei is the sum of 100 m/s for the close navigation (D-E) and possible hovering over Apophis (E-F) and 1400 m/s for the reentry maneuver(s). This 1500 m/s total impulse requires Around 4800 kg of fuel, the initial mass of the MPCV being 13 mT and the mass of the Crew Module 7 mT.

V – CONCLUSIONS

We are only 16 years before the close approach of Apophis. The Apophis Express mission, as presented here, obviously needs a lot of studies and, as it requires at least 3 launches (one for the pathfinder robotic mission, two for the the crewed mission), it will certainly be a costly endeavor.

Compared to other mission scenarios that are considered in the frame of the NASA led NHATS (Near-Earth Object Human Space Flight Accessible Targets Study), Apophis Express fits very well in the criteria, except for the minimum stay time which is less than one day instead of 8 as a NHATS objective. Nevertheless, the contribution of the pathfinder robotic mission for fulfilling the mission objrectives should be taken into account.

One important feature of the Apophis Express is that the crew is always on a trajectory that naturally brings it back to the Earth. If for any reason, the Upper Stage fails, a safe return is still guaranteed.

Considering that the NEO issue is a global one and that, as such, it is under consideration by the United Nations (COPUOS Committee), an international expedition can be envisioned. For instance one major space agency could take the lead of the pathfinder robotic mission while another one would lead the crewed mission, with a wide international cooperation.

Setting up an international cooperation is a lengthy process, so, if this Apophis Express mission design is considered to be valuable, there is no time to waste for preparing it.