ITALIAN ACTIVITY IN SPACE DEBRIS MEASUREMENTS

F. Piergentili[(1)], F. Paolillo[(2)], C. Cappelletti[(2)], G. Cevolani[(3)],
G. Grassi[(3)], M. Marti[(3)], G. Pupillo[(3-4)], G. Trivellone[(3)], C. Portelli[(5)], M. Porfilio[(6)], F. Graziani[(2)]

[(1)] University of Bologna, DIEM - II Faculty of Engineering, via Fontanelle 40, 47100 Forlì, ITALY,
Email: Fabrizio.piergentili@unibo.it
[(2)] Scuola di Ingegneria Aerospaziale, University of Rome "La Sapienza", Via Eudossiana 18, 00184 Roma, ITALY,
Email: Filippo.graziani@uniroma1.it
[(3)] CNR-ISAC, via Gobetti 101, 40129 Bologna, ITALY, Email: G.Cevolani@isac.cnr.it
[(4)] INAF-OATO, via Osservatorio 20, 10025 Pino Torinese (To), ITALY, Email: G.pupillo@isac.cnr.it
[(5)] ASI, Italian Space Agency, Viale Liegi 26, 00198 Roma, ITALY, Email: Claudio.portelli@asi.it
[(6)] ASI, Italian Space Agency, Viale Liegi 26, 00198 Roma, ITALY, Email: manfredi_porfilio@hotmail.com

ABSTRACT

In the frame of the Italian Space Agency programme on Space Debris, the Measurement issue plays an important role. The paper deals with two of the activities which are currently going on in this field:

1. optical measurements: a semi-transportable optical observatory for space debris monitoring has been developed and is operative;

2. radar measurements of re-entering particles: a multi-static system for detecting meteoroids entering Earth atmosphere is being improved and used for re-entering orbiting debris too.

The paper describes the mentioned facilities and the first results achieved.

1. INTRODUCTION

The Italian space debris detection activity began in 2002 with the first optical observation test campaign [1] carried out by GAUSS (Group of Astrodynamics of the University of Rome "La Sapienza"). The observation had continued for a few years exploiting amateur astronomers' facilities, see [2], [3] and [4], also in the frame of the IADC (Inter-Agency Space Debris Coordination Committee) co-ordinated measurement campaigns.

In October 2006 the Italian Space Agency (ASI) founded the "*Detriti Spaziali*" (Space Debris) programme. The purpose of this programme is to improve the Italian expertise in the field of space debris while increasing the collaboration among Italian groups involved in research activities on this subject. The programme addresses the "measurement", "modelling", "protection" and "mitigation" activities.

In the framework of this programme, GAUSS started the designing and manufacturing of the first Italian optical observatory dedicated to space debris monitoring.

The main driver of the observatory design was the semi-transportability. The facility include two optical tubes, with 30 cm and 40 cm diameters, a Charge Coupled Device (CCD) camera, a robotic mount, a dome and a laptop PC. The software packages installed on the PC provide the hardware with the capabilities of autonomous tracking, programmable image acquisition and download and dome control; an internet connection allows the observatory overall remote control.

Due to the large amount of data collected during the observation campaigns, a specific software has been developed for image processing automation and for the correlation of the detected objects with the catalogue. This software has been used to process all the images obtained during the IADC coordinated campaigns.

ASI Space Debris programme also addresses radar observations, featuring two research lines:

- centimetric and sub-centimetric debris detection in LEO by means of bi-static radar facilities;
- observation of up to sub-millimetric particles in re-entry phase by means of a multi-static radar system.

The following sections describes the facilities and the first results achieved with the optical observatory and with the multi-static radar system for re-entering particles detection.

2. THE FACILITIES

2.1. The SpaDe optical observatory

GAUSS designed and developed, under ASI contract, the first Italian optical observatory completely dedicated to space debris detection (called SpaDe, SPAce DEbris; see [5]). The SpaDe peculiar requirement is the transportability; this was a driver for all the design choices.

For this project two optical tubes have been procured: the first one is a 400 mm diameter Modified Cassegrain, with a focal ratio of *f*/1.8. This configuration has a parabolic primary mirror, a parabolic secondary mirror and a corrector meniscus of 3" on the primary. The corrector meniscus on the primary mirror is a not a common configuration, so we call it "Modified" Cassegrain to dis-

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tinguish it from the traditional Cassegrain configuration, which permits a corrector meniscus on the secondary mirror. With the modified configuration a shorter focal length (thus a wider field of view, FOV) and a greater stability on the mount (useful for LEO objects tracking) are achieved with respect to a classical Cassegrain tube.

The optical system (the two mirrors and the meniscus) and three rods (which impose the focal length) were bought. A support for the primary mirror, that also plays the role of support for the whole telescope, was designed by GAUSS (see Figure 1).

The second optical tube of the SpaDe observatory is a Baker-Schmidt with a diameter of 300 mm and a focal ratio of *f*/2.8, Figure 2. It is a classical Baker-Schmidt configuration with a spherical primary mirror, an hyperbolic secondary mirror and a correction lens that removes the aberrations of the mirror as coma and astigmatism.

Figure 1. Modified Cassegrain optical tube.

Figure 2. Baker-Schmidt optical tube.

Figure 3. Paramount GT 1100 ME.

Table 1. SpaDe CCD parameters.

Number of Pixels	4096(H) x 4096(V)
Pixel Size	9 µm (H) x 9 µm (V)
Chip Size	38.6 mm(H) x 37.76 mm(V)
Quantum Efficiency (@ 500 nm)	60%

Figure 4. FLI Proline and adapter.

For space debris optical observation campaigns a tracking system is required. For this reason a Paramount GT 1100 ME commercial mount has been chosen (see Figure 3). This mount is capable to support up to 45 Kg and to rotate with a maximum angular velocity of 5 deg/s in right ascension and 7 deg/s in declination.

SpaDe observatory has been equipped with a FLI Proline 16803 CCD camera, with a Kodak Kaf 16803 sensor. This is a commercial off-the-shelf CCD camera; its main features are summarized in Table 1. This CCD has a downloading speed of 12 Megapixels per second. In Figure 4 the FLI Proline, with the Baker-Schimdt adapter is shown. This CCD permits to achieve a field of view of about 2.6 deg for the Baker-Schmidt and about 3 deg for the Modified Cassegrain.

The semi-transportability requirement pushed to design and manufacture a new kind of dome, easily transportable, even by car. The structure is based on four quadrangular arcs which rotate around a central axis (see Figure 5) by means of an electrical motor. It has a Poly/450/pvc coverage. The main characteristics of this dome are modularity and lightness, both essential to comply with the transportability requirement; the structure can be actually disassembled in small modules. The dome is ready to be remotely controlled. Figure 6 shows a picture of the dome.

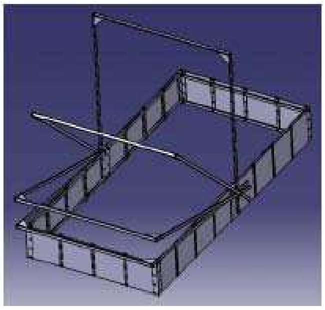

Figure 5. Dome design.

Figure 6. The dome in closed configuration.

Table 2. Collepardo observatory features.

Site:	Collepardo, Italy
Latitude [deg – North/South]:	41°45'54'' N
Longitude[deg – East/West]:	13°22'29'' E
Altitude [m]:	576
Seeing (FWHM) [arcsec]:	8.48

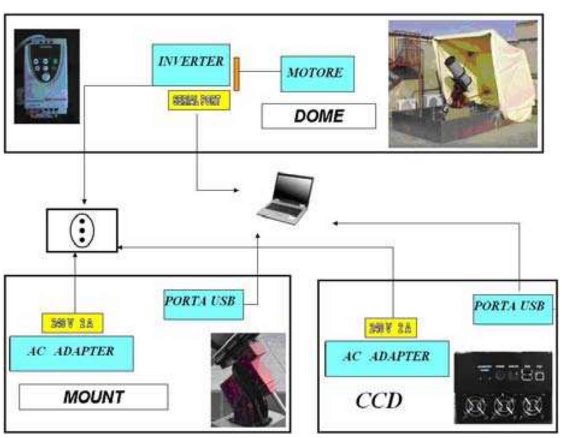

Figure 7. SpaDe observatory connections.

The observatory was initially assembled at University of Rome, in order to perform hardware and software tests. At the moment, SpaDe observatory is located in Collepardo, nearby the "Collepardo Automatic Telescope" of the "*Associazione Astronomica Frusinate*" amateur astronomy society.

Table 2 reports geodetic position and seeing (full width at half maximum, FWHM) of the site.

Figure 7 depicts the observatory control scheme; all SpaDe functions can be operated by means of a laptop PC, which, in turn, can be remotely controlled through an internet connection, thus providing the observatory with complete remote control.

2.2. The BLM radar facility

The BLM (Bologna-Lecce-Modra) forward scattering (FS) meteor radar utilises a continuous wave transmitting frequency at 42.7 MHz with 1 kw mean power, having the transmitting station at Budrio (near Bologna, Italy) and the receiving stations at Lecce in Southern Italy and Modra (Slovakia) (see Figure 8). Calculation of the peak received power from a typical FS echo indicates that most debris/meteoroids with electron densities $q \geq 5 \times 10^{12}$ el/m will be detected by the system, corresponding to $m = 10^{-8}$ kg masses and d = 100 - 200 micron sizes, by assuming standard conditions (see [8]).

Figure 8. The BLM radar system.

3. RESULTS

3.1. Results of the optical campaigns

In this section the results are presented, relevant to the high Earth orbit (HEO) monitoring campaigns performed from February to June 2008. For the sake of completeness, all the results are reported, including those achieved with the Collepardo Automatic Telescope (CAT). This allows also to assess a rough comparison of the performances of SpaDe with respect to a telescope which was widely used by GAUSS in the optical campaigns of the previous years. In Table 3 the main features of the two optical systems (SpaDe and CAT) are summarized. We remark that the two telescopes were co-located in Collepardo, Italy.

Table 3. Main features of the SpaDe and CAT optical systems.

	SpaDe	CAT
Optical tube:	Baker-Schmidt	Baker-Schmidt
Diameter [m]:	0.300	0.250
CCD size [pixels]	4K x 4K	512 x 512
Field of view (FOV) [degrees]:	2.6° x 2.6°	0.74° x 0.74°
Pixel scale [arcs/pixel]:	2.2	5.16
Tracking [sidereal only or any rate]:	Any rate	Any rate

Table 4 shows the results of the HEO orbit monitoring campaigns carried out in the framework of the IADC Action Item (AI) 23.4.

All the orbiting objects were automatically detected and identified with the software developed in the framework of the ASI Space Debris Project (see [6]); this software is capable to automatically process all the images of an observation campaign. Images were taken with three different observation strategies as hereafter detailed. All the images were taken during new moon periods. Each row of the table reports the data referring to a single observation night. The table columns report the following information:

- Column 1
  - the date (dd-mm-yyyy) of the observation campaign;
  - the Universal Time Coordinated (UTC) at the beginning and at the end of the images sequence.
- Column 2
  information about the observation site and the optical system used. It is also showed the ratio between the total number of frames achieved and the total time spent during the night of observation.
- Column 3
  the number of pixels in the CCD image (depending on the binning used). It is important to point out that some observation campaigns have been carried out with two different binning settings, in order to verify and test the optimal image acquisition configuration in the “seeing” conditions of Collepardo observation site.
- Column 4
  the ratio between usable frames and the total number of frames achieved during the observation campaign. A typical example of useless frame is one heavily affected by bad weather conditions.
- Column 5
  the number of frames taken with the three different observation strategies used:
  - STM - Sidereal tracking mode: the pointing is fixed with respect to the inertial reference frame.
  - OTM1 - Object tracking mode 1: during the exposure time the mount is fixed with respect to the Earth, while it is moved back to the same inertial coordinates before taking a new image. With this method the GEO objects are point-shaped.
  - OTM2 - Object tracking mode 2: the mount is fixed with respect to the Earth. This method allows the same GEO object tracking during the whole observation session.
- Column 6
  the detected orbital objects are classified as it follows:
  - CTs - Correlated Targets: orbital objects correlated with NASA’s “Geosynchronous Catalog Report”.
  - USCTs - UnSuccessfully Correlated Targets: orbital objects not correlated with the “NASA Geosynchronous Catalog”.
  - OF-USCT – One Frame UnSuccessfully Correlated Targets: orbital objects not correlated with the “NASA Geosynchronous Catalog” and detected in one image only.
- Column 7
  - USs - UnSeen: orbital objects in the “NASA Geosynchronous Catalog” that should have been in the frames but actually not detected in the images.

The CAT telescope participation in the IADC joint campaign provided the possibility to compare images of the same orbital region, with the same sky illumination conditions, taken with different optical systems. The SpaDe larger FOV allows to monitoring a larger orbit region and to collect a larger number of images of the same object (resulting in better results in the orbital determination of the detected debris).

The software developed by GAUSS is able to automatically process all the images of an observation campaign regardless for the observation strategy (STM, OTM1 and OTM2), allowing to detect and identify the orbiting objects in each frame.

It is also important to point out that most of the SpaDe observation campaigns have been carried out with a 2x binning, in order to obtain a CCD size of 2K x 2K pixels and a pixel scale of 4.4 arcseconds, see [7]. This is the best accuracy achievable taking into account the seeing of Collepardo site. In fact the pixel size corresponds to about one half of the seeing FWHM (which is 8.48 arcseconds, see Table 2). Moreover the image size decreases (32 Mbyte for a 4K x 4K CCD size and 8 Mbyte

Table 4. Results of the GEO Orbit measures carried out by ASI-GAUSS group from February 2008 to June 2008.

OBSERVATION DAY AND TIME	TELESCOPE (N° FRAMES / OBSERVATION TIME)	IMAGE PIXELS	USABLE FRAMES / TOT. N° OF FRAMES	OBSERVATION STRATEGY	DETECTED OBJECTS				US
					CT	USCT	OF-USCT	TOT	
11-02-2008 21:57:59 22:27:01	**SpaDe** (103 fr. / 0,5 h)	1365x1365	103/103	**STM** (103 fr.)	**0**	**1**	**0**	**1**	**0**
				OTM1 (no fr.)	/	/	/	/	/
08-03-2008 21:11:53 00:05:04	**CAT** (361 fr. / 2,87 h)	512x512	300/361	**STM** (300 fr.)	**4**	**2**	**1**	**7**	**0**
				OTM1 (no fr.)	/	/	/	/	/
09-03-2008 00:18:23 03:32:00	**SpaDe** (500 fr. / 3,23 h)	2kx2k	420/500	**STM** (420 fr.)	**6**	**3**	**1**	**10**	**0**
				OTM1 (no fr.)	/	/	/	/	/
09-03-2008 00:21:57 02:52:23	**CAT** (340 fr. / 2,52 h)	512x512	340/340	**STM** (340 fr.)	**4**	**4**	**1**	**9**	**0**
				OTM1 (no fr.)	/	/	/	/	/
04-04-2008 20:09:00 20:28:00	**SpaDe** (9 fr./ 0,32 h)	4kx4k	0/9	**STM** (no fr.)	/	/	/	/	/
				OTM1 (no fr.)	/	/	/	/	/
05-04-2008 21:03:20 02:59:00	**SpaDe** (246 fr. / 5,93 h)	4kx4k	226/246	**STM** (70 fr.)	**4**	**1**	**0**	**5**	**0**
				OTM1 (156 fr.)	**6**	**7**	**0**	**13**	**0**
01-05-2008 19:38:00 02:30:00	**SpaDe** (333 fr. / 6,87 h)	4kx4k	132/132	**STM** (42 fr.)	**13**	**0**	**0**	**13**	**0**
				OTM1 (90 fr.)	**26**	**3**	**2**	**31**	**1**
		2kx2k	201/201	**STM** (68 fr.)	**31**	**3**	**3**	**37**	**0**
				OTM1 (133 fr.)	**38**	**9**	**5**	**52**	**0**
02-05-2008 19:30:00 01:01:00	**SpaDe** (289 fr. / 5,5 h)	2kx2k	132/289	**STM** (68 fr.)	**16**	**2**	**1**	**19**	**0**
				OTM1+OTM2 (38 fr.)+(26 fr.)	**8**	**4**	**1**	**13**	**0**
03-05-2008 19:30:00 02:30:00	**SpaDe** (321 fr. / 7 h)	4kx4k	82/89	**STM** (33 fr.)	**1**	**1**	**1**	**3**	**1**
				OTM1 (49 fr.)	**1**	**4**	**1**	**6**	**0**
		2kx2k	232/232	**STM** (93 fr.)	**6**	**8**	**1**	**15**	**2**
				OTM1 (139 fr.)	**4**	**8**	**2**	**14**	**2**
06-05-2008 23:01:00 02:30:00	**SpaDe** (173 fr. / 3,5 h)	2kx2k	142/173	**STM** (56 fr.)	**0**	**5**	**0**	**5**	**0**
				OTM1 (86 fr.)	**4**	**4**	**3**	**11**	**0**
07-05-2008 19:31:00 02:30:00	**SpaDe** (335 fr. / 7 h)	2kx2k	244/335	**STM** (147 fr.)	**6**	**5**	**0**	**11**	**1**
				OTM1 (97 fr.)	**5**	**9**	**3**	**17**	**0**
30-05-2008 20:01:00 21:14:00	**SpaDe** (76 fr. / 1,22 h)	4kx4k	76/76	**STM** (no fr.)	/	/	/	/	/
				OTM1 (76 fr.)	**1**	**1**	**3**	**5**	**3**
01-06-2008 22:52:00 00:59:00	**SpaDe** (105 fr. / 2,12h)	4kx4k	105/105	**STM** (no fr.)	/	/	/	/	/
				OTM1 (105 fr.)	**0**	**3**	**3**	**6**	**2**
03-06-2008 20:53:00 23:23:00	**SpaDe** (108 fr. / 2,5 h)	2kx2k	0/108	**STM** (no fr.)	/	/	/	/	/
				OTM1 (no fr.)	/	/	/	/	/
04-06-2008 20:34:00 22:48:00	**SpaDe** (113 fr. / 2,23 h)	2kx2k	58/113	**STM** (no fr.)	/	/	/	/	/
				OTM1 (58 fr.)	**0**	**1**	**1**	**2**	**0**

for a 2K x 2K CCD size), allowing a faster image processing procedure.

Figure 9 shows the results of the HEO monitoring campaigns carried out by ASI-GAUSS in the framework of the IADC AI 23.4, from February to June 2008 (see also Table 4). 305 orbiting objects (184 CTs, 88 USCTs and 33 OF-USCTs) were automatically identified while 12 objects resulted unseen.

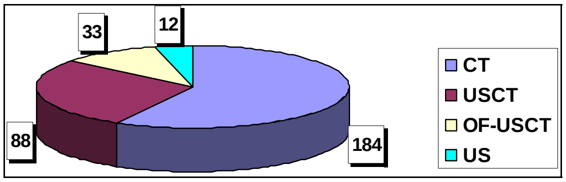

Figure 9. Detected And unseen object in the HEO monitoring campaigns, February - June 2008.

Bad weather conditions affected most of the IADC 2008 observation campaigns. There were only a few nights with good weather condition: the 01-05-2008 session, carried out in both STM and OTM1 observation strategies (see Table 4), is an example of a good weather condition observation campaign, with 133 orbital objects detected (108 CTs, 15 USCTs and 10 OF-USCTs) and 1 unseen.

In the 02-05-2008 observation session all the three observation strategy (STM, OTM1, OTM2) were used in order the compare the different results. Moreover this night of observation was the first test of the OTM2 automatic image processing procedure.

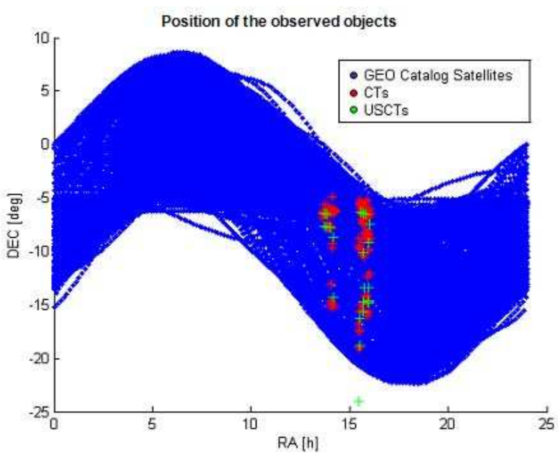

Figure 10. Position of the detected objects and of the geosynchronous objects in the Collepardo-centred celestial reference frame.

The ratio between the total number of frames and the usable frames achieved during the 2008 IADC campaign (Table 4) is 2793/3412 (619 frames have been badly affected by adverse weather condition), with a total time spent of 53.31 hours.

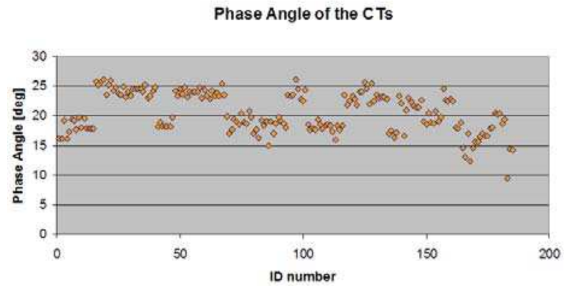

Figure 11. Phase angle of the 184 CTs.

Figure 10 shows the position of the identified objects with respect to the propagated positions of the objects in NASA's "Geosynchronous Catalog Report". The coordinate system used is the equatorial celestial frame, centred in Collepardo observation site. It is important to emphasize that the ratio between USCTs and CTs increases moving away from -6° declination, (which is the declination of the geostationary ring with respect to Collepardo).

Figure 11 shows the phase angle of the 184 CTs of Figure 9 (a phase angle of zero degrees represents the best illumination condition).

3.2. BLM Radar preliminary results

A program has been developed to simulate the entry of debris into the atmosphere, as the output data of the interferometer system shown in Figure 8. The simulation program gives the distribution of 3000 echoes selected among 10000 echoes according to the intensity of the reflected signal (Figure 12). A Gaussian distribution of heights between 55 and 95 km (peaked at 75-80 km) is assumed.

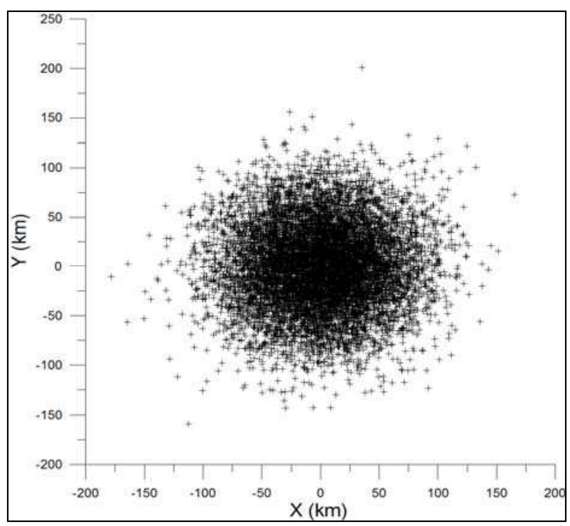

Figure 12. Simulated positions of 3000 echoes projected on a horizontal plane including the radar baseline.

Results of the program for the 3000 echoes give mean values of R_1 (transmitter-trail distance) = 369 km and R_2

(receiver-trail distance) = 371 km, φ (bisector of the angle between R_1 and R_2) = 73° - 77°, and β (angle between the trail and the propagation plane) = 0°-20°/ 160°-200° (Figure 13).

Preliminary debris observations were carried out in October-December 2008. Mean values of $R_1 = R_2 = 370$ km, $\varphi = 75°$ and $\beta = 20°$ are used to determine the speeds of debris and meteoroids.

Figure 14 and Figure 15 give the cumulative fluxes of space debris in comparison with the total fluxes (meteoroids plus debris) *vs* the echoes' durations, as observed by the BLM radar respectively in October and December 2008.

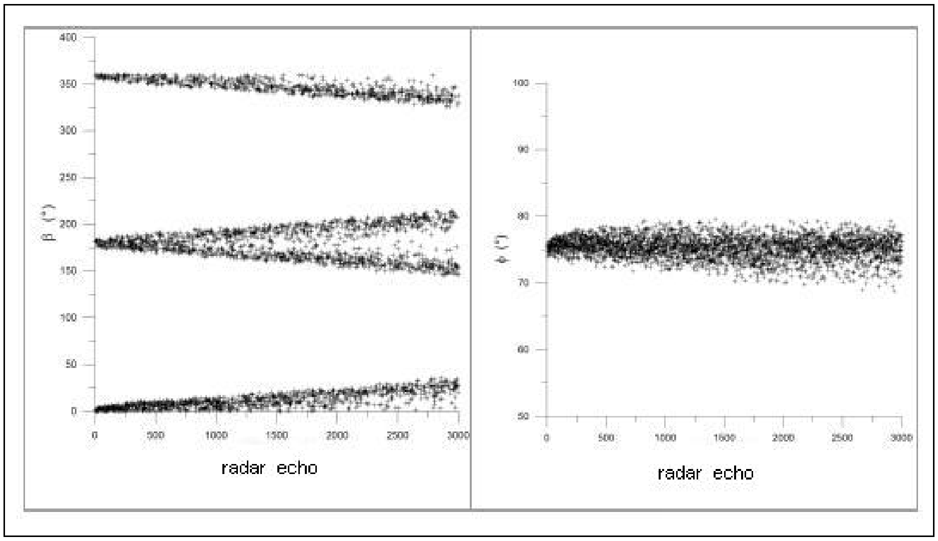

Figure 13. Distribution of the interferometric angles β and φ relative to the 3000 echoes.

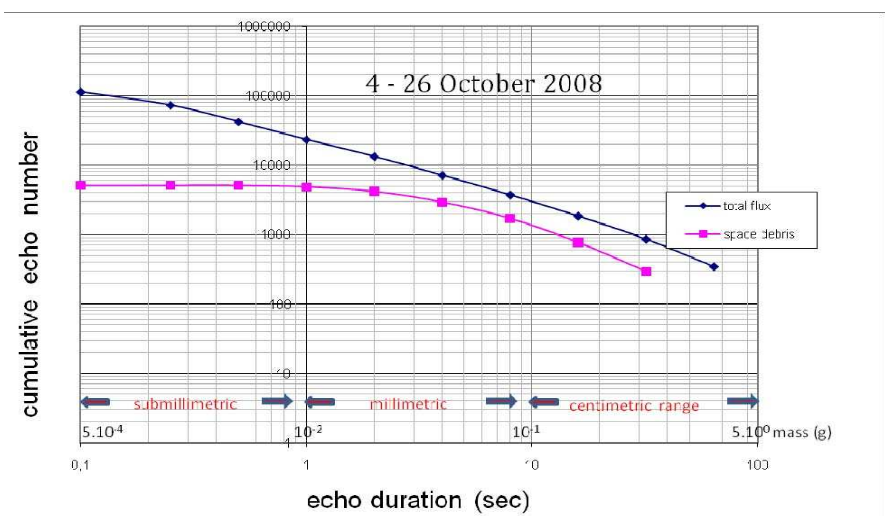

Figure 14. Cumulative number of 114 469 echoes vs their durations from meteoroids plus debris (total flux) and debris, recorded during 4-26 October 2008.

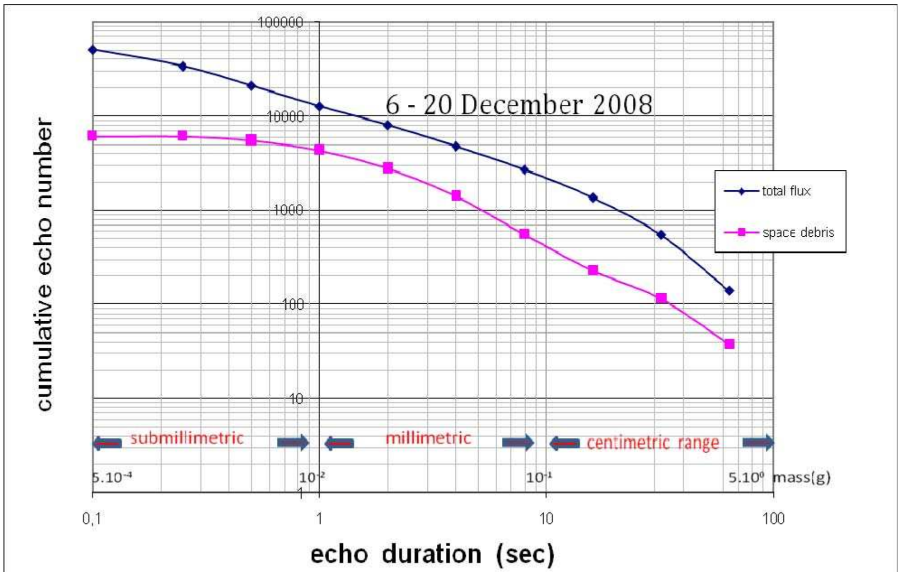

Figure 15. Cumulative number of 51 144 echoes vs their durations from meteoroids plus debris (total flux) and debris, recorded during 4-20 December 2008.

4. CONCLUSIONS

In the paper the results of the Italian 2008 optical HEO monitoring campaign have been depicted. The whole campaign was carried out by the new Italian Space debris Observatory (SpaDe), whose main features are briefly summarized in the first part of the paper.

About three hundred objects were detected, 88 objects were not correlated with the geosynchronous catalogue issued by NORAD.

Concerning the Italian radar facility for the detection of re-entering particles, it has been briefly described how valuable *rise-time* speeds of small debris can be obtained from the BLM radar utilizing the maximum gradients of the amplitude series up to peak amplitude echo measurements. It can be noticed however that at present the radar system is not able to provide reliable fluxes of sub-millimetric debris. Normal accuracy in rise-time speeds, stated at better 10-12%, is expected to be improved by the full employment of the radio interferometer.

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