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Addressing the imminent impactors threat from distant retrograde orbits (DRO)

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Abstract

Planetary Defence is gaining momentum after the launching toward the Didymos binary system of NASA DART, the first asteroid deflection mission, foreseeing also the deployment of ASI's LICIAcube. Moreover, the ESA Hera spacecraft, which will contribute to assessing the DART impact momentum transfer, is in full realization phase. After the well-established US planetary defence activities, the European Union has recently included the NEO hazard in its own Space Programme in order to extend and complement the ESA initiatives i.e. the establishment of NEO Coordination centre at ESRIN and the realization of the wide-field high-sensitivity Flyeye telescope. Both NASA and ESA also plan to improve the efficiency of their observational networks by launching space mission devoted to NEO observations from space. Finally, the ever-growing NEO discovery rate moves toward increasingly smaller objects passing close to our planet, thus posing new challenges in performing follow- up observations for determining their orbital and physical properties.
Within this framework, addressing the so called ”imminent impactors” threat, posed by objects in the 10-40 m range in route of collision with the Earth (the Tunguska-class objects), has become a key issue for planetary defence. Deflection capabilities are useless if a celestial body large enough to produce significant damage can sneak up on the Earth undetected, as could asteroids hiding by the Sun, lurking in the well-known blind spot that ground-based observations can never peer into. In this respect the advantages of placing a telescope on a stable Distant Retrograde Obit (DRO) around the Earth when compared with other orbital configurations have already been proven, and they are now well established in the literature.
In this work the feasibility of a mission scenario foreseeing a constellation of four spacecraft in DRO is invesitgated in detail, comparing several target orbits and different transfer strategies, including lunar swing-bys. The more efficient orbital configurations in terms of accessibility and detection capabilities are investigated and validated using case studies of historic asteroid undetected close encounters. Results prove that a DRO constellation would be able to detect and refine the trajectory of a Tunguska-size object with a warning time exceeding the requirement set for natural disasters. The possibility of contributing to the physical characterization of an imminent impactor is also discussed, which is essential for building up an efficient rapid response system for civil protection purposes.

1. Asteroid Hazard

Assessing the asteroid hazard has greatly profited of the coming into operations, from the early 2000's, of all-sky surveys which have allowed to fulfill the US Congress mandate of discovering at least 90% of the objects with diameters larger than $1km$. Moreover, the new-generation telescopes deployed in the last decade have contributed to the onset of a clear trend in NEO discoveries to peak toward smaller and smaller objects. Among them, the so-called 'imminent impactors' are those in the $10 - 40m$ range that are detected when passing close to the Earth.

Therefore, the next challenge for planetary defence is twofold. The first goal is to reach a high percentage of completeness also for objects down to $140m$ in size (the original deadline posed by the US government i.e. 2020 turned out to be too demanding), which is considered the treshold for an impact producing regional devastations. The other objective is to set up a rapid response system for properly dealing with the hazard posed by the imminent impactors. This means to be able to discover them with sufficient warning time for performing both, astrometric follow-up observations and physical characterization in order to decide whether an impact will actually occur, determine its location, evaluate the damage on the ground and put in place, when needed, civil protection mitigation actions. Although the near-future ground-based surveys, notably the US Vera Rubin observatory and the ESA

Flyeye telescope, are likely to address to both issues, their efficiency could be greatly enhanced by the deployment of space assets. To this end both, NASA and ESA, plan to launch missions devoted NEO detection from space: the former is studying the NEO Surveyor mission, which could be launched as early a 2026, while the latter has proposed the NEOMIR space observatory. Both spacecrafts will be equipped with infrared telescopes and will be placed on halo orbits around the Earth-Sun lagrangian point L1 in order to decrease the region of space out of reach for ground-based telescopes due to extremely low solar elongations. The differences between the two missions in terms of e.g. observing strategy and sensor characteristics, ensures complementarity among them.

Within this framework the feasibility of a space-based asteroid impact warning system on a Distant Retrograde Orbit (DRO) is analyzed in detail, following the mission concepts in [1] and [2]. According to them, a DRO allows to adopt an anti-solar observing strategy which accounts for favourable phase angles, thus representing a major advantage for timely detecting the imminent impactors. Simple geometrical considerations impliy that the DRO orbit altitude is tightly related to the magnitude of the warning time in principle achievable, therefore a $5-$day time span (as typical for natural disasters) has been adopted. The visibility coverage of a constellation of 4 spacecrafts placed on a $0.06au$ DRO is analyzed and various transfer possibilities present in the literature (see for example [3], [4] and [5]) have been implemented and compared using a high fidelity propagator. A further Moon fly-by transfer to DRO is then proposed, proven to minimise fuel consuption and ensure mission feasibility.

Asteroid accessibility and detection capabilities of the proposed DRO constellation are then validated using the undetected very close encounter with Earth of asteroid $2013TX68$.

Section 2 provides a quick overview on Distant Retrograde Orbits (DROs), Section 3 and 4 explain the link between asteroids osservability, warning time and orbital altitude. Section 5 compares the different types of transfers to DRO proposed in the literature, and Section 6 proposes a Moon fly-by for optimising the transfter. Section 7 validates the concept through a real scenario. In Section 8 the advantages and drawbacks of the proposed scenario are discussed within the framework of the present / near future planetary defence programmes

2. Distant Retrograde Orbits

Distant Retrograde Orbits are periodic solutions of the CR3BP, where the massless body revolves around the main primary with the same period as the second primary, same revolving plane, resulting in an apparent (retrograde) motion around the latter (as seen from a synodic frame of reference), despite not being in capture with it. These are stable for extended periods of time [6], and suitable for asteroid detection missions as they ensure continuous communication with Earth.

DROs are built from the periodic solutions of the Hill's approximation of the CR3BP [7], numerically refined via a differential corrector to be periodic in the CR3BP.

Let be $O_{\hat{x},\hat{y},\hat{z}}$ a synodic frame of reference centred in the Sun/Earth-Moon baricentre, the $\hat{x}/\hat{y}$ plane being their orbital plane, with the $\hat{x}$ axis pointing from the Sun to the Earth. Scale units of distance, mass and time such that the sum of the primaries masses and their distance are set to 1 and the period of their mutual revolution to 2π, calling μ the scaled mass of the smaller primary. In this system, the CR3BP is described by the classic Hamiltonian:

$$\begin{aligned}\mathcal{H} = & \tfrac{1}{2}\left(p_x^2+p_y^2+p_z^2\right)+yp_x-xp_y \\ & -\tfrac{1-\mu}{\sqrt{(x-\mu)^2+y^2+z^2}}-\tfrac{\mu}{\sqrt{(x+1-\mu)^2+y^2+z^2}} \\ & +\tfrac{(3-\mu)}{2}(1-\mu)\end{aligned} \tag{1}$$

From it, the so called Hill's approximation of the CR3BP is obtained, for small μ, shifting the system of reference to the smaller primary, and further scaling the distances with a factor $\mu^{\frac{1}{3}}$, than developing the Hamiltonian in series of μ and ignoring high orders, which yields:

$$\begin{aligned}\mathcal{H} = & \tfrac{1}{2}\left(P_x^2+P_y^2+P_z^2\right)+YP_x-XP_y \\ & -\tfrac{1}{\sqrt{X^2+Y^2+Z^2}}+\tfrac{1}{2}(X^2+Y^2+Z^2) \\ & +\tfrac{3}{2}X\end{aligned} \tag{2}$$

whose solution can be explicitly find, following a procedure analogue to the one in [8], for DROs with periapsis between the primaries:

$$\begin{cases} x(t) = \frac{2}{\mu^{\frac{2}{3}}}\bar{P}_{3,0} - \sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\sin\left(\bar{Q}_{1,0}+t\right) \\ y(t) = \bar{Q}_{3,0} - 3\frac{\bar{P}_{3,0}}{\mu^{\frac{2}{3}}}t - 2\sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\cos\left(\bar{Q}_{1,0}+t\right) \\ z(t) = -\sqrt{\frac{2\bar{P}_{2,0}}{\mu^{\frac{2}{3}}}}\sin\left(\bar{Q}_{2,0}+t\right) \\ \dot{x}(t) = -\sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\cos\left(\bar{Q}_{1,0}+t\right) \\ \dot{y}(t) = -\frac{3\bar{P}_{3,0}}{\mu^{\frac{2}{3}}} + 2\sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\sin\left(\bar{Q}_{1,0}+t\right) \\ \dot{z}(t) = -\sqrt{\frac{2\bar{P}_{2,0}}{\mu^{\frac{2}{3}}}}\cos\left(\bar{Q}_{2,0}+t\right) \end{cases} \tag{3}$$

Initial guesses for DROs in the Hill approximation are then generated from (3) by imposing the planarity $Z = 0, \dot{Z} = 0$) and periodicity $y(2k\pi) = \dot{x}(2k\pi) = 0$, with $k \in \mathbb{Z}$ conditions, namely $\bar{P}_{2,0} = 0$, $\bar{P}_{3,0} = 0$, $\bar{Q}_{1,0} = \frac{\pi}{2} + k\pi$ and $\bar{Q}_{3,0} = 0$, obtaining:

$$\begin{cases} x(t) = -\sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\cos(t) \\ y(t) = 2\sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\sin(t) \\ z(t) = 0 \\ \dot{x}(t) = \sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\sin(t) \\ \dot{y}(t) = 2\sqrt{\frac{2\bar{P}_{1,0}}{\mu^{\frac{2}{3}}}}\cos(t) \\ \dot{z}(t) = 0 \end{cases} \tag{4}$$

These are passed through a differential corrector to obtain initial states DROs for CR3BP in (1).

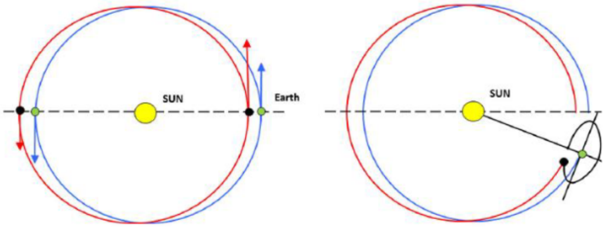

Fig. 1: Distant Retrograde Orbits (in red) are periodic solutions of the CR3BP, where the massless body revolves around the main primary with the same period as the second primary, same revolving plane, resulting in an apparent (retrograde) motion around the latter.

As DROs period is fixed to match the one of the second primary, DROs are completely identified by their eccentricity, which, for geometrical considerations, also defines their altitude in au from the Earth, i.e. the distance from Earth when the spacecraft crosses the Sun Earth line, at its periapsis.

For DROs of about $0.1au$ and above, the CR3BP provides a rough approximation of the real system, and more refined models should be adopted for realistic estimations of mission costs. For these reasons, in this paper, the main results have been obtained using AGI's Systems Tool Kit (STK) high fidelity propagator HPOP.

3. Asteroid warning time

The orbital altitude necessary to a constellation of satellites to ensure the detection of all Tunguska-class asteroids (i.e. $40m$) with a 5 days warning time, fixed in analogy with Hurricane warning time and average population response [9], must now be determined.

Considering a mean asteroidal Earth impact velocity of $18km/s$ [10] (in good agreement with the $17.95km/s$ in [11], the $17.3km/s$ from [12] and the $20.18km/s$ from [13]), straight forward calculations lead to a circular $7776000km = 0.052au$ radius zone to be constantly monitored to achieve the aim above.

For geometrical considerations due to the Spacecraft-Sun exclusion zone, this maps directly into the orbital altitude required for the spacecraft (see Fig. 2).

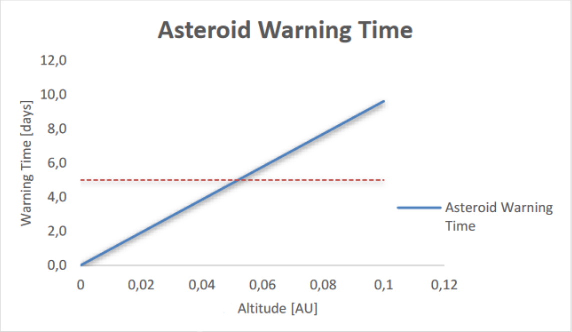

Fig. 2: Warning time and orbital attitude.

In this paper we will consider DROs with altitude of $0.06au$ to account for a reasonable margin.

4. Asteroid visibility computation

The detectability of an object in the sky is measured via its apparent magnitude, calculated as the reverse logarithm its brightness, as seen by an observer on Earth and adjusted to the value it would have neglecting the effect of the atmosphere.

A telescope limiting apparent magnitude V_{lim} is the highest apparent magnitude it can detect, expressing a measure of the dimmest objects it can spot in the sky.
The current leading NEOs discovery survey, Panstarrs, has a mean limiting magnitude of $22.5 V_{lim}$, which can stretch to $23 V_{lim}$ in particularly favourable conditions, while the only working space-based NEO survey, NEOWISE, uses a thermal infrared technology, thus its limiting magnitude is not easily defined.

In this paper, a reasonable limiting magnitude of $21.5 V_{lim}$ is assumed for space-based telescopes, to account for reduced telescopes dimensions. Moreover, as in [14] it is assumed that multiple ground and space-base surveys are available at any time, and that all the sky is surveyed, except a solar exclusion zone of approximately 40 degrees from the sunlight direction [15].

Following [14], the observation capabilities of a telescope are modelled using equation (5), which links visual and apparent magnitudes (see [16]), and the well known equation (7), linking absolute magnitude and diameter of an object.

$$\begin{aligned} V = H &+ 5\log_{10}\left(R_1(t)R_2(t)\right) \\ &-\tfrac{5}{2}\log_{10}\left(1-G\right)\Phi_1(k(t)) + G\Phi_2(k(t)) \end{aligned} \tag{5}$$

where:

$$\begin{aligned} \Phi_1(k(t)) &= \exp\left(-3.33\tan\frac{k(t)}{2}^{0.63}\right)H \\ \Phi_2(k(t)) &= \exp\left(-1.87\tan\frac{k(t)}{2}^{1.22}\right)H \end{aligned} \tag{6}$$

- V visual magnitude of the object.
- H absolute magnitude of the object.
- $R_1(t)$, $R_2(t)$ object distances from Sun and observer respectively (in au).
- $k(t) = \frac{\cos\left(R_1^2(t)+R_2^2(t)-R_3^2(t)\right)^{-1}}{R_1(t)R_2(t)}$ Sun-object phase angle, ($k(t) = \pi$ when the asteroid is between the illuminator and the observer)
- $R_3(t)$ Sun and observer distance (in au).

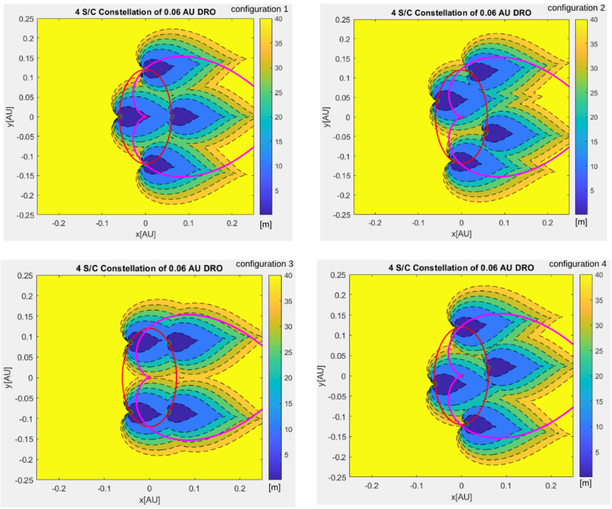

Fig. 3: The evolution in time of the constellation of 4 telescopes on a $0.06 au$ DRO with contours of detectable objects.

- G Phase solpe parameter describing how the asteroid brightness falls with increasing solar phase angle. In this paper we set $G = 0.15$, corresponding to a low-albedo for $C-type$ asteroids (see [17]).

The absolute magnitude is linked to the diameter (in m) of the object by the equation:

$$D = 1.329 \times 10^6 \sqrt{p} 10^{-0.2H} \tag{7}$$

where p it the albedo of the asteroid, whose value is often unknown and has to be assumed, resulting in large uncertainties in the size determination. In this paper $p = 0.14$ is assumed, as used in the NEO Coordination Centre technical portal.

Combining the two equations, for each fixed limiting visual magnitude, hearth shaped contours of detectable objects diameters can be found, as function of distance from the object, solar phase angle and asteroid albedo.

A constellation of 4 satellites will thus be built to ensure the geometric coverage of the 5 days warning region (see Fig. 3).

5. Transfer to DRO

Several papers have investigated the variouos possibilities for LEO to DRO transfer trajectories (see for example [3], [4], [18] and [5]). In this paper the main transfer possibilities of impulsive transfers from a parking

Low Earth Orbit (LEO) to different altitudes DROs are compared, in order to clarify their general usability.

The discussion is then focussed on building the 4 spacecraft constellation on a $0.06au$ DRO.

5.1 Direct transfer to DRO

The first transfer considered is a Hohmann transfer, defined as the classical direct transfer [18], consisting a departure manoeuvre from LEO at the $\hat{x}$ axis crossing, and a tangential insertion into DRO. The fuel consuption of this transfer was analysed in [1], however, with the aim of reducing fuel consumption, this can be modified using an adapted half cycle path of an Earth Return Orbit (ERO), as suggested in [5].

EROs, also called a/c family [7], are unstable retrograde orbits of the CR3BP around Libration points with very close approaches to the secondary body. An ERO can always be chosen so that it intersects tangentially with the desired target DRO. However EROs do not, in general, intersect the initial LEOs tangentially. A differential corrector must thus be used for this condition to be matched, minimising fuel consumption.

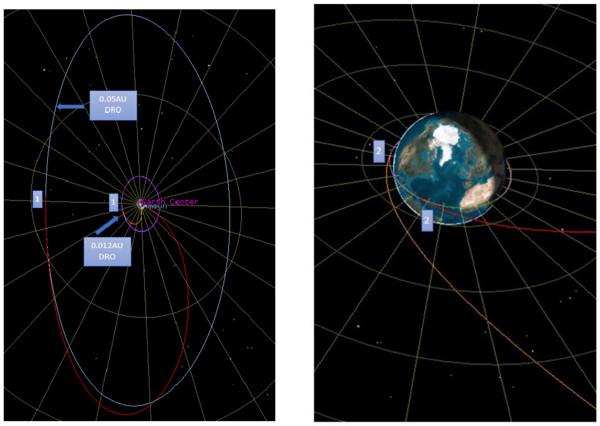

Fig. 4: Two examples of transfers to a $0.012au$ and a $0.05au$ DROs using EROs. Point 2 marks the impulse to leave the parking orbit, point 1 the impulse needed for entering in DRO.

Figure 4 shows two examples of transfers to a $0.012au$ and a $0.05au$ DROs using EROs.
In it, point 2 marks the impulse to leave the parking orbit, point 1 the impulse needed for entering in DRO.

5.2 HLO to DRO

EROs family bifurcates from the Horizontal Lyapunov Orbits (HLOs) for high orbital energies, therefore its usability is limited to orbits with altitude higher than $0.025au$ [19]. For smaller orbits, while a 2 impulse transfers are still possible, these will be considerably more expensive than ERO-like transfer orbits. For these cases Horizontal Lyapunov Orbits (HLOs) could be used.

These orbits have associated manifolds (stable and unstable) and transit orbits which do approach Earth very closely, making them attractive to be used as transfers from LEO.

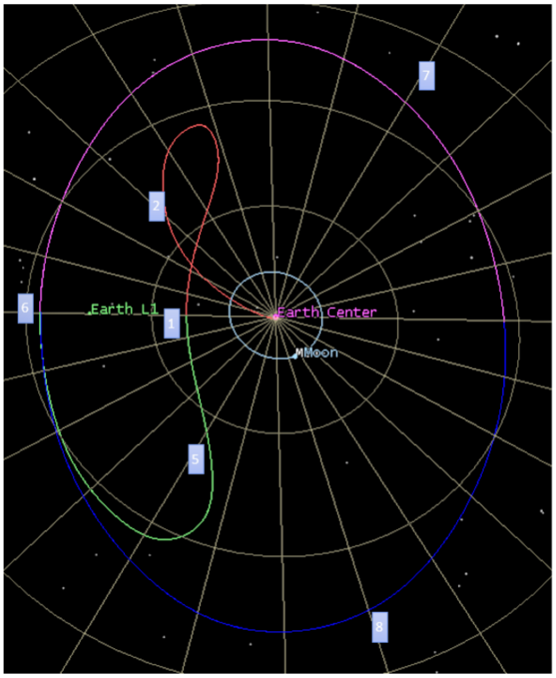

Fig. 5: shows the different segments of HLO transfer to DRO. 2 labels the manifold transfer to the HLO, 1 marks the insertion manoeuvre into HLO. 5 is the DRO insertion point, and 6 the final orbit

Figure 5 shows the different segments of HLO transfer to DRO. In it 2 labels the manifold transfer to the HLO, 1 marks the insertion manoeuvre into HLO. 5 is the DRO insertion point, and 6 the final orbit.

5.3 Results

A comparison is performed, to determine which transfer strategy provides the cheapest (in terms of Δv) means of transfer from LEO to DRO, depending on the DRO altitude.

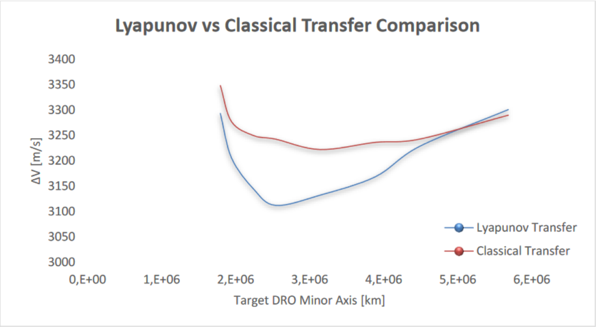

Fig. 6: total mission Δv found classical and Lyapunov transfers, for increasing size DROs

Figure 6 shows the total mission Δv found for the classical and lyapunov manifold transfers, implemented with the software STK for DROs of increasing size.

Results show the existence of an optimal DRO amplitude for the classical method around $0.02au$ and that invariant manifolds perform better for "small" DROs with a minimum fuel consumption in $0.013au$, at the cost of considerably higher time of flight and an increase in transfer complexity (i.e. instability of the transfer orbit).

It is interesting to notice that HLO method naturally converges into the classical transfer when EROs bifurcate from the Lyapunov orbits, around $0.035au$, the Δv advantages cease to exist, possibly due to the instability of the HLOs for these altitude ranges, making this transfer strategy is unsuitable for our mission.

6. Moon Fly-by Transfers

As for the intended final mission orbit of $0.06au$ a classical two-impulse transfer is preferable over the HLO manifold option, a modified classical transfer is here investigated, with the inclusion of a lunar gravity assist to further reduce the Δv requirements.

This strategy is found to provide significant benefits (i.e. $> 50m/s$) for DROs of altitudes between $0.04au$ to $0.095au$.

Figure 7 shows an example of the lunar flyby transfer for the 4 satellites constellation to the $0.06au$ DRO, while

Figure 8 provides a qualitative idea the advantage of provided by the Lunar flyby against the alitude of the selected DRO.

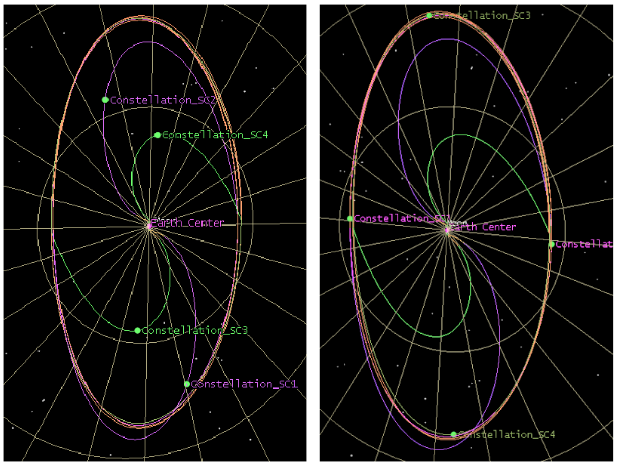

Fig. 7: The lunar flyby transfer for the 4 satellites constellation to the $0.06au$ DRO.

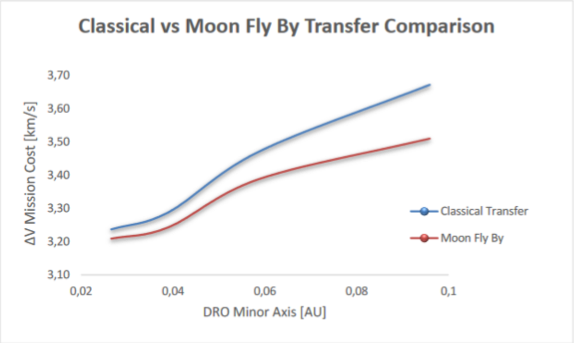

Fig. 8: Classical and Moon Fly By Transfer Comparison

7. Application to Historic Asteroid Close-Encounter

The performance of the warning constellation described is now shown for the case of the 8^{th} March 2016 near miss of Asteroid $2013TX68$, discovered four days before its possible Earth flyby.

This $30m$ object had a huge uncertainty on the orbit, ranging between $24000km$ to $5 \times 10^6 km$, due to its approaching direction in line with the Sun, making astronomers unable to refine astrometries [20].

Simulations with STK show that the asteroid enters the detection zone on February 29^{th}, approximately 8 days before the eventual Earth close encounter, thus demonstrating the potentialities of the warning systems discussed.

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the potentialities of the warning system presented. This result shows that using the DRO approach it is possible to detect and refine the trajectory of the incoming objects with a warning time largely compliant with the assumed 5-day natural disaster requirement, thus representing a promising option for complementing both, ground and space based observations

8. Discussion and conclusions

The many advantages of using a DRO for timely detecting the imminent impactors have been highlighted in [1], including both observational and mission analysis considerations. The most demanding drawback turned out to be the need of accessing interplanetary space, especially because of the multiple-spacecraft scenario envisaged, thus suggesting the use of low-energy dynamics in order to decrease the delta-V requirements.
In this paper a detailed modelling of a $4-$spacecraft constellation placed on a $0.06au$ DRO (assumed as the lowest orbital altitude for satisfying the typical natural disaster warning time) has been carried out, taking into consideration different transfers (classical, low-energy, lunar swingby). It has been shown that after a certain treshold the advantage of using space manifolds decreases rapidly with the DRO altitude, and that for the selected orbital altitude it is more convenient to use a classical two-impulse transfer with the inclusion of al lunar swingby. The asteroid visibility analysis has also confirmed that observing in the anti-solar direction represents a clear advantage with respect to more traditional configurations (e.g. Earth-Sun L_1 halo orbit) for detecting the imminent impactors and that DROs satisfying the related operational constraints (accessibility, warning time etc) do indeed exist.
The $4-$spacecraft constellation scenario proposed could also profit of a reduced mass budget for each spacacraft and of an incremental deployment.

It is worthwhile stressing that the proposed system could play a key role in the build-up of a rapid response system able to quickly and fully characterize a possible impactor. The real-case experiment recently carried out within the framework of the EU NEOROCKS project [21] has demonstrated that both highly automatized astrometric follow-up and quick physical characterization of a newly discovered object can be carried out in a matter of days [22], thus fulfilling the early warning scenario presented in this paper. Such a system could be extremely useful also for allowing quick physical characterization of the low-diameter end of the NEO size distribution which is very interesting for science [23] because of an excess of dark carbon-rich bodies with further potential applications in asteroid mining.

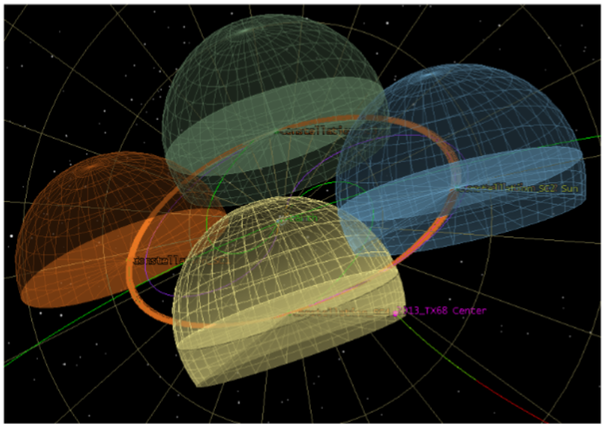

Fig. 9: $2013TX68$ entering the field of view of one of the telescopes, approximately 8 days before the eventual Earth close encounter.

Figure 9 shows the simulation of the trajectory of $2013TX68$ and the instant in which it enters the field f view of one of the telescopes.

9. Acknowledgment

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