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Results of the first Italian planetary radar experiment

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Abstract

We describe the first intercontinental planetary radar initiative undertaken in Italy.

We present the results of the observations of Near-Earth Asteroid (NEA) 33342 (1998 WT24), performed in December 2001 using the bistatic configurations Goldstone-Medicina and Evpatoria-Medicina, with the 32-m Medicina dish used to receive echoes in both cases.

The experiment goal was to characterise the system for radar follow-up observations of NEA and artificial orbiting debris, in the framework of a feasibility study which aims at using the Sardinia Radio Telescope, at present under construction, also as a planetary radar facility.

Keywords: Asteroids; Radar; Remote sensing; Spectroscopy

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1. Introduction

We report the main results of investigations carried out by the IRA–CNR and the OATo groups, with the purpose of exploring the scientific potential of a new planetary radar initiative, using the existing facilities in Italy.

A peculiar feature of radar astronomy is the human control over the transmitted signal used to illuminate the target. While every other astronomical technique implies passive measurement of reflected sunlight or naturally emitted radiation, radar uses coherent illumination whose time/frequency structure and polarization state are defined by the scientist. The general stratagem of a radar observation is to transmit a signal with well-known characteristics and then, by comparing the echo to the original transmission, deduce the target properties.

The planetary radar technique has revealed its unique capability of investigating geometry and surface properties of various Solar System bodies (Ostro, 1993). The radar technique has advantages over the optical ones in its high spatial resolution and ability to obtain three-dimensional images. Moreover, it can greatly contribute to the exploration of such bodies and to the identification of potentially hazardous objects.

A single radar detection improves the orbit knowledge, lowering the instantaneous positional uncertainties by orders of magnitude with respect to an optically determined orbit and greatly improving the accuracy of long-term trajectory predictions.

Radar is a uniquely capable means to spatially resolve NEAs by measuring the distribution of the echo power in time delay (range) and Doppler frequency (line-of-sight velocity) with extreme precision in each coordinate, as it provides unique information about the target physical properties, including size, shape, rotation, near-surface bulk density and roughness, and internal density distribution (Ostro, 1993).

Nowadays, radar facilities exist in Evpatoria (Ukraine) and in Kashima (Japan), but currently only the GSSR (Goldstone Solar System Radar—JPL) in California and the National Astronomy and Ionosphere Center Arecibo

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Table 1
Asteroid 33342 main features

33342 (1998 WT24) Main orbital and physical parameters	
Absolute magnitude H	17.93
Rotational period	3.698 h
Orbital period	222.17 d
Perihelion	0.4180 AU
Aphelion	1.0189 AU
Eccentricity	0.4182
Inclination	7.3826 deg
Close approach range (December 16, 2001)	0.0125 AU

Observatory (Puerto Rico) produce observations of Solar System objects.

The Medicina 32-m antenna was used for the first time as the receiving part of a bistatic configuration during a test experiment (September 2001) held to check the capabilities of the entire data acquisition system. This test was possible thanks to the collaboration undertaken with the Evpatoria (Ukraine) radar station, and consisted in the observation of the ETALON-1 low orbit satellite. These test data are not discussed in this paper.

2. The target

The target of our observations was NEA 33342 (1998 WT24). This asteroid—an Aten object—was discovered by LINEAR on November 25, 1998.

In Table 1 we show the 1998 WT24 main orbital and physical parameters.

The asteroid was a very good target for this international bistatic radar experiment, since it was visible in a high-declination position, easily allowing a common observation window.

3. The system setup

In this bistatic radar experiment, radio signals at different wavelengths were transmitted from the Goldstone 70-m antenna (3.5 cm, X-band) and from the 70-m antenna in Evpatoria (6 cm, C- band), while the radar echoes reflected from the asteroid surface were received by the 32-m antenna in Medicina (Bologna, Italy). These bistatic radar configuration are shown in Table 2.

During the experiment the X-band incoming signal was analysed in real time using two different spectrometers tuned on the Right circular polarization (RCP) only: MSpec0 and SerendipIV. The C-band part of the experiment consisted instead in the acquisition of the data in the time domain, and the analysis was carried out offline by the Russian staff.

3.1. THE MSpec0 system

The back-end used for this detection experiment is a Fast Fourier Transform (FFT)-based digital spectrometer (Montebugnoli et al., 1996) designed for SETI program and radioastronomy applications. The system was originally conceived to allow the Medicina (Bologna, Italy) radio telescopes to participate in SETI program activities. The original idea was to build a cost effective spectrum analyser able to achieve top performances when used as a back end for microwave line observations. The first version of the system was completed in 1994 and was used to investigate (in terms of radio emissions) the impact zones of the Jupiter/SL-9 comet fragments collision in July 1994. In that occasion it made possible a very important detection: the water line emission on the E fragment impact point. The present version is powered by two ultra fast commercial DSP boards (from Valley Technologies^{TM}) in a VME environment. The DSP computing core is completely programmable in terms of input bandwidth (sampling rate), number of channels (size of the FFT) and number of spectrum to be averaged before the storage phase on a Hard Disk. The system constantly computes the FFT of an input data streams from an 12 bit A/D converter and computes the signal spectra.

The spectra can be averaged over a programmable time interval. The MSpec0 main characteristics are described in Table 3.

Using FFT algorithms, MSpec0 can produce spectra from 512 frequency bins to 131,072 frequency bins. If requested, the system can either supply single spectra or average up to 65,536 single spectra to reduce the noise variance of the signal to acceptable levels.

Table 2
Antennas configuration

	Goldstone (Tx)	Medicina (Rx)	Evpatoria (Tx)	Medicina (Rx)
Receiver	X-band	X-band	C-band	C-band
Diameter	70 m	32 m	70 m	32 m
Maximum effective area	2694 m^2	389.3 m^2	2520 m^2	466 m^2
Maximum G_{ant}	74.4 dB	66.0 dB	69.4 dB	62.1 dB
T_{sys}	15 K	50 K	65 K	50 K
Half power beam width	1.8′	4.9′	3.6′	7.5′
Transmitted power	460 kW	—	150 kW	—
Transmitted frequency	8560.0 MHz	—	5010.024 MHz	—

Table 3
MSpec0 parameters list

Parameter specification	
Input bandwidth	0.05 to 20 MHz
Typical efficiency single channel mode	100% at 12 MHz, 56% at 20 MHz
Dual channel mode	100% at 6 MHz, 28% at 20 MHz
FFT size	1 K, 2 K, ..., 256 K
Number of channels	512, 1 K, 2 K, 4 K, ..., 128 K
Number of averages	Up to 256 at step of 1 > 256 at step of 256
Output format of averaged data	32 bit floating point

3.2. The Serendip IV (SIV)

The high-resolution SIV spectrum analyser comes from the Berkeley SETI group (Werthimer et al., 2000) and it represents a very suitable system for extremely high-resolution real-time spectrum analysis. It is primarily designed for the detection of artificial radio signals coming from potential extraterrestrial civilization and it continuously works in piggy back mode with the VLBI 32 m dish.

The system works in real time, using an input bandwidth of 15 MHz and 25,165,800 channels.

It is powered by a certain number of Austek A41102 FFT chips and the on line post processing is based (in our configuration) on 6 Intel 80960 CF processors, each of which executes instructions at a sustained rate of 100 MIPS (Werthimer et al., 1996). The post-processing phase performs baseline normalization, searches for peaks above the selected threshold and reports the results to the control computer. The channels where the threshold was exceeded are stored on the host computer Hard Disk.

The frequency resolution is 0.6 Hz. This means a radial velocity component resolution of 21 mm/s at 8.56 GHz.

4. Observation

The experiment was carried out on 2001, December 16th–17th.

During the previous 2 weeks a continuous update on the target ephemerides had been performed using the JPL HORIZON online generator, in order to achieve the best accuracy on the coordinates and the doppler shift of the expected echo. As the asteroid was reaching the closest approach and both its position and apparent radial velocity rapidly changed, it was necessary to compute these quantities with a step of 5 min, to guarantee the best pointing and the initial correct tuning of the local oscillators—in order to keep the possible echo within the narrow band.

4.1. X-band detection

The MSpec0 spectrometer at first was employed as a real time previewer of the echo presence, in the following configuration: 0.5 MHz of bandwidth and 65,536 channels, a sampling rate of $1.1 \times 10^6\ \mathrm{s}^{-1}$ chosen in order to satisfy the Nyquist criterion, giving a spectral resolution of 8.3 Hz channel.

At the same time the Serendip IV system was supposed to give immediate information about the signal frequency drifting.

The CW transmission from Goldstone started at 22:30UT (December 16th) and stopped at 02:45UT of the following day. The echo was instantly detected by both devices.

To ascertain the echo identification, a fundamental test was performed: an off-source acquisition that did not show any signal.

The next step was to acquire the spectra using on-off cycles calibrated by means of an injected mark. An average of 29 of these spectra, taken from 23:59:17UT to 01:09:56UT is shown in Fig. 1, where the frequency drift (about 11 kHz) is evident.

Contemporaneously, the Serendip IV spectrometer recorded the signal rapidly drifting in frequency (about 73 Hz/min).

4.2. X-band results

An off-line analysis of the acquired data was carried out focusing on a single cycle in the middle of the previously presented series (the 14 cycle).

The resulting spectrum profile gave immediate evidence of the primary importance of a correct Doppler compensation: as is clear from Fig. 2, the profile shows four peaks (P1, P2, P3, P4), each corresponding to a different on-source block.

The separation between adjacent peaks (2 channels) is consistent with the one predicted considering the elapsed time among the on-source blocks and the asteroid acceleration.

Given this circumstance, it was necessary to perform any further analysis on spectra resulting from a single block. Analysing the four blocks composing the fourteenth cycle, we obtained the spectra which are shown in Fig. 3, and whose line parameters are summarized in Table 4.

The average values allowed an estimation of the received power of 7.4×10^{-20} W, yielding an observed RCP radar cross section of about 0.04 km^2, with an uncertainty of 10% on the antenna temperature due to the error on the calibration mark value. While the measured line width corresponds to the one obtained by the monostatic observation carried out in Goldstone, no comparison can be made about the cross section, since the Goldstone antenna faced severe calibration problems.

4.3. C-band observations

During the signal reception, digital samples of the signal voltage were recorded directly into a format more suitable

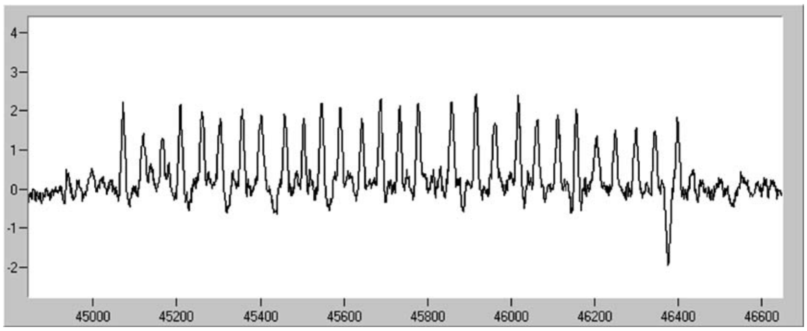

Fig. 1. Average of 29 cycles, each consisting of 4 on-source/4 off-source/1 calibration blocks, with every block having an integration time of 7 sec. *x*-axis: channel number, *y*-axis: antenna temperature (Kelvin).

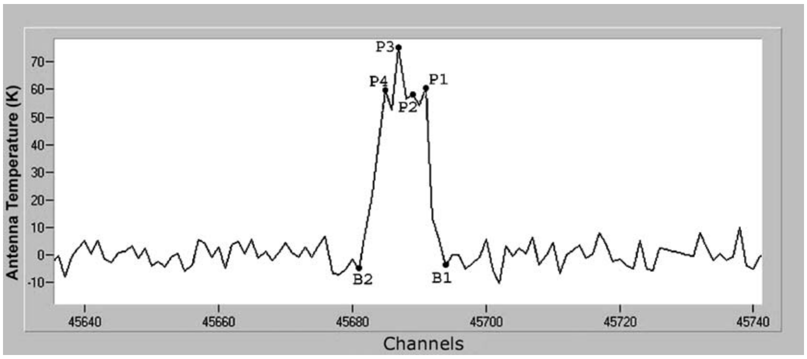

Fig. 2. The spectrum profile of the 14 cycle.

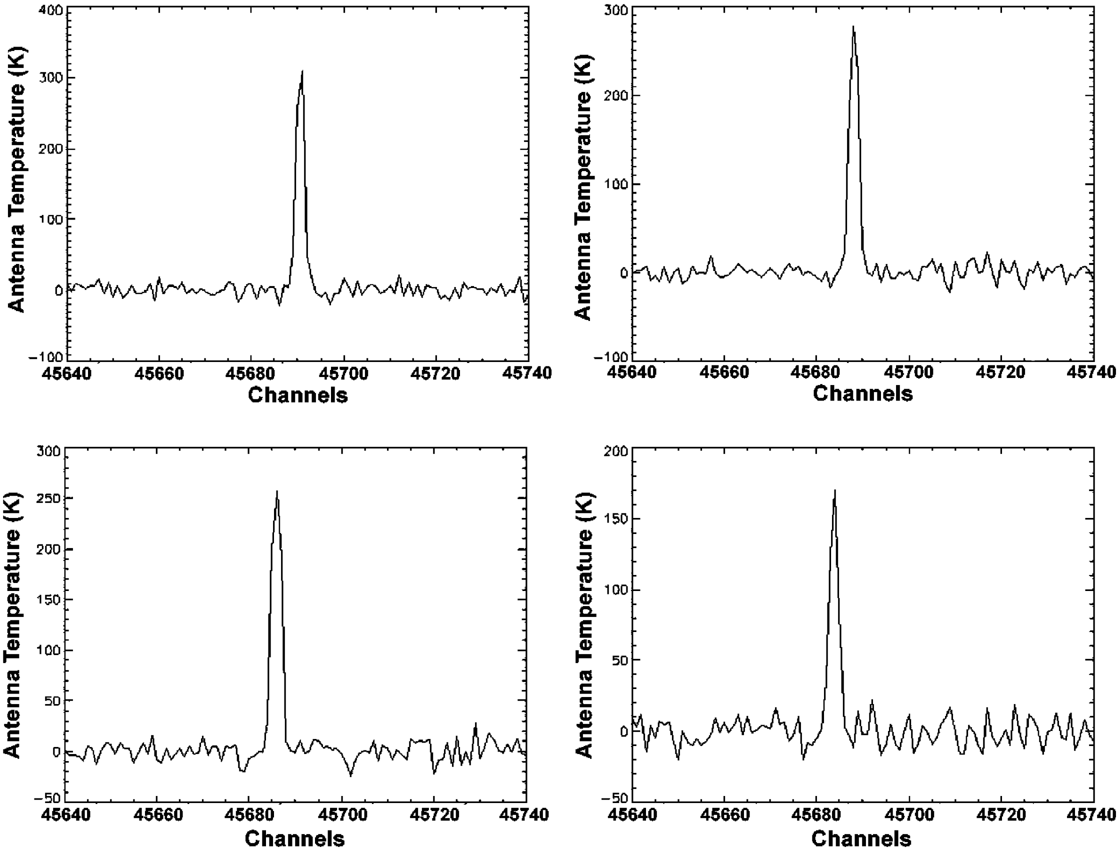

Fig. 3. Uncalibrated spectra resulting from the single blocks.

Table 4
Line parameters achieved using a "gaussian fit" procedure

	T peak (K)	Peak channel (interpolated)	FWHM (Hz)
Block #1	371	45690.583	14.8
Block #2	313	45688.106	20.2
Block #3	291	45685.957	20.3
Block #4	184	45683.788	19.0

to offline processing. The radar echo at 6 cm was not detected on-line with real-time spectral analysis, either in the OC (opposite circular) nor in the SC (same circular) polarization. The detailed off-line analysis of time-domain information was carried out in the Institute of Radio Engineering and Electronic, Friazino, Russia.

4.4. C-band results

The off-line scrutiny (Zaitsev et al., 2002) was successful: a weak but evident echo was detected in six different sections of the stored data, and the relative power spectra were obtained (Fig. 4).

Table 5 lists the time acquisition of the different sections.

The frequency resolution was about 0.15 Hz and the echo is visible at 156 Hz (almost half bandwidth). The integration time per spectrum was 90 s.

The signatures show evident power variations, some of which may be due to an inexact orientation of the transmitting antenna: as the C-band signal was not detected in real time, some pointing shifts were tried during the data acquisition. The observed cross section turned out to be around (0.02–0.01) km^2. This value is not easily comparable to the one obtained at 8.56 GHz, which is surely affected by an overestimation of the line FWHM (due to the frequency drift). In addition it is not possible to perform very accurate computations because a precise Evpatoria gain curve (gain values varying with elevation) is not available.

The polarization ratio, defined as $\mu_c = \sigma_{sc}/\sigma_{oc}$, where σ is the radar cross section for OC or SC polarization, was nearly 1 without any significant variations, in agreement with the monostatic observation made in Goldstone (1.1 ± 10%). The echo's Doppler frequency dispersion (line width) is

$$W = (4\pi D/\lambda P)\sin\alpha$$

and depends on the asteroid's size D, the synodic rotation period P and the aspect angle α (angle between the spin vector and the line of sight). Fig. 4 shows the OC and SC echo spectra for six time intervals. The frequency resolution was 0.15 Hz, random noise fluctuations were small enough and W can be consequently estimated.

The main parameters of radar echo are listed in Table 6. The unexpected results are that the spectra for OC and SC polarization have coinciding parameters for the different rotation phases. To estimate the Radar albedo we put the asteroid diameter as 600 m (Ostro, e-mail comm.)

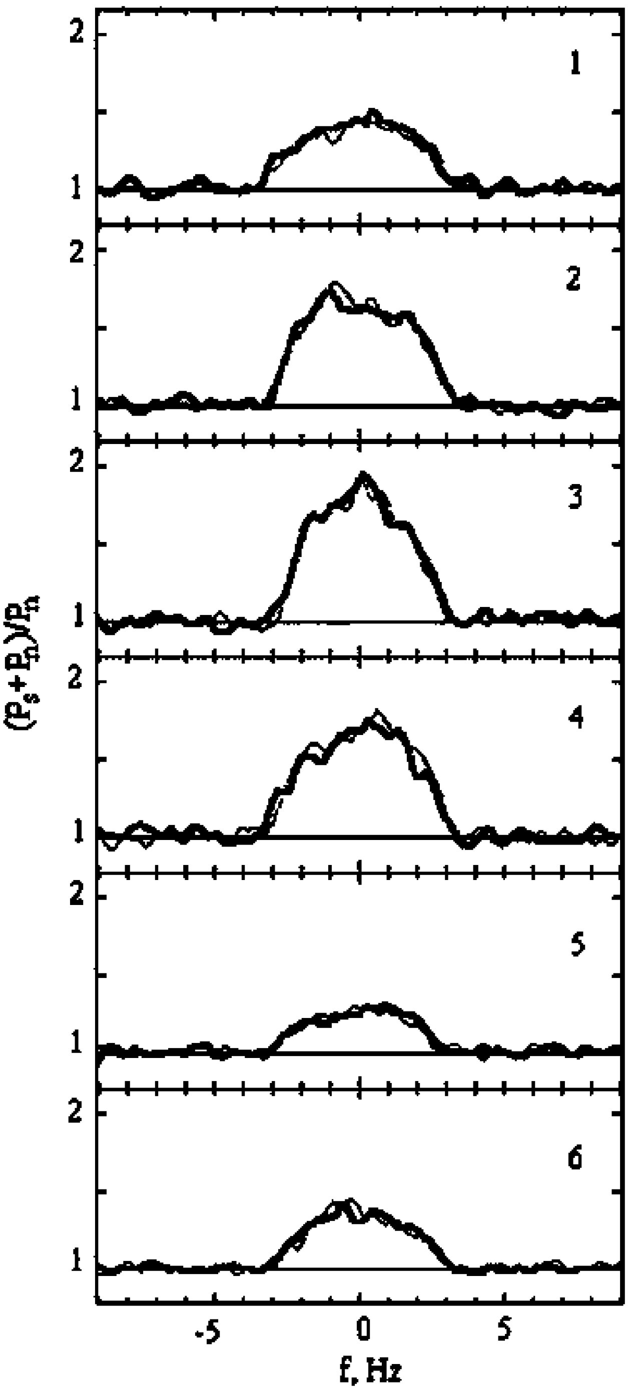

Fig. 4. Weighted sums of cw echo spectra obtained for 1998WT24 in six time intervals in the OC and SC polarization (thick and thin curves). Value $f = 0$ Hz corresponds to hypothetical echoes from the asteroid's center of mass. Echo spectra are normalized to the average noise level, so the y-axis values represent the ratio between the signal and the mean noise level.

The Evpatoria-Medicina data, considered above, provide indications on the asteroid dimension and properties. The

Table 5
Time intervals relative to each section, distance of the asteroid during the acquisition and phase angle (estimated assuming it is equal to zero at the time of first detection, having a spin rate equal to 3.6977 h)

Number	Time (UTC)	Distance (AU)	Phase (deg)
December 16th			
1	13:00–13:55	0.0125	0–89
2	18:10–19:10	0.0126	143–24
3	19:35–20:10	0.0126	280–337
4	20:35–21:00	0.0127	18–58
December 17th			
5	12:18–13:08	0.0138	109–190
6	13:15–14:15	0.0139	201–298

Table 6
Main parameters of the radar echo

No	σ, km^2	Radar Albedo	μ	W(Hz)
1-OC	> 0.013	> 0.046	1.07	6.7
SC	> 0.014	> 0.050		
2-OC	0.020	0.071	0.99	6.7
SC	0.020	0.071		
3-OC	0.021	0.074	1.05	6.2
SC	0.022	0.078		
4-OC	0.021	0.074	0.95	6.6
SC	0.020	0.071		
5-OC	> 0.010	> 0.035	1.04	6.0
SC	> 0.010	> 0.035		
6-OC	> 0.014	> 0.050	1.01	6.3
SC	$- > 0.014$	> 0.050		

most interesting result of these radar measurements is the near-unity circular polarization ratio and low radar albedo. The same value was obtained earlier by Ostro at 3.5 cm in Goldstone (radar albedo equal to 0.05). Radar albedo is correlated with near-surface bulk density, while the polarization ratio is correlated to the degree of near-surface structure at wavelength scale. Such a near-unity circular polarization ratio requires extreme wavelength-scale structural complexity near the surface.

5. Conclusions

The radar echo was successfully detected and this asteroid became the first planetary body observed from Italy by means of an intercontinental radar bistatic configuration.

The success of this asteroid radar experiment in Italy is very encouraging and demonstrates considerable potential for future contributions to planetary radar astronomy. Following this positive experience, we plan to continue the experiments measuring the echoes from asteroids approaching the Earth in the near future.

At present, a suitable transmitter to allow this type of science is not available in Italy. Nevertheless, a 64-m antenna—the Sardinia Radio Telescope—is under construction, and within this project Ka-band (32 GHz) and X-band transmitters are being considered.

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