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The SRT, Near-Earth objects, and space debris

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Abstract. The improvements, by means of radar observations, of the accuracy with which the orbits of near Earth asteroids and comets are determined are a key factor in order to be able to exclude future collisions of any of these bodies with the Earth. The SRT, once equipped with a suitable transmitter, can have an important role in this context. Another application of its capabilities is the detection and orbital cataloging of the man-made orbital debris that is in orbit around the Earth.

1. Introduction

Near-Earth Objects (NEOs) are asteroids and comets on orbits with perihelion distance $q \leq 1.3$ AU. They are scientifically interesting because of their relationships with meteorites, and because they represent samples of more distant reservoirs of small bodies (the main asteroid belt, the trans-Neptunian region, the Oort cloud) that host the remnants of planetary accretion.

An additional reason of interest of NEOs is their possibility of colliding with our planet. Most of them, as a result of the action of secular and mean motion resonances, fall into the Sun, as shown by Bailey et al. (1992) in the case of comets and by Farinella et al. (1994) in the case of asteroids. However, the heavily cratered surfaces of the Moon, as well as the increasing number of impact craters found on the Earth, testify the continuous presence, throughout the history of the solar system, of an important flux of Earth-impacting bodies (Werner et al. 2002; D'Abramo et al. 2001; Morbidelli et al. 2002).

The mitigation of a large impact occurring on our planet is, of course, an issue for civil protections and governments; however, the development of the ability to predict the occurrence of such an impact is a task that falls under the responsibility of the scientific community, and in particular of the astronomical community. It would be difficult to argue, in case astronomical observations were needed in a very critical case, that some other undertaking could have higher priority. This task has only recently been dealt with, and is currently being carried out with satisfactory results.

2. NEO impact monitoring

The numerical algorithms necessary to predict Earth impact possibilities of Near-Earth Asteroids (NEAs) for decades in the future have been developed in Italy in 1999 (Milani et al. 1999, 2000), and have led to a systematic activity of impact monitoring.

Since 1999 the software robot NEODyS (`http://newton.dm.unipi.it/neodys/`), at the University of Pisa, daily computes all the orbits of newly discovered NEAs, and recomputes the orbits of the already known NEAs that have been re-observed in the last 24 hours. Then, since the end of 1999 another software robot — CLOMON, superseded by the second-generation CLOMON2 since the spring of 2002 — searches for impact possibilities of any NEA with our planet within the current epoch and 2080. Both NEODyS and CLOMON2 are duplicated, for redundancy, at the University of Valladolid, in the framework of a collaboration between the two universities.

Since the spring of 2002, a newly developed impact monitoring software robot, Sentry, that looks for Earth impacts within the next century, has been put into regular service at the Jet Propulsion Laboratory (`http://neo.jpl.nasa.gov/risk`). Results are routinely cross-checked between the Pisa/Valladolid and the JPL systems. The algorithms on which CLOMON2 and Sentry are based are described in Milani et al. (2005); an analytical theory of planet-impacting orbits is described in Valsecchi et al. (2003).

3. Radar vs. optical astrometry

Unless a NEA is really on a collision course with the Earth, the impact possibilities with our planet that are found by impact monitoring robots are simply a consequence of our more or less poor knowledge of its orbit. In fact, the size of a *collision solution* (the region in orbital elements space that contains the orbits that lead to Earth impact at a given date) is in general very small (for an analytical estimate, see Valsecchi et al. 2005), while the size of the *confidence region* (the region in orbital elements space that contains all the orbits compatible with the available observations of the given NEA) can be rather large (Milani 1999).

Improvement in the knowledge of NEA orbits is the key to remove impact possibilities; for this purpose, radar astrometry is much more effective than optical astrometry because:

- NEO radar astrometry provides exactly the information (range, range-rate) that optical astrometry (that gives angles only) does not;
- NEO radar astrometry can be extremely accurate, e.g., $\simeq$ 50 m in range, $\simeq$ 1 mm/s in range-rate.

Recent achievements of NEO radar astrometry include the measurement of the Yarkovski effect on the orbit of (6849) Golevka (Chesley 2005), and the possibility to extend impact monitoring for (29075) 1950 DA nine centuries into the future (Giorgini et al. 2002).

4. (99942)Apophis

In late December 2004 the impact monitoring robots found that the NEA 2004 MN_4 would have an extremely close approach to the Earth on 13 April 2029, with a probability of hitting our planet that rose up to 2.6% on 27 December. On that date, precovery optical observations made on 15 March 2004 were found in the archives of the Spacewatch survey; as a result, the impact probability for 2029 dropped to zero. Radar observations made from Arecibo on 27, 29 and 30 January and on 7 August 2005 further improved the orbit of (99942) Apophis, as 2004 MN_4 had in the meantime been numbered and named, so much so that adding optical astrometry right now is not useful. The current orbital uncertainty (RMS) translates into an along-track displacement in 2029 of about 1 000 km.

The asteroid orbit will suffer a very large perturbation, so that it will change orbital type, from Aten ($a < 1$ AU) to Apollo ($a > 1$ AU). The range of post-encounter orbital periods currently allowed by the available astrometry encompasses the resonance 6/7 between the mean motion of Apophis and that of the Earth. This opens the door to the possibility of a *resonant return*, with both the asteroid and the Earth making an integer number of heliocentric revolutions, and coming back to collision in 2036.

In the target plane of the 2029 encounter, i.e. in the plane centred on the Earth, and normal to the geocentric velocity of Apophis, the

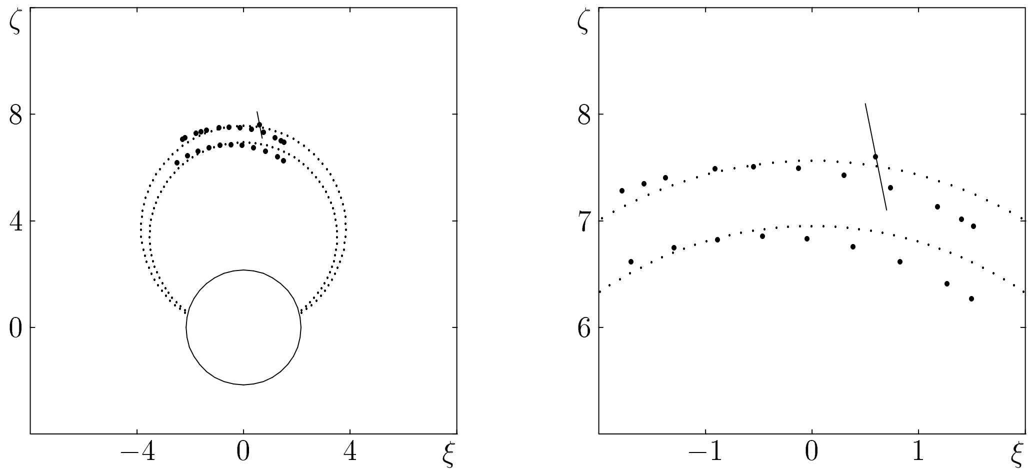

Fig. 1. Left: the *b*-plane of the 2029 encounter of Apophis with the Earth. The unit length is the Earth radius, and the ζ-axis is anti-parallel to the direction of the heliocentric motion of the Earth; the circle about the origin is the region that corresponds to immediate Earth impact (its radius is greater than 1 because of gravitational focusing). The two dotted circles correspond to the mean-motion resonances 5/6 (the inner one) and 6/7, determined analytically according to Valsecchi et al. (2003), and can lead to collision in 2035 and 2036, respectively. The actual 2035 and 2036 keyholes are delineated by the full dots, that represent numerically computed impact solutions. The small inclined line represents the current region of uncertainty, with the nominal orbit identified by a dot; as can be seen, the currently available astrometric data exclude an impact in 2035. Right: an enlargement of the left panel.

small region through which the NEA has to pass in order to end up impacting the Earth at the 2036 resonant return is called *keyhole*, due to its very small size. In fact, the 2029 Earth encounter is so effective that two hypothetical particles co-moving with Apophis, and hitting the target plane of Fig. 1, separated by d along the ζ-axis, would be separated by about $40,000\ d$ at the corresponding encounter in 2036. A keyhole is nothing more than the pre-image of the Earth on the target plane of the first encounter of the resonant return pair (Valsecchi et al. 2003); its width in the ζ-direction is of the order of the diameter of the Earth, divided by the divergence ratio, in this case $\simeq 40,000$. Thus for Apophis the keyhole for impact in 2036, measured on the 2029 target plane, is only $\simeq 600$ m wide.

5. Radar astrometry and Apophis

If we were certain that Apophis would impact the Earth in 2036, deflecting it before 2029 would be quite feasible, given its size (about 300-350 m across), and the very small Δv required (a few μm/s). However, if we were to wait until after 2029 before doing anything, and if the post-2029 observations would show Apophis to be on a 2036 collision orbit, the Δv required for deflection would be of a few cm/s, quite unfeasible with current technologies.

Radar observations can solve this problem, as shown by Chesley (2005). In fact, there are a number of radar opportunities in the coming years, the most favourable in 2013 and 2021; the probability that radar observations in 2013 will shrink the confidence region so much that the 2036 impact could be ruled out is about 95% (Chesley 2005). This can be understood from Fig. 1, right panel, knowing that the length of the region of uncertainty will be decreased by a factor $\simeq 30$ by the 2013 radar data.

In the unlucky case that the 2036 collision remains possible after the 2013 radar observations, there would be the need for another way to decrease the orbital uncertainty by another order of magnitude well before 2029.

One solution would be a space mission with a transponder to accurately track Apophis. The European Space Agency (ESA) is developing the Don Quijote mission concept, that could fulfill both the accurate tracking and, if necessary, the pre-2029 deflection, in case the latter turned out to be necessary.

6. Space debris

About 15 000 objects with linear dimension larger than 15 cm are currently orbiting the Earth. Most of these larger objects are cataloged by the United States Space Command in the Two–Line Element (TLE) catalog. In this catalog about 10 000 objects are listed along with their current orbital parameters. The limiting size of the objects included in the catalog is about 5 to 10 cm below a few thousand km of altitude and about 0.5-1 m in higher orbits (up to the geostationary ones).

Only about 6% of the objects in the TLE catalog are operative satellites. Approximately 24% are non-operative spacecraft, around 17% upper stages of the rockets used to place satellites in orbit. About 13% are mission-related debris (e.g., sensors caps, yo-yo masses used to slow down the spacecraft spin, etc). Finally some 40% are debris generated in catastrophic events, such as about 170 explosions and 2 collisions which have involved rocket upper stages or spacecraft in orbit (Klinkrad et al. 2004). About 99% of the mass in orbit is due to the large objects included in the catalog.

The orbits of the TLE catalog objects are maintained thanks to the observations performed by the Space Surveillance Network (SSN). The network is composed of 25 sensors, both radars and optical sensors. The radars include mechanically-steered dishes, one radar interferometer (the NAVSPASUR "radar fence", composed by a network of three transmitting and six receiving radar sites spanning the continental US along the 32^{nd}–33^{rd} parallel) and large phased-array radars capable of tracking several objects simultaneously. These last radars can track objects from just above the horizon to just short of the zenith over an azimuth of 120°. Capable of generating more than 30 megawatts of radio frequency power, they can track space objects in excess of 40 000 km in range and represent the largest source of information for the catalog, especially in Low and Medium Earth Orbit. The recent introduction of the large L-band "Cobra Dane" radar in Alaska, for example, raised the number of objects in the catalog by about 10%, pushing the network to its limits in terms of processing and archiving power, to the point that, at present, the principal limitation to the cataloging capabilities seems to be the processing structure and not the sensors power. Above several thousand km of altitude the radar power is not enough to monitor the small space debris, as the returned flux is proportional to the -4 power of the distance, so the SSN uses optical sensors for the higher objects.

To get data on the smaller objects in Low Earth Orbit (LEO) not included in the catalog, different sensors, or the same sensors but operated in a different way, are needed. Radar campaigns have been carried out to detect objects of 1 cm and less by putting the radar in a "beam park" mode, where the radar stares in a fixed direction and the debris randomly passing through the field of view are detected. This allows a counting of the number of objects, i.e., the determination of the objects' flux and density, but only a rough determination of their orbits.

Until about 10 years ago, the fragmentation debris were thought to be the only small particles present in space. Radar and in-situ measurements (analysis of surfaces that have been exposed for some time to the space environment) brought to light a series of new unexpected debris population. The observing campaigns performed with the Haystack X-band radar, located in Massachusetts (USA), lead first to the discovery of a large family of objects determining a prominent peak in number density around 900 km of altitude. This density peak is mainly due to the presence in this altitude band of a large number of sodium-potassium liquid metal droplets (used as a coolant for the on-board nuclear reactor) leaked from the Russian ocean surveillance satellites (RORSAT) (Foster et al. 2003). About 70 000 drops with diameter between 0.5 mm and about 5.5 cm have been estimated to orbit the observed region. The Haystack radar has an antenna diameter of 36 m, a peak power of about 400 kW and is always used as a mono-static device.

Another previously unknown debris population, at around 2 900 km of altitude, consisting of the so-called *West Ford Needles*, has been detected by radar surveys. Using the powerful Goldstone radar, Goldstein et al. (1998) found the remnants of the copper dipoles, 1.77 cm long, which were released in space in 1961 and 1963 by the American satellites Midas 3 and Midas 6, for telecommunication experiments. They were conceived to reenter the atmosphere in about 5 years, but apparently some of them stuck together after the release, thus lowering their area over mass ratio and therefore augmenting their orbital lifetime. According to the Goldstone observations, a population of about 40 000 such clusters is orbiting between 2 400 and 3 100 km of altitude. The Goldstone radar works at a wavelength of 3.5 cm in bi-static mode. A 70-m diameter antenna is used as a transmitter (with peak power between 400 and 466 kW) and a 35-m antenna (located at 497 m from the transmitter) is used as receiver.

The Haystack observations were also instrumental in pointing out the importance of another unexpected source of space debris, the aluminum oxide (Al_2O_3) particles coming from the burns of the rocket motors with solid propellant (Jackson et al. 1997). During these burns a large number of sub-millimeter sized particles are ejected. As a matter of fact the solid rocket motor (SRM) exhausts are probably the main contributors to the debris population between 10 μm and 100 μm. Between 100 μm and 1 cm the SRM exhausts are again one of the main components of the population, together with fragments and paint flakes that detached from spacecraft surfaces exposed to the space environment.

The current estimate, derived from the observations and the simulated populations, is that the total number of non-trackable particles of 1 cm and greater is around 350 000, while those larger than 1 mm could be more numerous than 3×10^8. The overcrowding of the space around the Earth makes collisions a serious threat. Currently hundreds of close approaches (i.e., passes within less than 1 km) between cataloged objects occur on a daily basis and indeed a few accidental collisions have already been recorded in LEO. To highlight the danger posed by the impacts with space debris, it should be kept in mind that the average impact velocity in Low Earth Orbit (LEO) is about 10 km/s. This means that, e.g., a particle of around 5 mm is able to directly penetrate the Shuttle cabin.

7. The possible role of the SRT

Space debris monitoring is a complex, large-scale problem, with important economic and strategic implications. Space agencies are strongly interested in the study of the space debris environment.

In the field of radar observation of space debris the US are currently playing a paramount role. Europe is starting to be more active and there are plans to set up a European network, similar to the US SSN.

The European efforts are mainly due to the Tracking and Imaging Radar (TIRA) of the FGAN, located at Wachtberg-Werthhoven in Germany. It is a single-pulse radar in the L-band, with a 34-m diameter antenna. Recently upgraded thanks to the support of ESA, the FGAN radar is operated (with ESA funds) both as a mono-static and as a bi-static system, together with the 100 m radiotelescope antenna of the Max-Planck-Institut für Radioastronomie at Bad-Münstereifel-Effelsberg (Leushacke et al. 1997).

In the last few years also the radar facilities of the European Incoherent Scatter Scientific Association (Tromsø, Norway), routinely used for ionospheric measurements, has been adapted (under an ESA Contract) for space debris detection. The first results of observing campaigns are already available (Markkanen et al. 2005).

The SRT represents a unique opportunity for Italy to play a significant role in the detection and study of the small debris population. Different configurations involving the SRT could be studied:

- a mono-static configuration with the SRT acting both as transmitter and as receiver;
- The SRT used as a receiver in a long-baseline bi-static configuration (e.g., using TIRA as the transmitter);
- The SRT used as transmitter, using existing Italian antennas (e.g., Matera, Medicina, Noto) as receivers, in a short-baseline configuration.

Each different configuration should be studied in terms of efficiency and costs. But certainly SRT could represent a unique opportunity for Italy to enter the fast developing field of space debris monitoring.

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