On the Attainability of the Near Earth Asteroids

E. Perozzi[1], L. Casalino[2], A. Rossi[3], G.B. Valsecchi[4]

[1] Telespazio, Roma, Italy

[2] Politecnico di Torino, Italy

[3] ISTI-CNR, Pisa, Italy

[4] IASF-CNR, Roma, Italy

Abstract. The accessibility of the Near Earth Asteroids (NEAs) population can be investigated by means of some basic celestial mechanics and astrodynamics. The classical results on the attainability of celestial bodies obtained by Walter Hohmann at the beginning of the XX.th century are generalised introducing an H-plot. This allows to develop an efficient targeting strategy for space missions aimed to the NEAs. Applications to the ESA phase-A missions studies ISHTAR and SIMONE and to a NEA sample return mission are also presented.

1. Introduction

The Hohmann transfer strategy was originally developed at the beginning of the last century for finding minimum energy orbital paths enabling a manned spacecraft to reach the Moon and the planets (McLaughlin, 2000). The method has been subsequently generalized to any transfer between circular and coplanar orbits (e.g. Roy 1988), taking into account relative inclinations (e.g. Boden 1997). The Hohmann strategy is very useful for assessing the accessibility of celestial bodies because it foresees two simple orbital manoeuvres (Fig.1) whose magnitude can be straightforwardly computed from basic keplerian motion. If we consider the case when the radius of the target orbit is larger than that of the departure orbit, the first manoeuvre injects the spacecraft into a transfer trajectory whose apocentre is tangent to the target orbit. The second manoeuvre - applied upon reaching the apocentre of the transfer orbit - increases the velocity of the spacecraft of the exact amount needed for circularization. Adding up the ΔV contribution of both manoeuvres, a reliable estimate of the energy requirements needed for performing a rendezvous mission (i.e. at encounter the spacecraft must have the same orbital velocity, and thus the same orbit, as the target) is obtained. A graphical representation of performing Hohmann transfers throughout the Solar System is shown in Fig.2, assuming that the departure orbit is that of the Earth. The two curves are representative of the strategy described above and have been obtained varying continuously the radius of the target orbit while keeping fixed at 1 AU that of the departure orbit. They also represent optimal mission profiles, provided that the ratio among the semimajor axis of the final orbit to that of the departure orbit is greater than 15.58, which is the threshold for bi-elliptic transfers to become more convenient (e.g. Roy 1988).

2. NEAs H-plot

The Hohmann formalism can be used as a basic targeting strategy for planning rendezvous missions to the eccentric and inclined orbits characterizing most NEAs by properly rearranging the order and the magnitude of the orbital maneuvers (Hechler et al. 1998). Results can be compared to the classical Hohmann transfers by plotting the aphelion distance of the target asteroid versus the

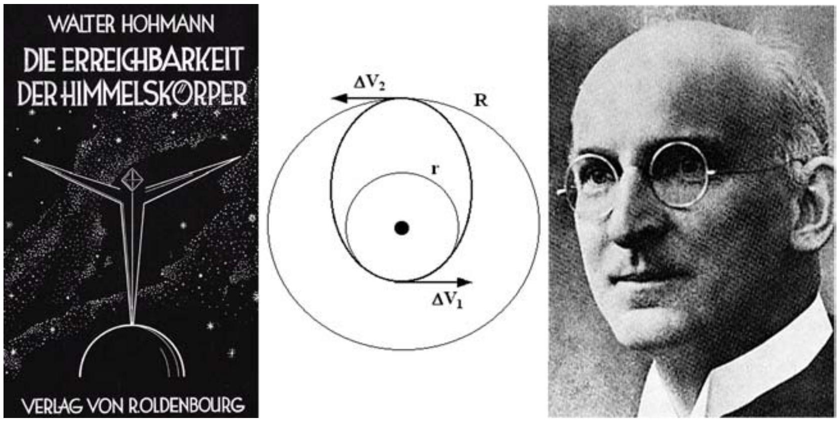

Fig. 1. Walter Hohmann (1880-1945) was a civil engineer, city architect of Essen (Germany). His enthusiasm for space science led him to become one of the most active members of the *Verein Fur Raumschiffahrt* (Society for Space Travel), together with Willy Levy and Wernher von Braun. His seminal investigations on interplanetary mission design are contained in his book *Die Erreichbarkeit der Himmelskorper* (The Attainability of Celestial Bodies), published in 1925. As William McLaughling (2000) states: "Hohmann's great contribution to astronautical progress was the discovery of a new use for an old object, the ellipse". Walter Hohmann died on March 11, 1945 during an allied bombing raid.

total velocity change needed to transform an initially zero inclination circular 1 AU orbit into one identical to that of the target (Perozzi et al., 2001). Note that this is equivalent, when treating the Earth escape branch of the transfer trajectory, to compute the hyperbolic excess velocity in the massless planet approximation, as described by Prussing and Conway (1993).

This dynamical framework has the advantage of being independent from the launch scenario: Earth phasing, the different capabilities of the launchers and/or the use of intermediate parking orbits make often difficult to carry out meaningful comparisons among different missions to different targets. The ΔV values used for filling the H-plot are instead a self-consistent data set representing the lowest figures achievable when both ideal phasing occurs (corresponding to the most favorable launch window geometry) and ideal orbital manoeuvres (i.e. strictly impulsive) are performed.

3. Targeting NEAs

The aim of the H-plot is to give a time-free dynamical evaluation of the accessibility of the NEA population. Therefore it can give indications to both, mission designers and astronomers. The formers may find it useful as a quick way of decreasing the number of potential targets according to mission specifications, before more accurate (and lenghty) trajectory optimization procedures are attempted. Astronomers can adopt the H-plot as a criterion for observing, among the thousands of known NEAs, those with lower ΔV requirements, more likely to be selected as targets for direct exploration. In the long run this would trigger a colosed loop: the more accessible asteroids are also those for which more data on their phisical characterization is available, which in turn increases scientific motivation and eases mission design. An example of this kind of application is reported in Binzel et al. (2003), where the H-plot representation is used for monitoring the accessibility of asteroids for which spectral classes have been determined through telescopic observations. Results show that no known metallic (M-type) asteroids (extremely interesting not only for science but also as extraterrestrial resources and/or for mitigation purposes) are accessible at less than 7 km/sec. If we consider that this value can be considered as the limiting ΔV budget at the present technological level (Perozzi et al. 2003), it is clear that a mission scenario different from simple Hohmann rendez-vous should be applied for missions aimed to M-type objects.

The H-plot targeting strategy has been successfully applied within the framework of the ESA phase-A studies (ESA AO4517 'NEO Space Mission Preparation', issued on February 2002) of the ISHTAR and SIMONE missions *(www.esa.int/gsp/completed/neo/index.htm)*. ISHTAR aims to

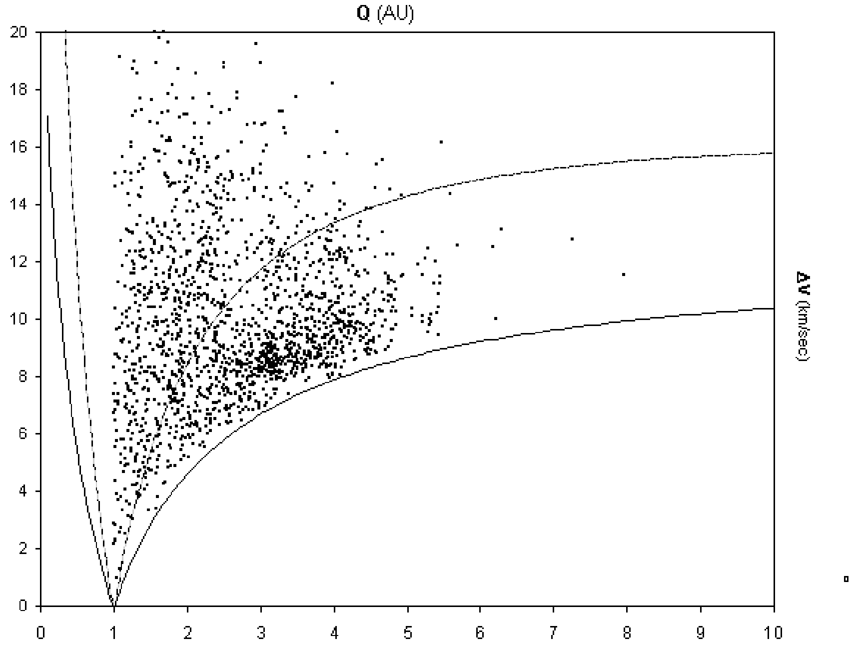

Fig. 2. In an H-plot the two reference curves give a graphical representation of the Hohmann transfer strategy. As an example, the solid line corresponds to the ΔVs needed to leave the starting orbit (of radius **r** in Fig.1) and being injected in a transfer ellipse of increasing apocenter distance (**R**). The dotted line is the sum ΔV1 + ΔV2 (see Fig.1) thus representing the total ΔV budget for a rendezvous mission. NEAs are widely dispersed in terms of ΔV: a significant fraction is less accessible than Jupiter. Note the extremely high requirements needed to reach the inner Solar System.

rendezvous two near Earth asteroids to investigate their internal structure by means of visual and radar tomography. During this study the H-plot helped target selection and allowed to visualise the improvements in the accessibility of the targets when more complex transfer trajectories exploiting Earth gravity assist (EGA) and/or Earth escape through weak stability boundary (WSB) trajectories were adopted. SIMONE addresses the issue of the gaining an understanding of the diversity of the NEO population by employing a number of relatively small and low cost missions that individually encounter specific NEAs of interest. The already described spectral H-plot approach allowed to isolate peculiar cases, as it will be discussed in detail in the next section. The validity of the H-plot approach as a best-case approximation has been confirmed even when the use of solar electric propulsion (SEP - implying low thrust levels for extended time spans) is envisaged, as it was the case for both, ISHTAR and SIMONE. This can be understood by remarking that with respect to the Hohmann strategy, which makes use of ideal impulsive manoeuvres at optimal dynamical configurations (i.e. pericenter or apocenter), SEP is always less efficient because the thrust is applied along extended arcs (thus in non-optimal locations) of the transfer trajectory. The advantages of SEP, from a flight dynamics point of view, are more concerned with the Earth phasing problem: low-thrust manouvering is very efficient in reducing the ΔV requirements when unfavorable launch windows occur.

4. The Case for Amun

The use of a resonant flyby strategy has been proposed (Perozzi et al., 2003) when a particularly interesting target for science turns out to be too demanding for rendezvous, which is often the case because of the frequent occurrence of high-eccentricity, high-inclination orbits among NEAs. This strategy exploits orbital resonances for performing repeated flybys of the same target. It represents an intermediate scenario between classical rendezvous and flyby missions, requiring almost zero inclination transfer trajectories to the asteroid node, while still offering a reasonable scientific return.

Within the framework of the SIMONE target selection process, M-type asteroids were not included in the rendezvous target list primarily because of excessive ΔV requirements. A search for M-types in the NEO population has therefore been performed to isolate potential resonant encounter candidates. The two objects (3554) Amun and (6178) 1986 DA (see Table 1) satisfied the basic requirements of having well determined orbits and reasonable size.

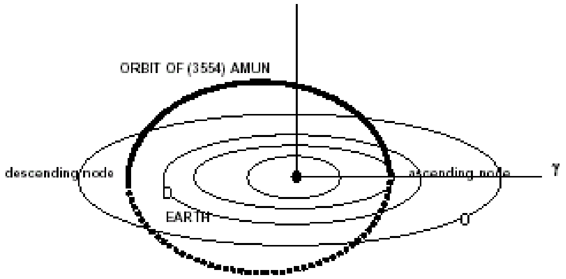

Fig. 3. The peculiar orbit of Amun

name	**H**	**P**	**e**	**i**	**ΔV*rv***	**asc.node**	**desc.node**	**P*syn***
	(abs. mag.)	(years)	(-)	(deg)	(km/sec)	(AU)	(AU)	(years)
(3554) Amun	15.8	0.961	0.28	23.4	11.6	0.70	1.25	24.4
(6178) 1986DA	15.1	4.711	0.59	4.3	9.1	1.87	1.35	1.3

Table 1. Orbital parameters of asteroid (3354) Amun and (6178) 1986 DA

When looking at the orbital parameters of the two objects, Amun clearly appears as the best choice. It has a period of revolution close to one year, thus allowing a 1:1 resonance which guarantees at least yearly encounters, while both nodes are in principle accessible, offering more chances of finding favourable mission opportunities. Furthermore, the orbit of Amun exhibits a peculiar geometry, with the semi-major axis nearly lying on the ecliptic (argument of perihelion = 359.4) and aligned with the vernal equinox (longitude of the ascending node = 358.7). Therefore nodal passages fall almost exactly at perihelion (ascending node) and aphelion (descending node). There are two notable consequences for the resonant flyby strategy: *a)* the relative velocity at encounter, being driven by the inclination between the asteroid orbit and that of the spacecraft, is maximum for ascending/perihelion encounters and minimum for descending/aphelion encounters; *b)* nodal passages fall almost exactly every half-period of revolution, thus allowing the search for a double resonant trajectory which encounters Amun twice per orbit (both at its ascending and descending nodes i.e. once every 6 months) leading to a regular and frequent science return.

Resonant trajectories to (3554) Amun have been searched using a low-thrust indirect optimisation method (Casalino et al. 1998). In order to drive the optimisation process, the constraint of encountering the asteroid at one of its nodes with a trajectory having the same eccentricity and orbital energy as that of Amun has been imposed. The orbital energy is directly related to the semi-major axis of the target, which in turn gives the period of revolution. This means that the targeted resonant orbit of the spacecraft differs from that of Amun only in the value of the orbital inclination (as close to zero as possible). This implies, by definition, that the two orbits intersect at their respective perihelia and aphelia, thus satisfying the *double* resonant condition (i.e. encounters do occur at both nodes, alternately, every Amun half period).

A sample actual mission profile is shown in Fig. 4, where the asteroid is first encountered at its descending node after 623 days from Earth escape at a relative velocity of 9.1 km/sec. About six months later a second flyby is achieved, although at a higher relative velocity (16.1 km/sec). The overall ΔV budget (4.8 km/sec) is well within the capabilities of the SIMONE spacecraft and much lower than the H-plot estimate for a rendezvous mission to Amun (11.5 km/sec).

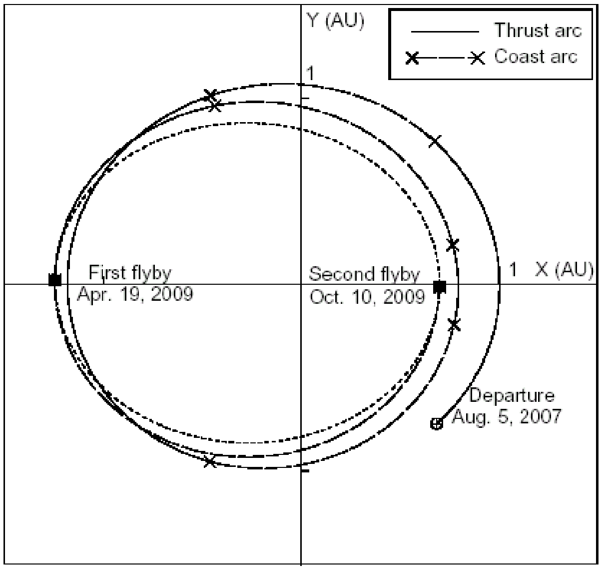

Fig. 4. A resonant flyby mission to Amun: the spacecraft trajectory is projected onto the ecliptic plane. Note that only the first two flybys have been displayed and that encounters may occur slightly off the ecliptic.

5. A Sample Return Mission

It is generally agreed that NEAs are among the most accessible bodies of the Solar System and that some of them could even turn out to be more accessible than the Moon. The former statement, although not generally true (see the caption of Fig. 2), can be easily verified looking at the H-plot of Fig.2, where the presence of objects deep inside the V-shaped region drawn by dotted lines indicates ΔVs less than those needed for reaching Venus or Mars. Meaningful omparisons with missions to the Moon are more difficult because of the different gravitational environments involved. In particular, the massless planet approximation used sofar to compute the H-plot does not take into account the Earth escape branch of the trajectory: hyperbolic escape modelling (Prussing and Conway, 1993) should be used instead. When doing so in a specific case, assuming departure from a 200 km LEO (low Earth orbit), it is possible to show that the ΔV needed for a Hohmann transfer to the Moon is slightly in excess than what is needed for inserting a spacecraft into a NEA-like interplanetary orbit with an aphelion tangent to that of the Earth and a perihelion inside the orbit of Venus.

The analogy with the Moon suggests that a sample return mission to a NEA could be realised at the present technological level. In order to check the feasibility of such a mission, we have chosen a scenario foreseeing the availability of an 800 kg spacecraft equipped with a state-of-the-art electric propulsion system, injected into interplanetary space from a 200 km LEO by means of chemical propulsion. The possibility of exploiting a single Earth gravity assist (in order not to increase too much the mission duration) is allowed. Launch dates are constrained within the time span 2010-2015 and reasonable sample return capsule velocity limits (12-16 km/sec) at Earth re-entry are assumed. Target selection was carried out merging both, scientific and technical considerations. As

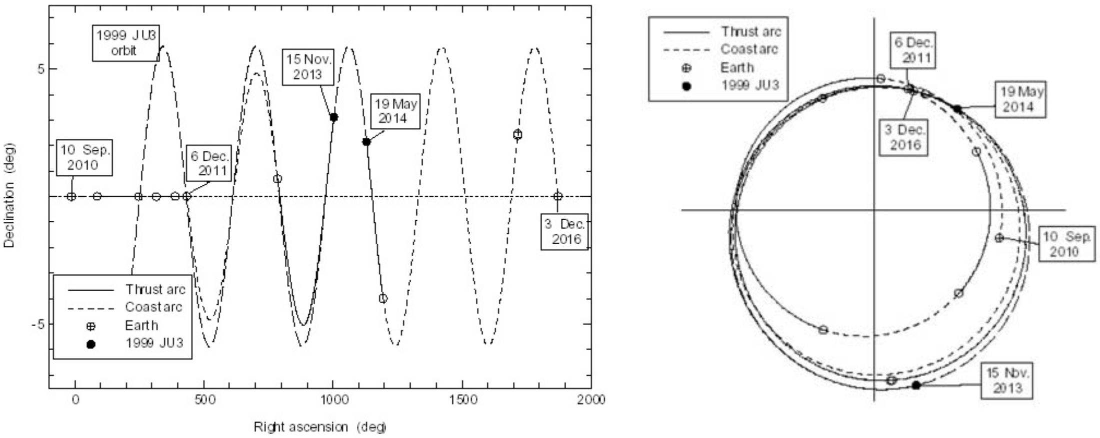

Fig. 5. The profile of a sample return mission to asteroid 199JU3 can be followed by the time evolution of its declination (left plot) and of its orbit (right plot). Note the major contribution of the Earth flyby on 6 December 2011 for changing the spacecraft orbital inclination.

a first step to reduce the number of potential candidates, NEAs having already determined spectral types and with rendezvous ΔVs less than 7 km/sec have been identified in the H-plot. Among them, only those belonging to the primitive D and C-types (a high priority for science because of the information on the early history of the Solar System) have been retained. Out of the 14 objects isolated in this way, sample return trajectories satisfying the technical constraints of the mission have been found only for the three C-type objects 1998 KY26 1999JU3 and 1996 FG3. Upon closer investigation 1999 JU3, a few 100m sized body on a low eccentricity and inclination orbit with a period of revolution of 1.3 years, appeared the best compromise between scientific interest and mission analysis considerations (1998KY26 is too small and 1996FG3 is in an unfavorable configuration during critical mission phases). Details on the proposed sample return mission are reported in Fig. 5. The whole mission was completed in about 6.2 years, with a total ΔV of abour 5 km/sec.

Acknowledgements. Nigel Wells, David Kemble and Andres Galvez for their helpful comments during the SIMONE and ISHTAR mission studies. Pierre Drossart and Antonella Barucci for our involvement in a NEA sample return mission proposal to CNES.

References

Binzel, R.P, Perozzi, E., Rivkin, A.S., Rossi, A., Harris, A.W., Bus S.J., Valsecchi, G.B., Slivan, S.M. (2003). Dynamical and Compositional Assessment OF Near-Earth Object Mission Targets. Meteoritics and Planetary Science (in press)

Boden, D.G. (1997). Introduction to Astrodynamics. In 'Space Mission Analysis and Design', Second Edition, W.J. Larson and J.R. Wertz eds. Microcosm Inc and Kluwer Academic Publishers.

Casalino, L., Colasurdo, G. and Pastrone D. (1998). Optimization procedure for preliminary design of opposition-class Mars mission. J. Guid. Contr. Dyn 21(1), 134-140.

McLaughlin W.I. (2000). Walter Hohmann's Roads In Space. Journal of Space Mission Architecture, 2, 1-14.

Perozzi, E., Rossi, A. and Valsecchi, G.B. (2001). Basic Targeting Strategies for Rendezvous and Flyby Missions to the NEar-Earth Asteroids. Planetary and Space Science 49, 3-22.

Perozzi, E., Casalino, L., Colasurdo, G., Rossi, A. and Valsecchi, G.B. (2002). Resonant Flyby Missions to Near-Earth Asteroids. Celestial Mechanics and Dynamical Astronomy 83, 49-62.

Prussing, J.E. and Conway, B.A. (1993). Orbital Mechanics. Oxford University Press, Oxford.

Roy, A. E. (1988). Orbital Motion. Adam-Hilger Ltd, Bristol.

Wells, N., and Fearn, D. (2001). Minimising the size and mass on interplanetary spacecraft. Paper IAF-01-Q.5.07