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The INAF contribution to the ASI Space Debris program: observational activities

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Abstract. Space debris are man made objects orbiting around Earth that pose a serious hazard for both present and future human activities in space. Since 2007 the Istituto Nazionale di Astrofisica (INAF) carried out a number of radar campaigns in the framework of the ASI "Space Debris" program. The observations were performed by using bi- and multi-static radars, composed of the INAF 32-m Italian radiotelescopes located at Medicina and Noto (used as receivers) and the 70-m parabolic antenna at Evpatoria (Ukraine) used as transmitter. The 32 m Ventspils antenna in Latvia also participated in the last campaign at the end of June 2010. Several kinds of objects in various orbital regions (radar calibrators, rocket upper stages, debris of different sizes) were observed and successfully detected. Some unknown objects were also discovered in LEO during the beam-park sessions. In this paper we describe some results of the INAF-ASI space debris research activity.

Key words. Space Surveillance – Near Earth Objects – Space debris – Observational Techniques: bistatic and multistatic radar

1. Introduction

Since the launch of the Sputnik-1 on October 4th 1957, the growing human activity in space has generated a huge number of objects orbiting around Earth. Only a small part of this shell is composed by active satellites, whereas the vast majority of Earth orbiting objects are debris. Examples of space debris are inactive spacecrafts, upper stages of launch vehicles, as well as small fragments created by upper stage explosions or collisions, particles from solid rocket motor propellant or droplets of NaK coolant. Since in the majority of cases debris are produced by fragmentation/collision processes, in terms of number the space debris population is dominated by smaller objects. Table 1 gives the estimated number of

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orbital debris in three size categories according to the MASTER-2001 population model developed by ESA (Klinkrad 2006). As can be seen approximately 40 percent of all debris larger than 1 mm in size is in Low Earth Orbit (LEO).

Average Size	1mm - 1cm	1cm - 10cm	>10cm
LEO region	140,000,000	180,000	9,700
All orbits	330,000,000	560,000	18,000

Table 1. Estimated number of orbital debris according to the ESA MASTER-2001 model.

Fig. 1 displays the increasing in time of different types of orbital objects according to the U.S. Space Surveillance Network (SSN) catalogue (Liou 2011). "Fragmentation debris" include satellite breakup debris and anomalous debris, whereas "Mission related debris" include all objects dispensed, separated, or released as part of the planned mission.

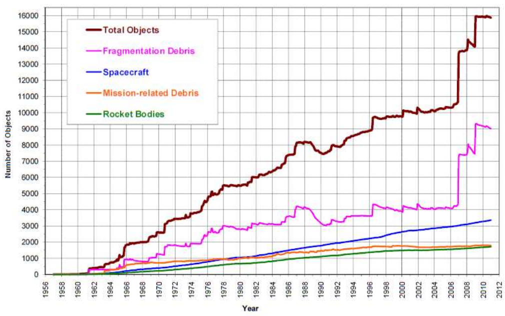

Fig. 1. Summary of all objects in Earth orbit officially catalogued by the U.S. Space Surveillance Network as a function of time.

Breakup events, as satellite explosions and collisions, are the principal sources of debris. The two rapid increases in the debris number observed in 2007 and 2009 were caused by the intentional destruction of the Chinese Fengyun-1C polar-orbiting weather satellite performed by Chinese government in January 2007 and by the collision between the IRIDIUM 33 and the COSMOS 2251 communication satellites occurred on February 10, 2009. It is important to point out that the six most severe breakup events occurred in the last 10 years.

The monitoring and characterization of the orbital debris environment has became one of the most important activities carried out by the worldwide space agencies. In order to achieve these goals a large number of ground based radars and optical telescopes has been employed. Optical observations reach very good performances in geostationary orbits (GEO) and geostationary transfer orbits (GTO), whereas radar systems outperform optical telescopes in LEO and Medium Earth Orbits (MEO).

Since 2006 the Italian Istituto di Radioastronomia (IRA) and Osservatorio Astronomico di Torino (OATO) of the Istituto Nazionale di Astrofisica (INAF) have been involved in the "Space Debris" program funded by the Italian Space Agency (ASI). The main goals of the INAF activity in this field were:

- the study of radar techniques for space debris application
- performing space debris radar campaigns
- the development of new data acquisition systems

The following sections describe some observational results obtained during the three years research activity.

2. radar techniques for space debris monitoring

Generally speaking, radars can be distinguished in two main different configurations: monostatic and bistatic. In a monostatic radar the antenna has both receiving and transmitting functions, whereas in a bistatic one transmitting and receiving antennas are different and separated by a large distance. Obviously, in a bistatic configuration, the antenna beams of transmitter and receiver must be intersecting. A multistatic radar can be conceived as an extension of a bistatic one, if more than two antennas are involved. In our program we utilized both bistatic and multistatic radar systems, therefore only observational techniques applicable to these configurations have been studied and/or tested.

The **beam-park**, or staring, is one of the most common technique used for space debris observations. With this method both transmitting and receiving antennas stare in a defined fixed direction for a long time. Orbiting objects crossing the common volume explored by the antennas are detected. The staring mode is mainly used to improve the knowledge about the debris population density in a defined space observation volume. On the other hand, the estimation of object size and orbital elements is not very accurate due to the short transit time of the target in the common volume. The beam-park technique, in bistatic configuration, has been the observational method mostly used during our space debris radar campaigns.

In the so called **tracking mode** the antennas follow the target for a long time allowing a precise determination of orbit, aspect and Radar Cross Section of the debris. In 2007 and 2008 the INAF antennas applied the precalculated tracking of the targets during two VLBR international radar campaigns coordinated by the Russian Keldysh Institute of Applied Mathematics (Molotov et al. 2008).

Another observational technique utilized by our group during the space debris campaigns was the **piggy-back**. This method consists in intersecting the beam of one antenna (Slave) with the beam of another one (Master) while this is employed in its ordinary activities (Montebugnoli et al. 2010). Even though the piggy-back does not allow for specific target pointing, it offers the advantage of a very long acquisition time without interfering with the scheduled programs carried out by the radiotelescope. In order to perform piggy-back observations, a dedicated secondary receiver, tuned to the radar frequency, should be installed and operated in parallel to the radioastronomical one. In order to check the feasibility of this kind of receiver on the 32-m antenna at the Medicina radioastronomical station, an electromagnetic study was carried out by the Applied Electromagnetic Group of the CNR - Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni (IEIIT). In the framework of this study, three different configurations for a piggy-back receiver close to the parabola's primary focus were investigated (Fig. 2).

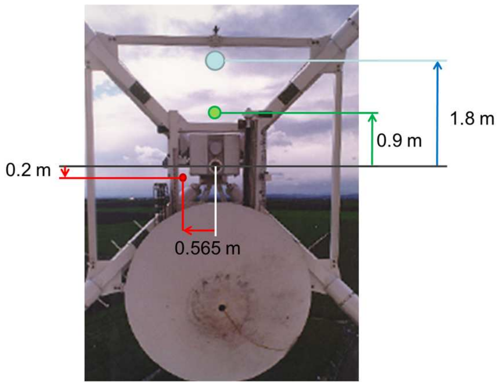

Fig. 2. View of the primary focus of the Medicina 32-m radiotelescope. In the figure the positions of the three simulated piggy-back feeds are showed.

Electromagnetic simulations demonstrated the feasibility of such a system with an acceptable loss of performances respect to the currently installed radioastronomical receivers (Table 2).

Receiver No.	Offset m	Gain dB	HPBW deg	Sec.Lobes dB
0	0	63.1	0.130	-30
1	0.6	55.1	0.360	-13
2	0.9	52.8	0.465	-16
3	1.8	50.2	0.616	-16

Table 2. Performances of the simulated piggy-back feeds. The receiver No. 0 is an ideal on-axis feed located in the antenna's primary focus. HPBW indicates the half power beamwidth of the feed. The last column displays the level of the secondary lobes.

The best solution in terms of sensitivity was provided by the receiver closest to the optical axis (No.1 in Table 2). Furthermore the most performing feeds No. 1 and No. 2 (in Table 2) could be only used for about 50% of the total observing time, when the antenna operates in primary focus configuration, due to the fact that in Cassegrain configuration the subreflector is moved in front of the primary focus receivers. On the other hand, the more off-axis receiver (the No. 3) could be operative full time, when the antenna is used in both Cassegrain and primary focus configurations, but with a lower gain level. Specific software for the calculation of the pointing angles of a slave antenna was developed and successfully tested during the second July 2007 radar campaign.

Within the multistatic radar techniques three different strategies, defined by the overlapping level of the receiving lobes, were investigated and experimented. In the first configuration all the receiving lobes are fully overlapped. This geometry represents the better choice when the target's orbit is sufficiently accurate. It permits the echo detection from all the receivers and a precise determination of the target velocity through bistatic doppler shifts measurements from different points of view. A second configuration, in which the receiving lobes are completely separated, resulted particularly performing for searching of still unknown debris, since the explored volume is maximized and therefore the probability of detection increased. However, in this configuration poor information on the target state can be obtained. Finally a partial overlapping of the receiving beams was also utilized to improve the angular resolution and to obtain information on the target direction.

3. INAF-ASI space debris radar observations

Since 2007 a total of 6 radar campaigns were performed in the framework of the INAF-ASI space debris program (Table 3).

In all radar sessions the 70-m (RT-70) parabola at Evpatoria (Ukraine) transmitted a continuous wave (CW) right circular polarized (RCP) signal at a frequency of 5010.024 MHz and with mean power of about 20-40 kW. The three 32-m radiotelescopes at Medicina (Italy), Noto (Italy) and Ventspils (Latvia) were utilized as receiving parts of the bi- and multistatic radar systems. A detailed explanation of the Medicina-Evpatoria bistatic radar setup is described in (Pupillo et al. 2009).

Date	Rx	Technique	Detected targets
17-19 Jul 2007	Mc	BP	16/21
12 Nov 2007	Mc	BP	8/9
23 Mar 2009	Mc	BP, DT	8/9
28 Apr 2009	Mc	BP	2/2
14 Oct 2009	Mc, Nt	BP	5/5
30 Jun 2010	Mc,Vt	BP	7/9

Table 3. List of the ASI-INAF space debris radar campaigns. In column 2: Mc = Medicina, Nt = Noto, Vt = Ventspils. In column 3: BP = Beam Park, DT = Differential Tracking.

Calibration is an important procedure in case of radar measurements performed to determine the target Radar Cross Section (RCS), i.e. the cross-sectional area of a perfectly reflecting sphere that would produce the same reflected signal as the target. For this purpose at the beginning and at the end of each observational session, some radar calibrators were pointed. Radar calibrators are special satellites having spherical shape and accurately known RCS (Fig. 3).

In the framework of the INAF-ASI space debris campaigns we observed different kinds of objects at any orbital region, from LEO to GEO: non operative geostationary satellites, rocket bodies and fragments of different RCS were pointed. Some specific orbits were also monitored for the detection of not yet catalogued debris. During each campaign targets were selected in order to fulfill a number of general and specific criteria. General criteria were, for instance, the availability of sufficiently recent orbital elements and the belonging to the common visibility window of all antennas, taking in account the limitations in azimuth and elevation of each antenna. One of the specific criteria consisted, for example, in selecting objects produced by a specific breakup event.

After the collision between Cosmos 2251 and Iridium 33 satellites we carried out dedicated radar experiments to detect some of the debris produced by this break-up event. During

Fig. 3. Radar calibrator Tempsat-1. This is an US military target satellite with a 36.0 cm spherical shape launched in LEO polar orbit.

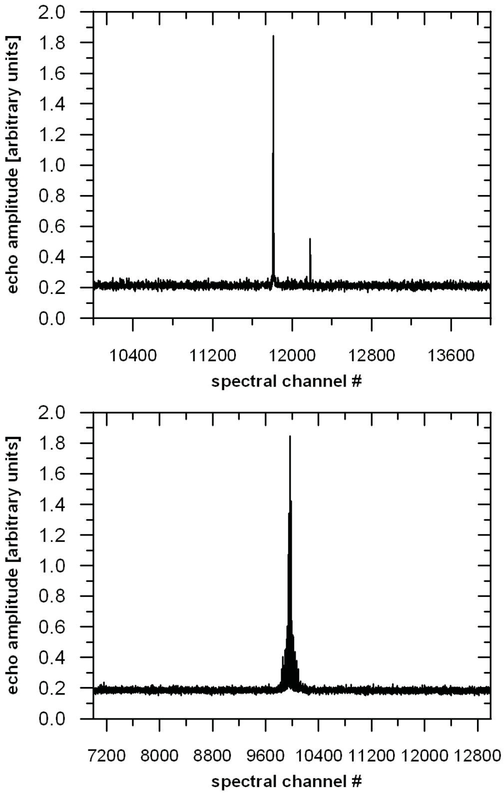

Fig. 4. Radar detections of an IRIDIUM 33 (top) and a COSMOS 2251 (bottom) fragments.

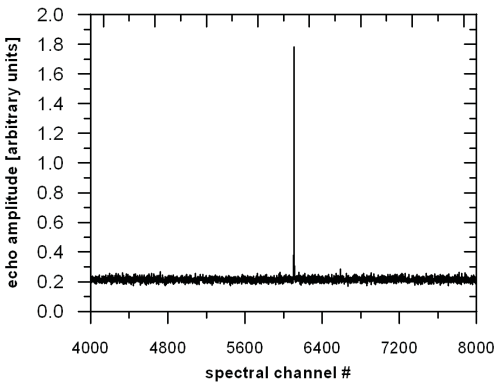

Fig. 5. Spectrum of a Fengyun 1C debris radio echo detected by the Medicina RT-32 antenna.

this observation both beam park and differential tracking modes were used. Echoes coming from Cosmos 2251 and Iridium 33 fragments and detected at the Medicina RT-32 are shown in Fig. 4.

Debris produced by the Chinese ASAT experiment were also successfully detected (Fig. 5).

The capability of our radar system to monitor small orbital fragments was demonstrated by the detections, with an high signal to noise ratio (SNR), of some among the smallest objects included in the US Strategic Command (USSTRATCOM) public catalogue. During the radar session on June 30, 2010 our receiver detected the echo from the debris 35716 (Fig. 6), a COSMOS 2251 fragment, with an estimated RCS of 0.0002 m^2 according to the USSTRATCOM catalogue issued few days before the observation.

The high sensitivity of the system also allowed the discovery of new uncatalogued debris during the beam park radar experiments. These experiments were mainly performed in a LEO region identified according to the PROOF-2005 space debris population model (Anselmo 2007) in order to increase the probability of detection. The geodetic coordinates of the centroid of the volume explored by the radar are listed in Table 4.

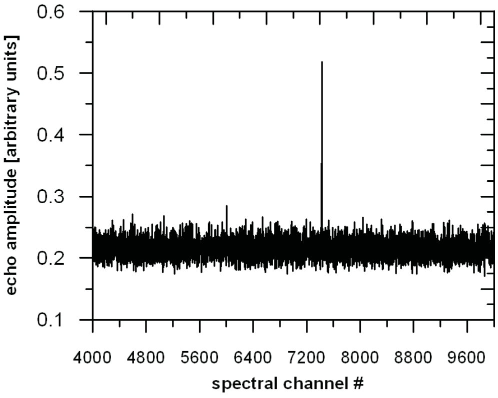

Fig. 6. Detection of the small debris 35716 (COSMOS 2251 DEB).

Height (km)	871.70
Latitude (deg)	47.800
Longitude (deg)	21.172

Table 4. Geodetic coordinates of the centroid of the region observed in beam park mode.

In Fig. 7 the radar detection of a still unknown space debris observed on the April 28, 2009 radar campaign is shown.

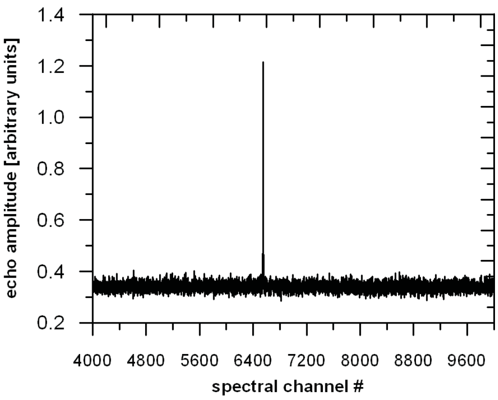

Fig. 7. Echo from a not catalogued debris orbiting at a geodetic height of 871.7 km. The echo was detected on April 28, 2009 at 15:26:54.960 UT.

Bistatic radar measurements can also provide several information about the target, as instance:

- Radar Cross Section
- Time of peak occurrence
- Polarization ratio
- Bistatic doppler-shift
- Target rotation

A software aimed to extract all these information from the radar data was developed in IDL (Interactive Data Language) environment by our group. In particular we were interested in measuring the difference between the observed and expected transit time of the target within the radar beam ΔT_{O-C}. This latter was calculated by using the orbital propagator SGP4/SDP4 with the updated Two Line Elements set (TLE) distributed by USSTRATCOM one or two days before the date of observation.

Table 5 shows the time differences ΔT_{O-C} of the targets observed on June 30, 2010.

Target ID No.	Expected time UT	Observed time UT	ΔT_{O-C} sec.
900	13:57:00.00	13:57:00.22	+0.22
1520	09:46:00.00	09:46:00.18	+0.18
21131	10:54:00.00	10:54:00.22	+0.22
26277	14:25:00.00	14:24:58.96	-1.04
31424	10:24:00.00	10:23:58.98	-1.02
34502	09:05:00.00	09:04:59.02	-0.98
35303	10:05:00.00	10:04:59.70	-0.30
35716	14:08:00.00	14:07:59.90	-0.10

Table 5. Differences between observed and expected transit time of the targets detected during the June 30, 2010 radar campaign.

The bistatic frequency doppler shift of the received radio echo is defined as:

$$\Delta f = -\frac{1}{\lambda}\frac{d}{dt}(R_T + R_R) \quad (1)$$

where λ is the transmitted wavelength, R_T is the distance between transmitter and target and R_R is the distance between target and receiver.

Raw data, acquired in the time domain by the Medicina and Noto recording systems, were analyzed in the frequency domain with a dedicated FFT software spectrometer.

Table 6 shows the difference between observed and expected bistatic doppler shifts, $\Delta f_O - \Delta f_C$, and the corresponding difference in the bistatic range variations (Δv_{O-C}).

Target ID No.	$\Delta f_O - \Delta f_C$ Hz	Δv_{O-C} m/s
900	+173	+10.3
1520	+220	+13.2
21131	+162	+9.7
26277	-912	-54.6
31424	-814	-48.7
34502	-1193	-71.4
35303	-150	-8.9
35716	-128	-7.6

Table 6. Differences between observed and expected frequency doppler shifts of the echo from targets detected on the June 30, 2010 radar campaign. The last column lists the corresponding differences in the bistatic range variation.

The differences between observed and expected time and frequency values seems to confirm the TLE's uncertainties reported by (Aida et al. 2009) and (Flohrer et al. 2009). An accurate determination of these differences may be extremely important to improve the precision in the target orbit knowledge.

4. Conclusions

Since 2007, six bistatic and multistatic radar campaigns were performed in the framework of the INAF-ASI "Space Debris" program. The main results of these experiments demonstrate that the bistatic and multistatic radars composed by the 32-m INAF and VIRAC radiotelescopes and by the RT-70 Evpatoria transmitter were very effective in the monitoring of space debris in all orbital regions. Due to their high sensitivity, these systems are capable to also detect centimetric fragments and to discover new debris in LEO. Moreover an electromagnetic study on the 32-m antenna at Medicina showed the feasibility of a piggy-back receiver close to the antenna's primary focus, that could significantly increase the space debris operational time without interfering with the astronomical observations. Finally, the preliminary post-processing of the radar data acquired on the last radar campaign allowed to confirm the large uncertainties in the TLEs provided by USSTRATCOM. This aspect needs to be carefully assessed, since it could have important implications in the evaluation of collision risk and in the planning of the collision avoidance maneuvers.

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