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The SRT as radar for asteroid and space debris studies

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Abstract. Within the definition of the scientific programs of the Sardinia Radio Telescope, our team proposes to use this facility as radar system for the study of near-Earth objects (NEOs) and space debris.

1. Introduction

Among Solar System bodies, asteroids are the largest population. Most of them orbit around the Sun in a region of space, the so-called "main belt", located between the orbits of Mars and Jupiter. Two groups (the "Trojans") are located in the L4 and L5 Lagrangian points of Jupiter, while others (known as NEAs, near-Earth asteroids) follow trajectories that cross the orbits of the terrestrial planets, therefore representing a potential hazard for the Earth. In fact, in the main belt, catastrophic collisions among asteroids take place, and the resulting fragments can be "injected", due to complex dynamical processes, in the inner regions of the Solar System. The hazard of a catastrophic impact with a NEA represents a serious threat for our planet. It is estimated that an impact producing severe consequences to the terrestrial ecosystem can occur every few hundred thousand years. The first step toward the "mitigation" of such a threat is space surveillance, in order to determine the orbits of most of the objects whose trajectories are close to Earth's orbit.

In recent years, the Group of Planetary Sciences of the INAF - Osservatorio Astronomico di Torino (OATo), in collaboration with the INAF - Istituto di Radioastronomia (IRA), started observations of NEAs by radar, which is one of the most powerful techniques for the study of the dynamics and the physical properties of these bodies. In fact, from the dynamical point of view it is possible to improve the accuracy of the orbits by orders of magnitude, a key factor to evaluate the impact hazard: unlike the "classical" optical measurements, the radar astrometric observations can make the difference in predicting if an asteroid will hit our planet or not. From the physical characterization point of view, radar allows us to obtain fundamental parameters such as the size, the shape, and the surface roughness of asteroids.

2. Asteroid radar astronomy

A radar observation of an asteroid consists in the transmission of a signal with fixed parameters and in the subsequent registration of the signal echo. The great advantage with respect to other "passive" techniques lies in the control by the observer of all the characteristics of the coherent signal (especially the wave form, time/frequency modulation, and polarization) used to illuminate the target (Ostro 1993).

From the echo analysis it is possible to determine the orbital elements of an object very accurately, allowing a very high precision of ephemeris calculation. In fact, measuring the signal propagation time with an accuracy better than 10^{-6} s, the radial distance of the target can be estimated with an error of some tens of meters. Moreover, the component of the asteroid velocity, V_{LOS}, along the "line-of-sight" (connecting the radar antenna with the target), produces a Doppler shift in the frequency of the echo signal, which, measured with an accuracy of ≈ 0.01 Hz, allows an estimate of V_{LOS} with an error of the order of 1 mm s^{-1}. Furthermore, the spin of the object generates a Doppler frequency dispersion of the signal; the measure of the power distribution of the echo signal, as a function of the time delay and of the frequency, allows one to obtain bi-dimensional images with spatial resolutions less than 100 meters if the transmitted signal is strong enough.

Finally, by measuring the polarization properties of the echo signal, radar observations permit to infer some surface characteristics of the target such as roughness, albedo and abundance of metallic elements, information which cannot be directly derived by using other astronomical techniques. In fact, the reflection due to a single reflecting plane surface reverts the handedness, or helicity, of a circularly polarized wave, so single back-reflections from dielectric interfaces, whose sizes and radii of curvature greatly exceed the wavelength, yield echoes almost entirely in the opposite circular (OC) polarization. On the contrary, same circular (SC) echo power can arise from multiple scattering, from single backscattering from interfaces with wavelength-scale radii of curvature (e.g., rocks), or from subsurface refraction effects. Therefore, the circular polarization ratio, that is, the ratio between the radar cross-section (defined as 4π times the reflected power per unit solid angle and per unit flux of incident power) measured in the two opposite polarization ways, σ_{SC} and σ_{OC}, of the reflected signal ($\mu_C = \sigma_{SC}/\sigma_{OC}$), is a useful gauge of the target's near-surface wavelength-scale complexity, or "roughness", from which important information about the nature of the surface regolith as well as the radar albedo and also the presence of superficial metallic elements, can be inferred (Ostro 1993).

Radar observations are consequently a unique, very powerful means to study the macroscopic physical properties and surface properties of the target.

3. Space debris radar observations

Another fundamental application of the radar technique is the study and monitoring of the space debris orbiting around the Earth, and the interaction of meteoroids with the atmosphere. The artificial material orbiting around our planet consists of actually operative structures only to a minimum extent; most of them come from out-of-use spacecrafts, rocket stages, fragments generated by explosions and collisions of artificial satellites.

Nowadays, optical and radar sensors are used to locate centimeter-sized particles (in Low-Earth Orbit, or LEO) or decimeter-sized objects (in Geostationary Orbits, or GEO). The USA, and, to a lesser extent, Russia, have a space surveillance system, while Japan is starting such a survey. So far, Europe does not have these facilities: only one radar (the TIRA of the FGAN Institute in Germany) and one telescope have been occasionally used by the European Space Agency (ESA) in order to detect and monitor space debris. In particular, in Italy such campaigns have never been undertaken.

The problem of artificial space debris is now analysed in a strict relation with the meteoroid environment. ESA defined the Meteoroid and Space Debris Environment Reference Model (MASTER) to determine the flux originating from the environment of particles following orbits close to those of space shuttles, in the LEO, MEO and GEO regions. The analysis of material coming from space and "in situ" experiments contributed in extending the knowledge on natural particles with millimetre- and micron sizes, which are the most abundant. With regard to spacecraft in LEO-type orbits, impact velocities range from 5 to 15 km s^{-1} with a mean value of about 10 km s^{-1} for space debris, and from 12 to 72 km s^{-1} with a mean value of 17-20 km s^{-1} for meteoroids. Studies on impact residues, carried out on the LDEF, EURECA and HST satellites, in order to discriminate between impacts by natural meteoroids and by artificial space debris, have been inconclusive, because of targets complexity.

In GEO-type orbits, the flux of natural particles prevails on the flux due to artificial particles, whereas it is supposed that collisions in LEO-type orbits are mostly due to artificial objects. Particles coming from meteoroids are dangerous for orbiting structures because their impact energy exceeds 2 kJ, a value corresponding to 3–10 g for some meteoroids and to 10–30 g for particles belonging to a meteor stream.

Therefore, in order to monitor the natural and artificial debris population and to understand their evolution both in short and long period, it is absolutely necessary to complete the models through observations carried out from the Earth and from space.

The information provided by a radar system can be exploited to validate current models of debris environment; they can also improve the precision on the knowledge of the orbital parameters of those catalogued debris for which a close encounter with an operative satellite, or a manned space shuttle, is predicted. Finally, they can verify the integrity of big wrecks and update, if possible, the catalogues of big debris being currently tracked.

4. SRT as radar for asteroid and space debris studies

Our interest in radar observations has been fostered by the next realization of the Sardinia Radio Telescope (SRT), that may be used both as a receiving antenna in a bistatic radar configuration and as an independent (monostatic) system in the case it would be equipped with a transmitter. Of course, this second configuration is the most desirable.

In December 2001 the first intercontinental experiment (Italy - Ukraine - USA) of radar detection of an asteroid took place, involving the OATo, the IRA in Bologna and NASA-JPL. From Goldstone (Mojave desert, California) and Evpatoria (Crimea, Ukraine) antennas, monochromatic radio signals were transmitted towards asteroid 33342, less than 2 million km from the Earth at the time. Echoes from the asteroid were detected by the 32-m VLBI antenna in Medicina, and analyzed by means of a high-resolution, high-efficiency spectral analyzer. After approximately 12 s from first detection, the echo could be sharply resolved on the screen of the receiving station back-end, thus successfully achieving the intended goals of the experiment (Di Martino et al. 2004 and Fig. 1).

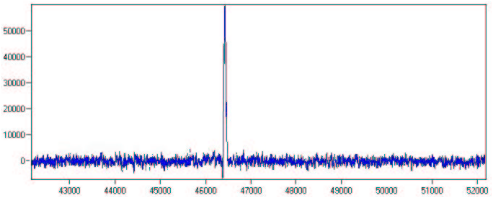

Fig. 1. The echo of NEA 33342, detected in X-band. Details in Di Martino et al. (2004).

This experiment could represent the first step towards an integrated intercontinental network for the monitoring of potentially dangerous NEAs, a network in which the SRT could play a key role.

5. Radar astronomy with the SRT

The scientific value of a radar experiment depends mainly on echo strength and receiver sensitivity. The received power P_R scales with the fourth power of the target distance R, and can be computed by means of the radar equation:

$$P_R = \frac{P_T\, G_T\, G_R\, \lambda^2\, \sigma}{(4\pi)^3\, R^4} \qquad (1)$$

where λ is the transmitted wavelength, P_T the transmitted power, G_T the gain of the transmitting antenna, G_R the gain of the receiving antenna, and σ the radar cross section of the target. The antenna gain is then given by:

$$G = \frac{4\pi}{\lambda^2} A_e \tag{2}$$

where A_e is the effective area of the antenna, obtained by multiplying the geometric area of the antenna by its efficiency.

The power of the received signal can be very small compared to the system noise power in the receiving system, which is given by

$$P_n = k\, T_s\, \Delta\nu \tag{3}$$

where T_s is the noise temperature in the receiver, k is Boltzmann's constant and $\Delta\nu$ is the bandwidth of the receiver.

The echo signal can be detected when the received power P_R is significantly above the threshold given by the RMS of the noise power. A quantitative measure of the extent to which the signal is stronger than the noise, that is the quality of a radar measurement, is expressed by the SNR. It can be shown that the SNR value expected for a radar observation is given by the following equation:

$$SNR = \frac{P_T\, G_T\, G_R\, \lambda^{2.5}\, \hat{\sigma}\, D^{1.5}\, P^{0.5}\, \sqrt{\Delta t}}{8.96 \cdot 10^3\, k\, T_s\, R^4} \tag{4}$$

where $\hat{\sigma}$ is the target radar albedo, defined as the ratio between its radar and geometric cross sections, D is the target diameter, and Δt is the integration time.

5.1. The SRT as receiver of a bistatic radar

We consider two different possibilities for the use of the SRT as a planetary radar: as a receiver in a bistatic radar system, and as a monostatic radar antenna.

In the first configuration, the SRT would act as the receiving station. The specifications for the receiver presented in Grueff & Ambrosini (1998) provide a highly versatile instrument, covering a frequency range spanning from 300 MHz up to 100 GHz. It is thus certainly possible to receive a signal transmitted, for example, by the DSS14 antenna at Goldstone, operating in the X-band (ν = 8560 MHz, λ = 3.5 cm). In this case, the values for the terms in the radar equation are $P_T \approx$ 500 kW, $G_T \approx$ 75.6 dB, λ = 3.5 cm. The gain for the SRT in the X-band is approximately 73 dB, T_s is around 30 K, and the diameter is 64 m, for an effective area of 1945 m^2. It is also necessary that the target is in a visibility window common to both antennas, meaning that the target must have a North declination greater than 45°.

5.2. SRT as monostatic radar

For a completely independent radar system, it is necessary to provide the radiotelescope with a power transmitter. If a comparison is made between the sensitivities of the SRT and DSS14 in the X-band, it can be seen that the SRT is approximately four times less sensitive. A better opportunity is offered by the use of a transmitter operating in the Ka-band (ν = 34 GHz , λ = 0.8 cm, $P_T \approx$ 1 kW): writing explicitly the effective dependence on the wavelength in the radar equation, one obtains in fact:

$$P_R = \frac{P_T\, \sigma\, A_e^2}{4\pi\, \lambda^2\, R^4} \tag{5}$$

the relative power of the echo signal produced by a transmitter operating in the Ka-band is thus given by:

$$\frac{\lambda_X^2}{\lambda_{Ka}^2} = \frac{3.5^2}{0.9^2} \approx 15 \tag{6}$$

that is 15 times larger than the one produced by a transmitter operating in the X-band, for the same radiated power. In terms of SNR, the net gain is reduced, because, as can be seen in equation (4), it scales as $\lambda^{-1.5}$. Furthermore, it is necessary to take into account the noise temperature of the receiver, which increases with frequency.

Table 1 illustrates the performance of the SRT in the two bands.

Table 1.

Band	G (dB)	T (K)	G/T (dB)
X	73	30	58
Ka	85	50	68

To obtain the net gain in terms of SNR for a Ka-band transmitter over an X-band transmitter, for the same integration time, it is sufficient to substitute the figures listed above in equation (4), obtaining that $SNR^2_{Ka}/SNR^2_X \approx 5$.

6. The SRT and space debris

The seemingly unstoppable increase in the amount of space debris in low orbits, especially below 2000 km altitude, poses increasingly larger threats to all space activities in that region. Any prediction of the evolution of their population, especially in the long term, and any protection and mitigation measure requires adequate knowledge of their present distribution, also following peculiar events such as an explosion or a loss of material.

Low-orbiting space debris with a size larger than 10 cm (now around 10,000) are routinely monitored mainly by the US-based USSPACECOM surveillance systems; their orbits are known only in terms of the so-called "two lines elements"[1] provided by NASA. To this class belong also space vehicles out of control, especially those which are re-entering the atmosphere: because predictions of place and time of their re-entry are affected by large uncertainties, it is important to have frequent updates of their orbit.

Our knowledge of the smaller debris, in particular that of millimetre size, is in general indirect and statistical: on the other hand, it is capable of producing significant damage to space systems, and it constitutes a large fraction of man-made debris (as is well-known, the amount of debris is inversely proportional to its size), larger than natural space debris.

The main technique for monitoring it is radar detection, requiring large-size instruments: for this task, the SRT would play an extremely significant role, also in the context of international space policy, especially ESA's. All major space agencies have in fact initiated ambitious programs for monitoring and prediction of, and protection from, space debris. Italy is a member of the Inter-Agency Space Debris Coordination Committee (IADC); among the four main areas in which the space debris problem is studied (Measurements, Environment and Database, Protection, Mitigation), the Italian contribution is particularly weak (practically absent) in the first one: the only radar observations of space objects performed in Italy are those of natural meteorites. Europe in general is not well equipped in this respect; the main instrument available is the military radar TIRA belonging to the German FGAN institute, which, under ESA control, has occasionally provided important observations. Thus, there is plenty of opportunity for SRT in this research field.

7. Conclusions

We propose to use the SRT for planetary radar observations, both in bistatic and in monostatic mode. In the second case, which is deemed more efficient both for achieving scientific results and for monitoring circumterrestrial space, it is proposed to provide the SRT with a power transmitter and associated auxiliary structures, such as two parallel receiving channels for simultaneous reception of same-sense and opposite-sense circular polarizations. In a study performed at JPL (Interoffice Memorandum 335.1-95-038), the technological feasibility of a transmitter operating in the Ka- band with a 1 MW power has been demonstrated, using either a single transmitter or a pair of 500 kW transmitters. The total cost of the device was estimated at 2,000,000 US$, currently corresponding to about 1,600,000 Euro.

This kind of operation requires high stability and accuracy both in time and frequency measurements, and, in the case of a bistatic system, in the synchronization between the transmitting and receiving stations.

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[1] `http://www.amsat.org/amsat/keps/formats.html`

Furthermore, the availability of such a complete instrument of investigation for both planetary and space debris studies would allow the creation of an entirely national radar network, together with the two twin 32-m antennas of Noto and Medicina.

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