Mem. S.A.It. Suppl. Vol. 20, 8

Memorie della
Supplementi

Forward Scatter Radio Observations of Atmospheric Space Debris and Meteoroids during 2009 - 2010

G. Cevolani[1], G. Grassi[1], G. Bortolotti[1], R. Bruco[1], M. Marti[1], G. Pupillo[2], M. Tepore[3], G. Trivellone[1], L. Visi[1] and V. Porubcan[4]

[1] CNR-ISAC, via Gobetti 101, 40129 Bologna, Italy
[2] INAF-OATO, via Osservatorio 20, 10025 Pino Torinese (To)/Osservatorio di Campi Salentina, via S. Giuseppe, I-73012 Campi Salentina, Italy
[3] Osservatorio di Campi Salentina, via S. Giuseppe, I-73012 Campi Salentina, Italy
[4] Astronomical Institute of the Slovak Academy of Sciences, 84248 Bratislava, Slovakia
e-mail: `G.Cevolani@isac.cnr.it`

Abstract. Systematic monthly observations of space debris and meteoroids in the atmosphere have been carried out during 2009-2010 by the bistatic Bologna-Lecce forward-scatter radar. Deductions of a simulation program allow us to determine speeds and fluxes of debris and meteoroids. By determining the total flux as a combination of meteor and debris fluxes, debris/total flux ratios are given together with the mean values calculated over the monthly observational period. Mean values observed in spring months appear to be lower than those in summer months. Monthly cumulative fluxes of echoes from meteoroids and debris versus their duration, are also shown together with theoretical curves extended to submillimetric dimensions.

Key words. space debris, meteoroid, forward scatter radar, radioecho

1. Introduction

Today, the meteoroid population is investigated in close connection with the space debris environment since meteoroid and debris flux models are fundamental for the design of space missions, as well important for determination of orbits of natural and artificial bodies (Drolshagen et al. 2001). Atmospheric fluxes of meteoroid streams and background are well known, but very little is known about the flux of space debris decaying into the atmosphere. The cataloged debris from recent hypervelocity catastrophic events (the destruction of the Chinese satellite Fengyun-1C in 2007, the U.S. head-on collision in 2008, and Cosmos 2251/ Iridium 33 collision in 2009) now represents an increase in the low Earth orbit (LEO) satellite population of more than 60% (NASA 2009). 'Rise time' debris speeds ($<$ 10 km/s) have been obtained from radio observations utilizing the maximum gradients of the amplitude series up to peak amplitude echo measurements (Cevolani et al. 2008) and enable us to distinguish debris from meteoroid speeds

Send offprint requests to: G. Cevolani

(11−71km/s). Space debris is expected to reach their maximum ionization at lower altitudes because of their lower speeds, since the ionization probability for collisional atoms of a small body entering into the atmosphere strictly depends on its velocity (Verniani 1974). Many measurements of entrance speeds are based on optical studies but these methods are difficult to employ and are applied only infrequently. Radar techniques generally cannot achieve the same speed accuracy but are able to detect smaller particles with respect to photographic and image intensifier methods (Baggaley & Grant 2005).

2. The simulation program

The FS meteor radar utilizes a continuous wave transmitting frequency at 42.7 MHz and about 1 kw mean power. The transmitting station is located at Budrio (44.6°N) near Bologna and the receiving stations are displayed at Lecce (40.3°N) in Southern Italy and Modra (48.3°N) (Slovakia)(Fig. 1).The two baselines Bologna-Lecce and Bologna-Modra are long 716 km and 690 km, respectively. A simple calculation of the peak received power from a typical FS echo indicates that most meteors/debris with $q \geq 5x10^{12}$ el/m will be detected by the system, corresponding to m = 10^{-8} kg masses and d = 100 – 200 micron sizes (Cevolani et al. 2008).

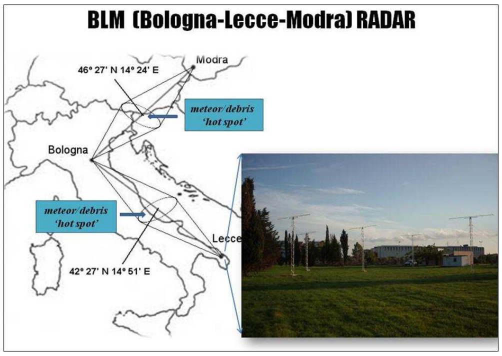

Fig. 1. The display of the BLM (Bologna-Lecce-Modra) radar system implemented by a 5-antenna radio-interferometer installed in 2008 at the receiving station in Lecce.

The specular reflection in a FS system occurs at the center of the Fresnel zone f (zone of maximum reflection of the signal) when the trail lies along a tangent to an ellipsoidal surface with the transmitter T (in Bologna) and the receiver R (in Lecce or Modra) in the foci (Fig. 2).

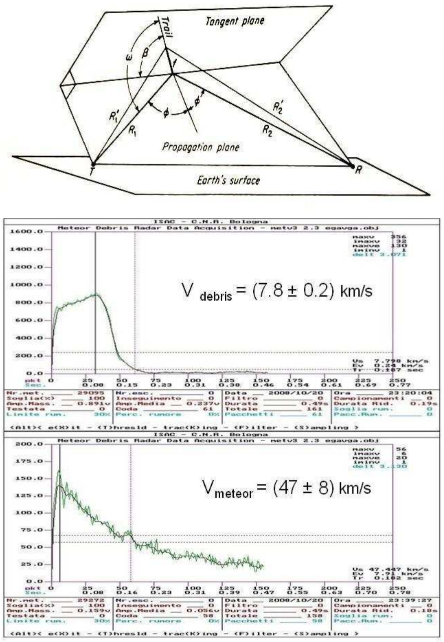

Fig. 2. (top) The geometry of a forward scatter system (f, the zone of maximum reflection of the signal). (bottom) Two radioechoes, the first from a space debris and the second from a meteoroid. Their different rise times (longer for the space debris) of the corresponding amplitude up to the maximum allow us to distinguish debris from meteoroid speeds.

The equations utilized to determine the debris/meteor speeds are (Cevolani et al. 2008):

$$V_r = \frac{1.35}{2\Delta t} \frac{F(R_1, R_2)}{\sin \omega} \tag{1}$$

where:

$$\begin{aligned} f &= \sqrt{\frac{\lambda R_1 R_2}{2(R_1+R_2)(1-\sin^2\varphi\cos^2\beta)}} = \frac{F(R_1,R_2)}{\sin\omega} \\ F(R_1, R_2) &= \sqrt{\frac{\lambda R_1 R_2}{2(R_1+R_2)}} \\ \cos\omega &= \cos\beta \sin\varphi \end{aligned} \tag{2}$$

A numerical program has been developed to simulate the debris/meteor entrance into the atmosphere as the output data of the 5-antenna interferometer shown in Fig. 1. Geometrical conditions of the system and gains of the transmitting and receiving antennas are considered. For geometrical conditions, the numerical simulation takes into account the following limitations: (i) conditions of the tangential point of the trail to an ellipsoid (foci are the positions of T and R); (ii) conditions of the height (the point of reflection is within the range 60-130 km);(iii) conditions of observability (the point must be visible from both T and R). With regard to antenna gains, the simulation considers some conditions for the antenna lobes. The gain of the combined transmitting and receiving antennas in bistatic systems has a maximum at the intersection of the main lobe of the antenna T and of the antenna R at the mid-path ($R_1 = R_2$), just at the 'hot-spots' (areas of the highest concentration of debris and meteors). The FS system is most sensitive to ionized trails which are nearly horizontal and directed along the transmission line (Forsyth & Vogan 1955). A trail perpendicular to the baseline (TR line) gives an echo that it is about five time lower than in the case of parallel direction and therefore, the choice of the reflecting point located closely to the mid-path appears justified by facts (Carbognani et al. 2000).

Fig. 3 shows different gain zones of the BL system at the two height extremes, i.e. for (top) h = 60 km and (bottom) h = 130 km (distance Bologna-Lecce d = 716 km, step = 5 km).

Maximum gain zones of the BL system are concentrated at lower heights. The radar cross section (rcs) displayed on a horizontal plane (XY) including the radar baseline, is estimated to be approximately of $10^4 km^2$. The program gives the distribution of 3000 echoes selected among 10.000 echoes, with respect to the intensity of the reflected signal (Fig. 4).

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 tangent to the propagation plane) = 0°-20°/ 160°-200°. Mean values

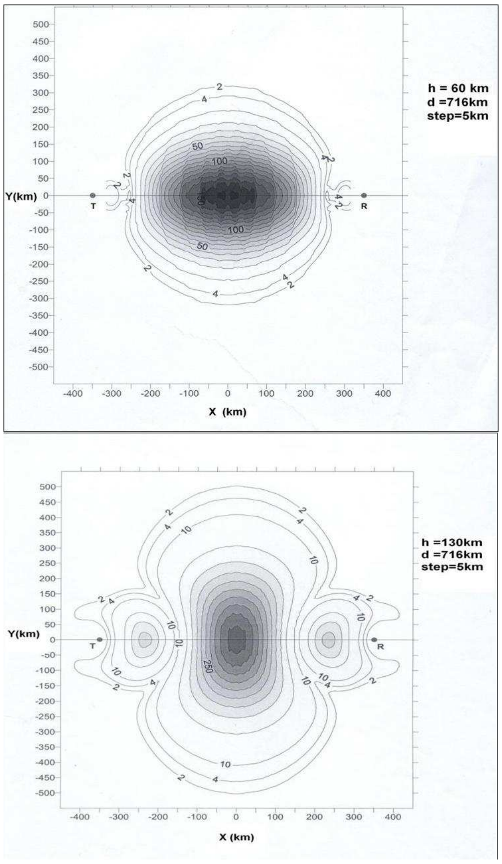

Fig. 3. Different gain zones of the BL system at the two height extremes, i.e.for (top) h = 60 km and (bottom) h = 130 km (distance Bologna-Lecce d = 716km, step = 5 km).

of $R_1 = R_2 = 370$ km, $\varphi = 75°$ and $\beta = 20°$ are included in equation (1) to determine speeds of debris and meteoroids.

Fig. 5 shows the distribution of the interferometric angles (top) φ and (bottom) β relative to the 3000 echoes, selected with respect to the intensity of the reflected signal.

3. Results

Monthly systematic campaigns of observations were conducted in 2009 and 2010. The set of monthly data for two complete years give primarily some highlights on contribution to the total influx of debris decaying into the atmo-

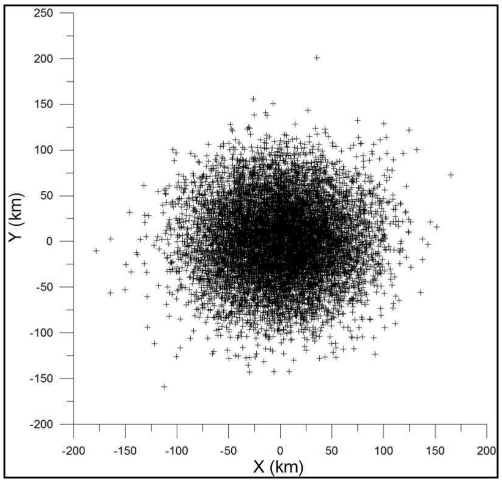

Fig. 4. Positions of 3000 echoes on a horizontal plane including the radar baseline, according to the simulation program. Only 30% of the total number was selected with respect to the intensity of the reflected signal. A Gaussian distribution of heights between 55 and 100 km (peaked at 75-80 km) is assumed.

sphere and moreover, on possible effects of the solar activity on the debris environment into the atmosphere, as evidenced recently for meteor background (Porubcan et al. 2009). Another interesting aspect is to investigate possible variations in different years of the frequency of atmospheric debris, after the last recent catastrophic events. For all periods of observations we have taken into account the number of hours of power interruption with respect to the total recording time. A comparison of the results for the two successive years is important because the recordings were performed while maintaining the same operating conditions. The echoes listed as natural and man-made objects in 2010 were a total of 334,429, a number close to 361,051 registered in 2009. Compared to 2009, observations of 2010 had a lower interruption percentage (about 2% in 2010 compared to 6% in 2009). It is interesting to examine the daily changes in the frequency of debris throughout the year in relation to the total flow, to ensure possible monthly and/or seasonal variations.

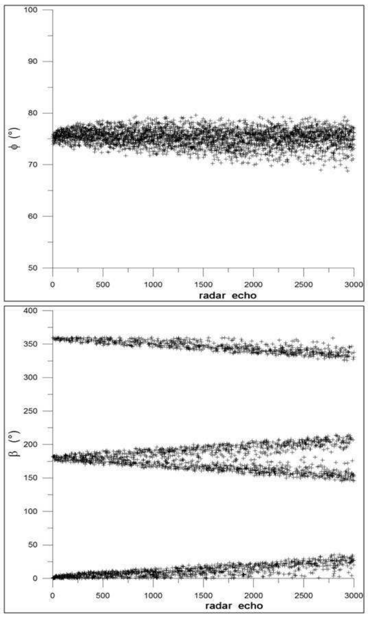

Fig. 5. Distribution of the interferometric angles (top) φ and (bottom) β relative to the 3000 echoes, selected with respect to the intensity of the reflected signal.

Fig. 6 shows values of the debris/total flux ratio recorded at Lecce (Italy) by the BL bistatic radar, together with the average calculated over the observational period, during (a) 11 - 29 April 2009 and (b) 03 - 15 April 2010. D/F mean values of about 6% and 8% are generally observed in spring of 2009 and 2010, respectively.

Fig. 7 shows values of the debris/total flux ratio recorded at Lecce (Italy) by the BL bistatic radar, together with the average calculated over the observational period, during (a) 17 - 28 July 2009 and (b) 06 - 15 July 2010. D/F mean values of about 8% and $11 - 12\%$ are generally observed in summer of 2009 and 2010, respectively.

Fig. 8 shows monthly cumulative fluxes of echoes (associated to meteoroids and debris) versus their duration, recorded at Lecce (Italy) by the BL radar system during (a) 07 - 23 November 2009 and (b) 15 - 25 November 2010. Theoretical curves of the fluxes are also

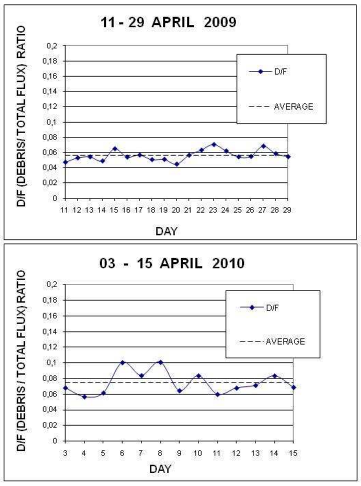

Fig. 6. Values of the debris/total flux ratio recorded at Lecce (Italy) by the BL bistatic radar, together with the average calculated over the observational period, during (top) 11 - 29 April 2009 and (b) 03 - 15 April 2010.

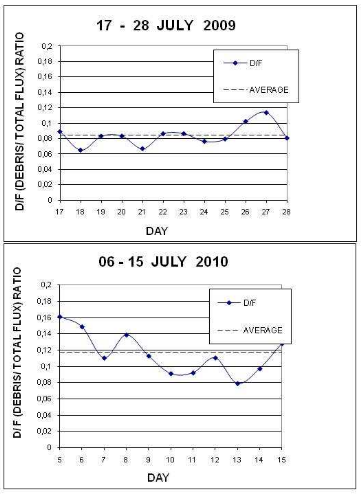

Fig. 7. Values of the debris/total flux ratio recorded at Lecce (Italy) by the BL bistatic radar, together with the average calculated over the observational period, during (top) 17 - 28 July 2009 and (bottom) 06 - 15 July 2010.

included to simulate the pattern of tiny particles (submillimetric size, mainly for space debris).

We found that the number of thin debris that produce shorter duration echoes (T = 0.1s, = 0.25s, = 0.5s) is lower than expected. This depends in large part by the rise time method used for the recognition of debris whose echoes have normally rise times of 100 - 600 ms . The larger number in proportion of debris at longer durations, may well depend on the material which forms the most compact debris (with respect to the elements usually lighter in an ordinary meteoroid), that prolongs the ablation time of the body. It must be realized that even if the acquisition system can monitor the echoes using a 'dynamic' threshold of noise able to adapt to the noise level, the system is able to interpret, at the shortest durations, the meteoric phenomenon better than the debris one.

Fig. 8 shows examples of correction at the shortest-duration echoes applied to the cumulative curves of meteoroids and debris, observed on (top) 07-23 November 2009 and (bottom) 15-25 November 2010. The theoretical curves obtained by using an exponential interpolation match the curve of the observed meteor flux for durations T > 0.25s and the curve of the debris flow for durations T > 1s.

Fig. 9 shows mean monthly percentages of debris/total flux in 2009 and 2010.

By examining the histograms of the mean debris / flux ratios during 2009 and 2010, we notice a general increase of ratios in the months of 2010 compared to the corresponding months of 2009, with the exception of September. In particular, with reference to the tests carried out in April and July for two years, in 2010 we observe an increase of $2-3\%$ compared to the corresponding values recorded in 2009. In spite of the consistency of the data collected

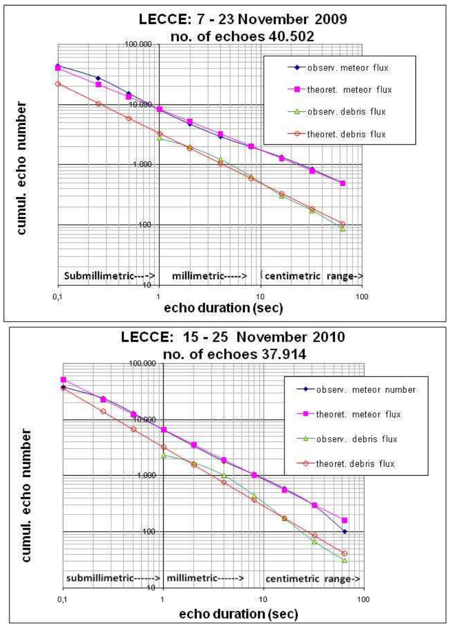

Fig. 8. Monthly cumulative fluxes of echoes (associated to meteoroids and debris) versus their duration, recorded at Lecce (Italy) by the BL radar system during (top) 07 - 23 November 2009 and (bottom) 15 - 25 November 2010. Theoretical curves of the fluxes are also included in order to simulate the pattern of tiny particles (submillimetric size, mainly for space debris).

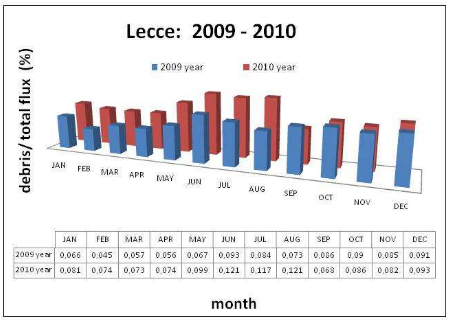

Fig. 9. Mean monthly percentages of debris/total flux in 2009 and 2010.

in the same instrumental conditions during the two years, only some preliminary conclusions can be drawn, such as: (1) monthly changes of D / F show a seasonal trend in the two years with a peak in summer and a minimum in spring; (2) annual changes of D / F related to the corresponding months show a significant increase in the mean values of 2010 compared to 2009. For the first point, we can refer to the atmospheric drag in LEO while for the second point, the production of additional fragments can be taken into account. The drag on the debris in low orbits around the Earth varies with the expansion and contraction of the atmosphere due to the effects induced by the solar activity. For the smallest debris, it should be taken into account the overall effect of the pressure of solar radiation that can alter their height distribution varying their orbital parameters (i.e., perigee). The input of the solar radiation is certainly higher in summer months with respect to the other months. Regarding the second aspect, the large number of additional fragments in LEO orbits after the recent catastrophic events, leads to a greater number of debris (especially in the submilli- and millimetric size) into the atmosphere. The higher values of D / F in 2010 could be connected with the presence of secondary fragments which represent an increase of more than 60% of the debris population in LEO. These supplementary fragments increases, not only the risk of debris impact on the population of resident fragments, but in addition, the instability of the overall debris population throughout effects of cascade collisions (Matney 2010).

4. Conclusions

Rise-time speeds of amplitudes prior to echo maximum allow us to discriminate small debris from meteoroids (Cevolani et al. 2008) and consequently, to calculate corresponding fluxes at different durations and dimensions. We found that the number of thin debris that produce shorter-duration echoes ($T < 0.5s$) is lower than expected. This depends in large part by the utilized method for the recognition of debris which have normally comparable rise times in the range of $100 - 600ms$. In this context, for meteoroids, there is a substantial agreement between the curves of observed fluxes and theoretical deductions, whereas for debris, the agreement exists only for milli- and centimetric bodies. Notwithstanding limitations of the acquisition system, the exponential extrapolation to submillimetric debris in theoretical curves can provide reliable information on the number of tiny debris decaying into the atmosphere. In spite of the consistency of the data gathered in 2009 and 2010, only preliminary conclusions can be drawn. Monthly changes of the debris/total flux (D/F) ratios show a seasonal trend in the two years with a peak in summer and a minimum in spring. A time evolution of space debris in the region 7-10km/s has been reported in meteor entrance speed determinations made with interferometric meteor radars (Hocking 2000). Annual changes of D / F related to the corresponding months show a significant increase in the average values of 2010 compared to 2009, possibly connected with the 24th solar activity cycle, peaking in 2012. (Porubcan et al. 2009) pointed out a significant influence of the solar activity on the observed increase in the meteor sporadic activity within the 23th solar cycle (1996-2007), as a possible consequence on the ionization state of the upper atmosphere.

Acknowledgements. The research is supported by the ASI Space Debris Project (N .I/046/07/1 contract).

References

Baggaley, J. & Grant, J. 2005, Earth, Moon, Planets, 95, 601
Carbognani, A. et al. 2000, Astron.Astrophys., 361, 293
Cevolani, G. et al. 2008, Mem.S.A.It.Suppl., 12, 39
Drolshagen, G. et al. 2008, in Proceedings of Meteoroids 2001 Conference, Kiruna, ESA SP-495, The Netherlands, 5533
Forsyth, P. A., & Vogan, E. L. 1955, 1998, Can.J.Phys., 33, 176
Hocking, W. K. 2000, Radio Science, 35, 1205
Matney, M. 2010, NASA ODQN, 14, 6
NASA 2009, ODQN, 13, 11
Porubcan, V. et al. 2009, Il Nuovo Cimento, 124B, 69
Verniani, F. 1974, J.Geophys.Res., 78, 8429