ANALYSIS OF THE CONSEQUENCES IN LOW EARTH ORBIT OF THE COLLISION BETWEEN COSMOS 2251 AND IRIDIUM 33

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ABSTRACT

On 10 February 2009, Cosmos 2251 and Iridium 33 collided in orbit at an altitude of about 790 km. It was the first accidental catastrophic collision between two intact objects, leading to the formation of two sizable debris clouds in the orbital region already most affected by previous launch activity and breakups. Having no specific information on the physical characteristics of the fragments, the ballistic parameter, based on decay calibrations, was estimated for five random samples of the fragments, three for Cosmos 2251 and two for Iridium 33, and the statistical inference method was then applied to infer the properties of the whole populations. In particular, it was found that both clouds presented a significant fraction of cataloged fragments with very high area-to-mass ratios, hundreds or thousands of times greater than those of intact satellites, leading to the conclusion that the generation of such orbital debris might be more common than formerly supposed. In an attempt to assess the impact of the collision on the low Earth environment, the clouds of cataloged debris were propagated for 100 years, taking into account the relevant orbit perturbations and the debris ballistic coefficient distributions based on orbit decay calibrations. It was found that a substantial fraction of the fragments will remain in space for several decades and approximately one century will be needed to remove most of the wreckage from orbit. Concerning, finally, the four Italian satellites operational in low Earth orbit (AGILE and three COSMO-SkyMed), as of the end of June 2009, the collision probability with cataloged objects had been increased by less than 10%.

1. INTRODUCTION

On 10 February 2009, at 16:56 UTC, two satellites collided at a geodetic altitude of 788.6 km above Siberia (latitude: 72.5°N; longitude: 97.9°E), generating two clouds of debris [1]. The relative impact velocity was about 11.6 km/s and approximately 1700 fragments had been detected and tracked by the US Space Surveillance Network (SSN) by the end of July 2009. Cosmos 2251 (COSPAR ID: 1993-036A; SSN Catalog Number: 22675) was a 900 kg Strela-2 Russian spacecraft used for military communications, decommissioned more than ten years earlier. Iridium 33 (COSPAR ID: 1997-051C; SSN Catalog Number: 24946) was instead an operational 560 kg spacecraft of the homonymous private constellation for worldwide voice and data communications using handheld satellite phones.

Even though in the past at least three unintentional hypervelocity impacts between cataloged objects had been documented in space, this was the first accidental catastrophic collision between two intact objects, leading to the formation of two sizable debris clouds in the orbital region already most affected by previous launch activity and fragmentation events (Fig. 1). As of 23 July 2009, 1182 fragments of Cosmos 2251, with inclinations in between 73.6° and 74.3° and altitudes in between 246 and 1707 km, and 504 fragments of Iridium 33, with inclinations in between 85.6° and 86.6° and altitudes in between 389 and 1485 km, had been detected [2]. Of these, 30 Cosmos 2251 and 16 Iridium 33 cataloged fragments had already reentered in the atmosphere [3].

Immediately after the impact, the fragments produced, depending on the velocity variation imparted, were scattered in various orbits sharing the collision point. Each of the two debris clouds maintained orbital planes close to the original ones, but a significant spread in altitude, both above and below the collision height, was generated approximately 180° away from the collision "pinch" point, i.e. over the Antarctic region. However, the orbital perturbations progressively spread out the clouds around the Earth in the following months (Fig. 2), both in right ascension of the ascending node and argument of perigee, gradually creating two new shells of debris around the planet.

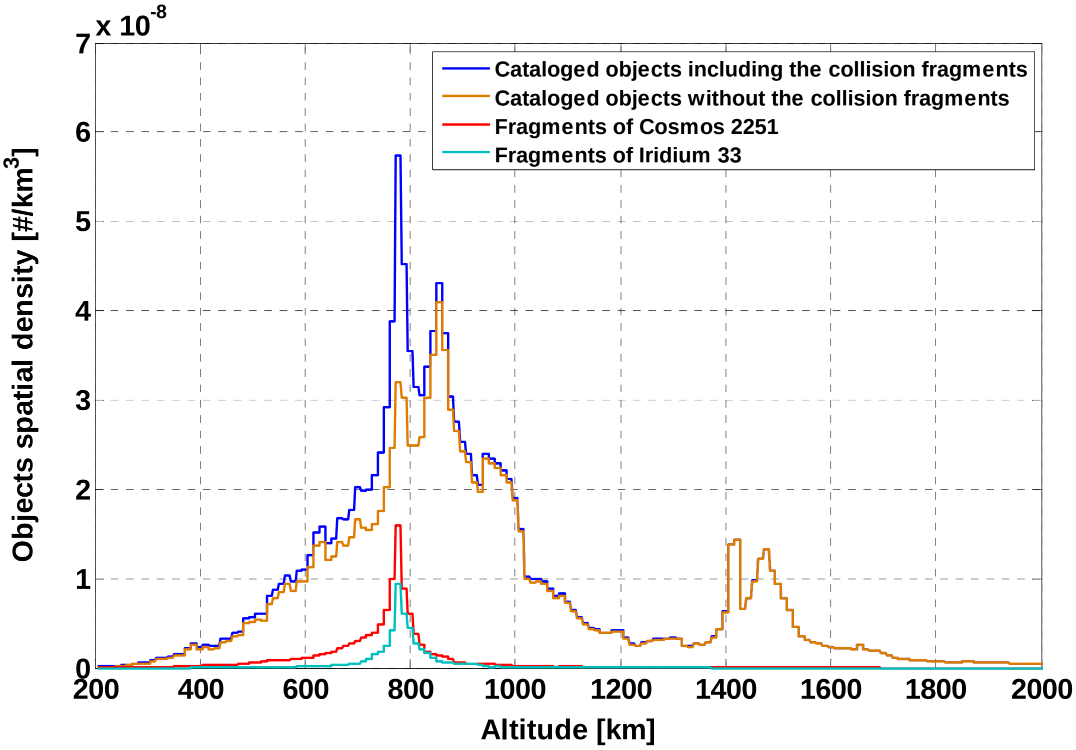

Fig. 1. Cataloged orbital debris spatial density in LEO, with and without the fragments of the collision between Cosmos 2251 and Iridium 33 (end of June 2009).

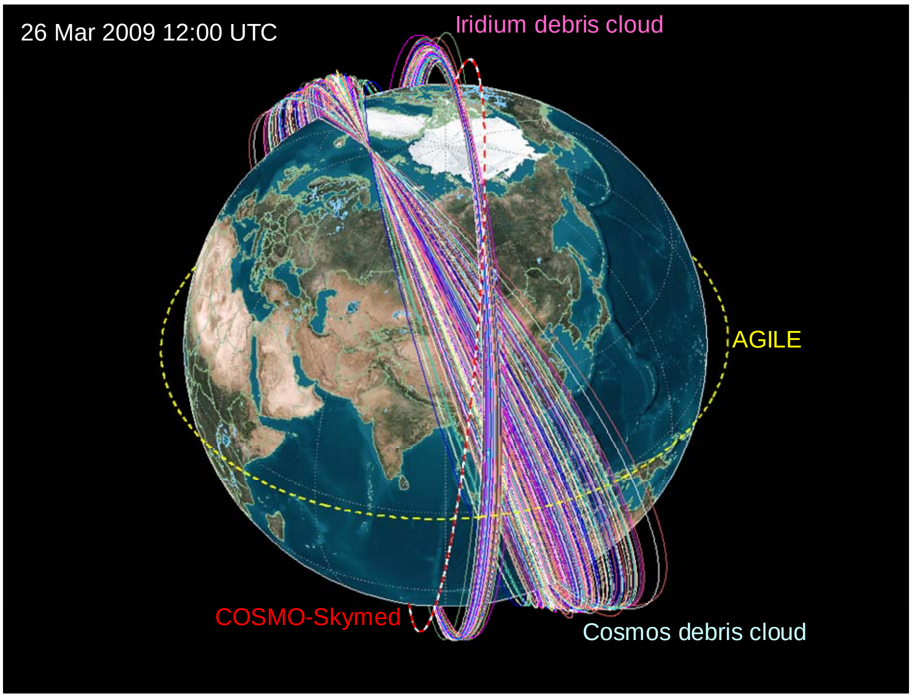

Fig. 2. Orbital dispersion of the two debris clouds 44 days after the collision. The orbits of the ASI spacecraft in LEO, AGILE and the COSMO-SkyMed constellation, are represented as well.

The purpose of the work described in this paper was to analyze the long-term evolution of the new debris clouds and their consequences on the orbital debris environment and the functioning spacecraft in Low Earth Orbit (LEO). In particular, the increase of the collision risk with cataloged objects for the satellites of the Italian Space Agency (ASI) operational in LEO was evaluated. For instance, considering the flux of cataloged objects before the collision, 16 debris close approaches at less than 1 km should have been expected, on average, every year for each satellite of the COSMO-SkyMed constellation. This means an average of 64 conjunctions per year at less than 1 km for the four spacecraft of the complete system [4]. The new debris added by the recent collision required an updated conjunction and collision probability assessment, in order to evaluate if operational changes had to be implemented in the future to cope with the additional impact risk.

2. CHARACTERIZATION OF THE COLLISIONAL DEBRIS PROPERTIES

Knowledge of the ballistic parameter and orbit of each fragment was needed in order to assess the evolution of the two debris clouds generated by the accidental collision. For the cataloged debris, for which a reasonably accurate orbit was available, the simplest approach would have been to compute the ballistic parameter B, defined as

$$B = C_D \cdot A/M \tag{1}$$

where C_D, A and M are, respectively, the fragment drag coefficient, cross-sectional area and mass, using the “BSTAR” (B^*) value of the Two Line Elements (TLEs) issued by SSN [5]. In fact, according to the TLEs orbital theory, the ballistic parameter B could be obtained from B^* in the following way [6]:

$$B = 12.741621 B^* \text{ m}^2/\text{kg}. \tag{2}$$

However, the underlying orbital theory leading to the generation of TLEs considers an atmospheric model that does not vary with solar activity, i.e. a model with a fixed density at any given height, by fitting the observed orbital decay with an appropriate value of the parameter B^*. Therefore, during periods of low solar activity, and correspondingly lower than average atmospheric densities at the altitudes of interest, such as during the months of 2009 following the collision among Cosmos 2251 and Iridium 33, the values of B^* are smaller than average and the corresponding ballistic parameters obtained from Eq. 2 might be systematically underestimated, even by a large amount.

Much more accurate values of B could be determined by analyzing the observed orbital decay of each fragment over relatively long time spans. However, due to the large amount of debris produced, this would have required too great an effort in terms of computational time and dedicated resources. Therefore, representative samples of the objects were selected and analyzed in detail.

As a consequence of the perigee (P_H) distribution of the Cosmos 2251 fragments, initially much more dispersed with respect to the Iridium 33 ones, three altitude shells were selected: 200 km $\leq P_H \leq$ 450 km, 450 km $< P_H <$ 750 km and $P_H \geq$ 750 km. In each of the shells, approximately 10% of the cataloged fragments were randomly sorted out and their ballistic parameters were directly determined by fitting, in a least squares sense, the semi-major axis decay inferred from the TLEs acquired over a period of about 45 days. In order to obtain a set of scaling factors mapping the values of B^* into the actual ballistic parameters, for each object the fitted ballistic parameter was compared with the value of B obtained by applying Eq. 2 to the average B^*, i.e. the arithmetic mean of the values of B^* determined by SSN over the same time interval used for the fit. Exactly the same analysis was carried out for the Iridium 33 fragments, but due to their lesser initial perigee height dispersion, the altitude intervals considered, in which to sort out approximately 10% of the objects, were only two: 450 km $< P_H <$ 750 km and $P_H \geq$ 750 km.

For all the five Cosmos 2251 and Iridium 33 debris samples, a mean scaling factor and its standard deviation were computed. Then, assuming a Gaussian distribution, with the mean and standard deviation thus found, randomly generated *B* scaling factors were applied to all fragments belonging to the appropriate perigee altitude interval. By merging the resulting populations, three for Cosmos 2251 and two for Iridium 33, the rescaled ballistic parameters of the whole debris clouds were eventually obtained.

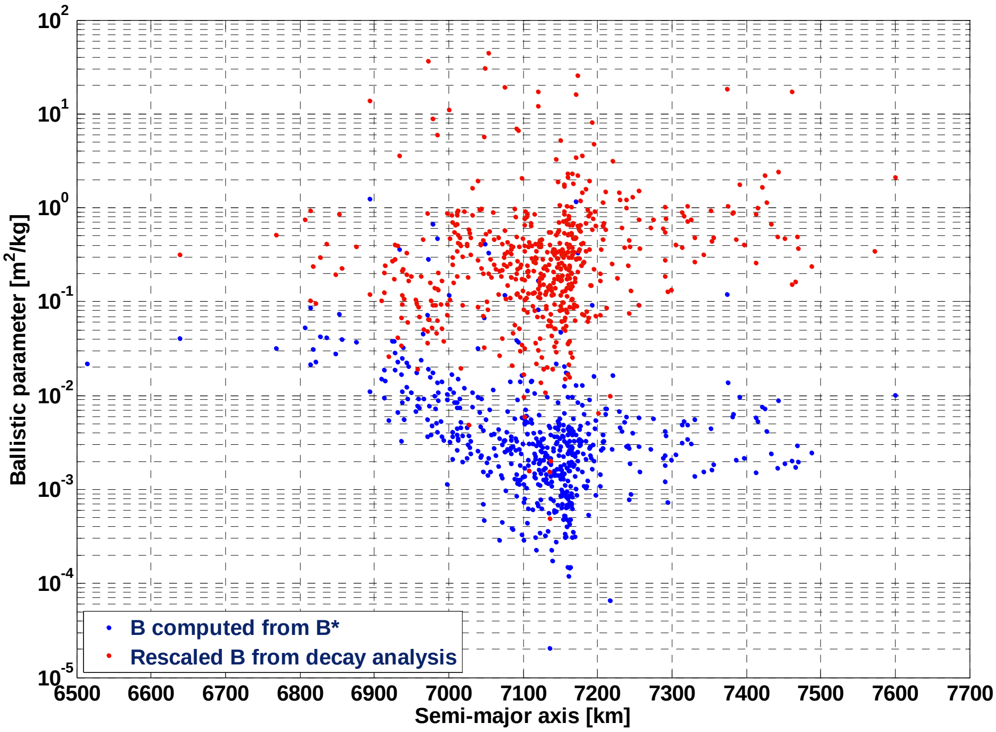

Fig. 3. Ballistic parameters of the Cosmos 2251 cataloged fragments, as of 1 April 2009.

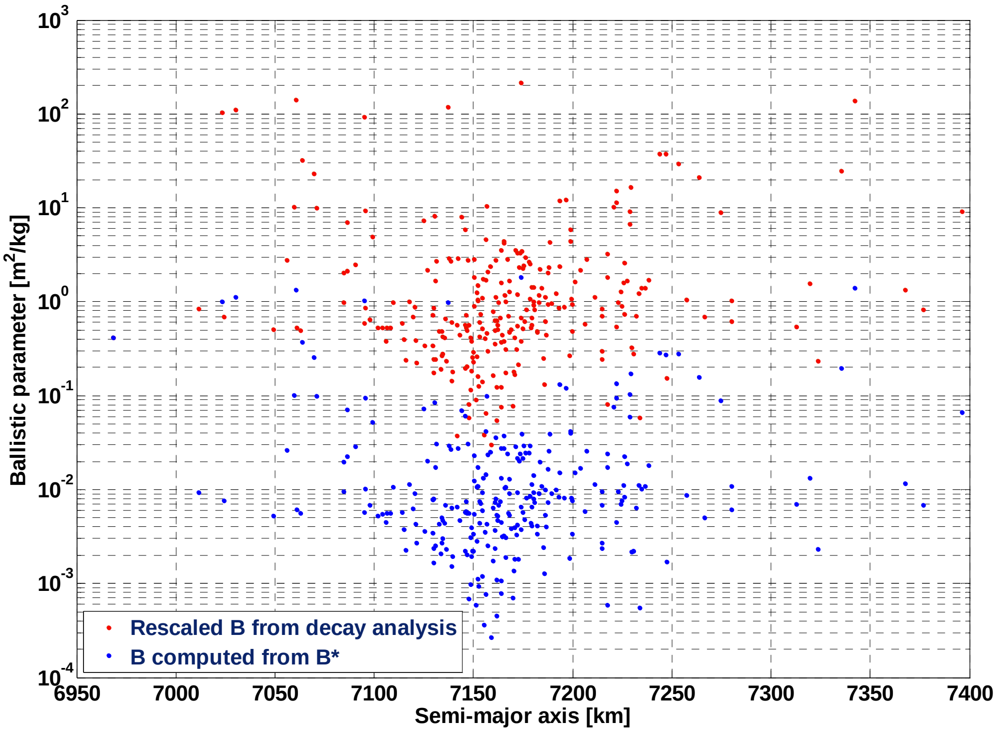

Fig. 4. Ballistic parameters of the Iridium 33 cataloged fragments, as of 1 April 2009.

The distribution of the rescaled ballistic parameters as a function of semi-major axis, compared with the values computed with Eq. 2, is shown in Fig. 3 for Cosmos 2251 and in Fig. 4 for Iridium 33. As expected, the values obtained from B^* were significantly underestimated (by almost two orders of magnitude) in these cases, characterized by conditions of minimum solar activity. The corresponding logarithmic area-to-mass ratio distributions of the fragments, assuming $C_D = 2.2$, are represented in Figs. 5 and 6, respectively. Having adopted the Jacchia-Roberts 1971 density model to calibrate the ballistic parameters, by fitting the sample debris orbital decay, and that Jacchia developed his models, based on satellite decay analyses, by assuming $C_D = 2.2$, i.e. the "standard" value adopted by King-Hele [7], it might be expected that the rescaled values plotted in Figs. 5 and 6 would indeed exhibit a realistic average *A/M* distribution of the fragments.

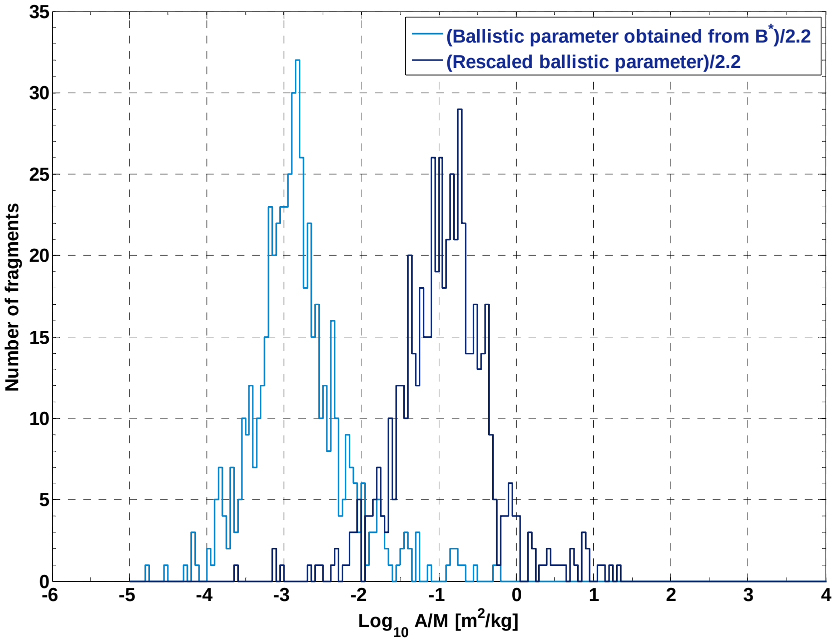

Fig. 5. *A/M* distributions of the Cosmos 2251 cataloged fragments, as of 1 April 2009.

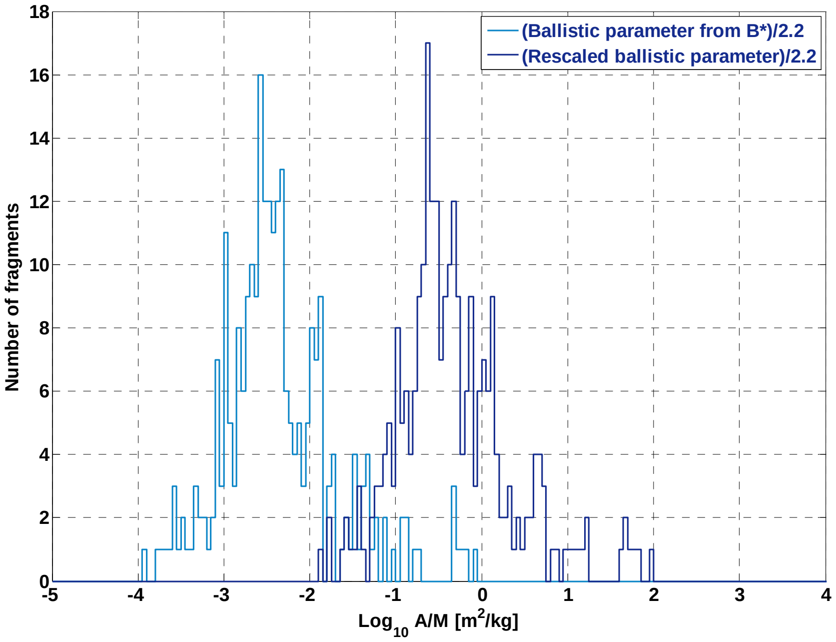

Fig. 6. *A/M* distributions of the Iridium 33 cataloged fragments, as of 1 April 2009.

As shown more clearly in Figs. 7 and 8, both *A/M* distributions present a significant number of objects with average *A/M* ≥ 1 m^2/kg [8] [9], that is with very high area-to-mass ratios, similar to those of a debris population discovered a few years ago in geosynchronous orbits [10] [11] [12]. In particular, in the case of Cosmos 2251 (Fig. 7), it was found that about 5% of the cataloged fragments had average *A/M* ≥ 1 m^2/kg and slightly more than 1% had average *A/M* ≥ 10 m^2/kg. Very similar results (Fig. 9) had been previously obtained with a statistical decay analysis of the Fengyun 1C debris, produced by the Chinese anti-satellite test carried out on 11 January 2007 [8] [9] [13]. However, a quite larger fraction of high *A/M* objects was obtained in the Iridium 33 case (Fig. 8), leading to a faster debris decay rate: 26% of the cataloged fragments resulted to have, in fact, average *A/M* ≥ 1 m^2/kg and 5% had average *A/M* ≥ 10 m^2/kg [9].

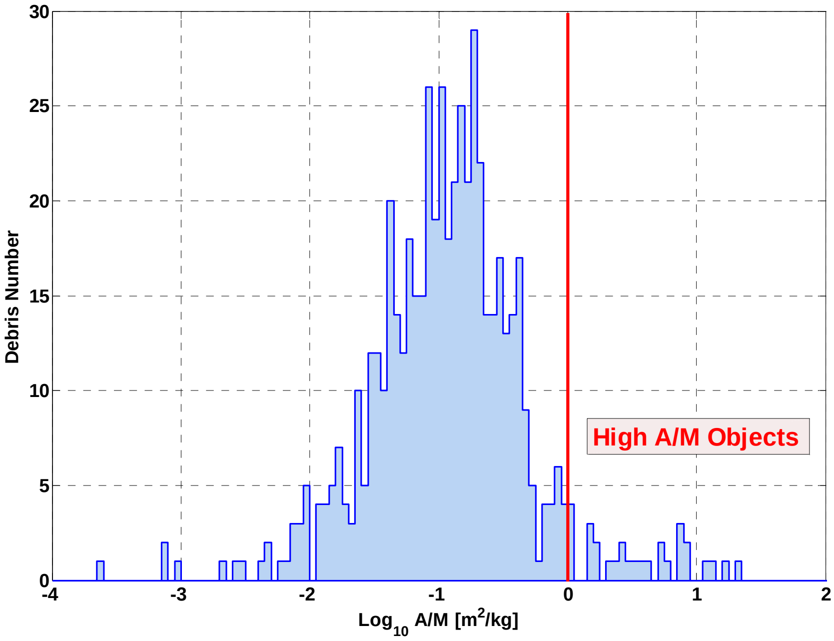

Fig. 7. *A/M* distribution of the Cosmos 2251 cataloged fragments deduced from decay analysis.

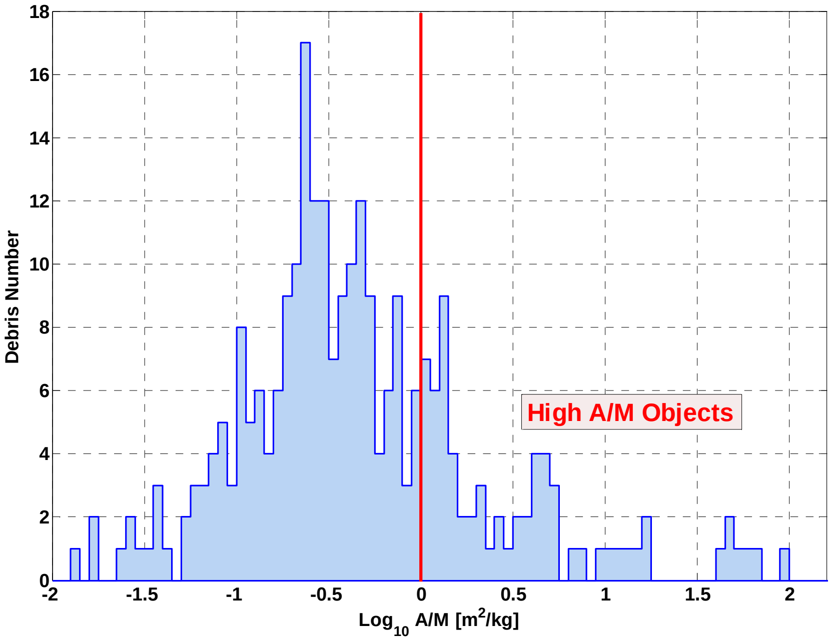

Fig. 8. *A/M* distribution of the Iridium 33 cataloged fragments deduced from decay analysis.

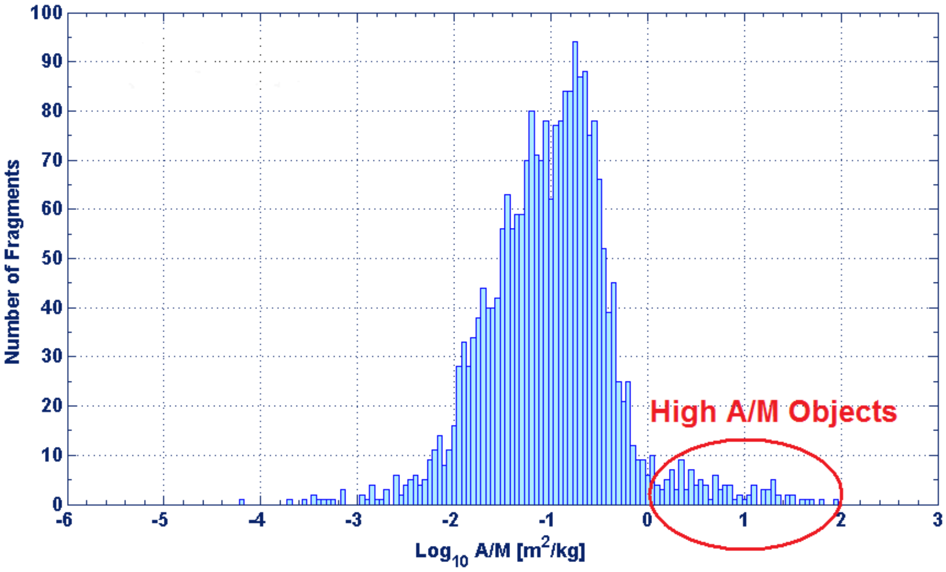

Fig. 9. *A/M* distribution of the Fengyun 1C cataloged fragments deduced from decay analysis.

Therefore, the generation of trackable orbital debris with average *A/M* hundreds or thousands of times greater than those of intact satellites might be more common than previously supposed, being one of the standard consequences of fragmentation events, both at high and low energy, involving, for instance, spacecraft or rocket bodies with multi-layered insulation blankets or other low density composite materials.

In order to infer the characteristics of the two clouds of fragments, deduced from the five random debris samples, three for Cosmos 2251 and two for Iridium 33, the statistical inference method was applied.

Concerning Cosmos 2251, for the sample with 200 km ≤ P_H ≤ 450 km, the mean ($\mu_{200 \leq PH \leq 450}$) of the scaling factors (i.e. the ratios between the rescaled ballistic parameter based on the orbital decay fit and the ballistic parameter computed from B^*) was 10.12. The corresponding standard deviation ($\sigma_{200 \leq PH \leq 450}$) was 4.82. By applying the statistical inference, $P(5.12 < \mu_{200 \leq PH \leq 450} < 15.12) = 0.99$ was obtained, i.e. a probability P of 99% of finding the mean of the overall population of objects with 200 km ≤ P_H ≤ 450 km in between 5.12 and 15.12. Then, using the χ^2 distribution for the given 99% confidence level, the confidence interval where the standard deviation for all the objects with 200 km ≤ P_H ≤ 450 km would lie was $3.11 < \sigma_{200 \leq PH \leq 450} < 13.71$.

Similarly, for the sample of objects with 450 km < P_H < 750 km, the mean ($\mu_{450 < PH < 750}$) of the scaling factors was 98.59. The corresponding standard deviation ($\sigma_{450 < PH < 750}$) was 51.08. By applying the statistical inference, $P(73.59 < \mu_{450 < PH < 750} < 123.59) = 0.99$ was obtained, i.e. a probability P of 99% of finding the mean of the overall population of objects with 450 km < P_H < 750 km in between 73.59 and 123.59. Then, using the χ^2 distribution for the given 99% confidence level, the confidence interval where the standard deviation for all the objects with 450 km < P_H < 750 km would lie was $39.45 < \sigma_{450 < PH < 750} < 75.28$.

Finally, for the sample of objects with P_H ≥ 750 km, the mean ($\mu_{PH \geq 750}$) of the scaling factors was 188.34 and the standard deviation ($\sigma_{PH \geq 750}$) was 84.62. By applying the methods of statistical inference, it was found $P(123.34 < \mu_{PH \geq 750} < 253.34) = 0.99$ and the 99% confidence interval where the standard deviation would lie was $58.98 < \sigma_{PH \geq 750} < 167.51$.

Concerning Iridium 33, for the sample with 450 km < P_H < 750 km, the mean ($\mu_{450 < PH < 750}$) of the scaling factors was 94.77. The corresponding standard deviation ($\sigma_{450 < PH < 750}$) was 7.39. By applying the methods of statistical inference, it was found $P(88.77 < \mu_{450 < PH < 750} < 102.77) = 0.99$ and the 99% confidence interval where the standard deviation would lie was $4.77 < \sigma_{450 < PH < 750} < 21.02$.

Lastly, for the sample with $P_H \geq 750$ km, the mean ($\mu_{PH \geq 750}$) of the scaling factors was 115.14 and the standard deviation ($\sigma_{PH \geq 750}$) was 20.07. By applying the methods of statistical inference, it was found $P(100.14 < \mu_{PH \geq 750} < 130.14) = 0.99$ and the 99% confidence interval where the standard deviation would lie was $13.99 < \sigma_{PH \geq 750} < 39.72$.

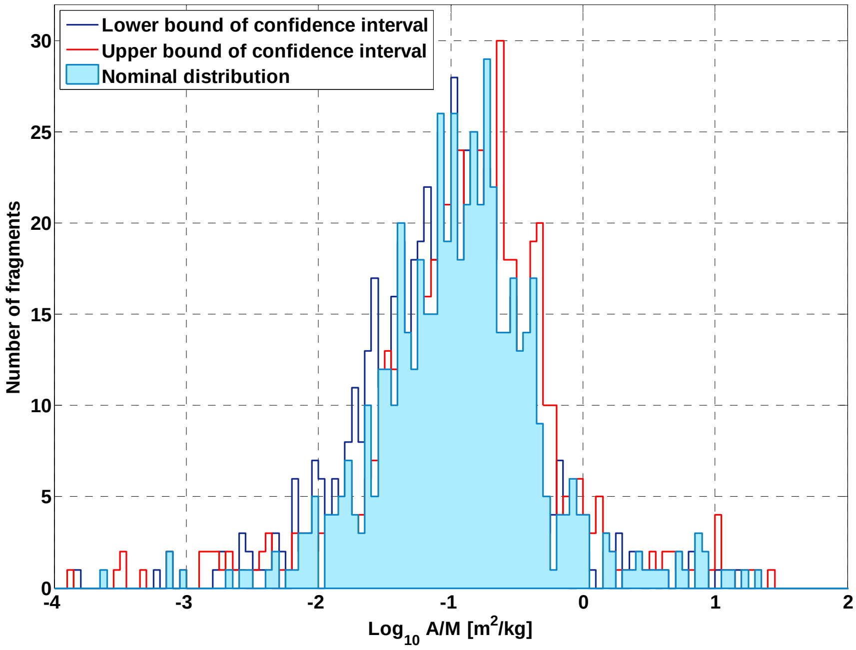

Fig. 10. Comparison of the *A/M* distributions of the Cosmos 2251 cataloged fragments obtained by considering the lower, medium and upper values of the 99% confidence intervals of the mean and the standard deviation.

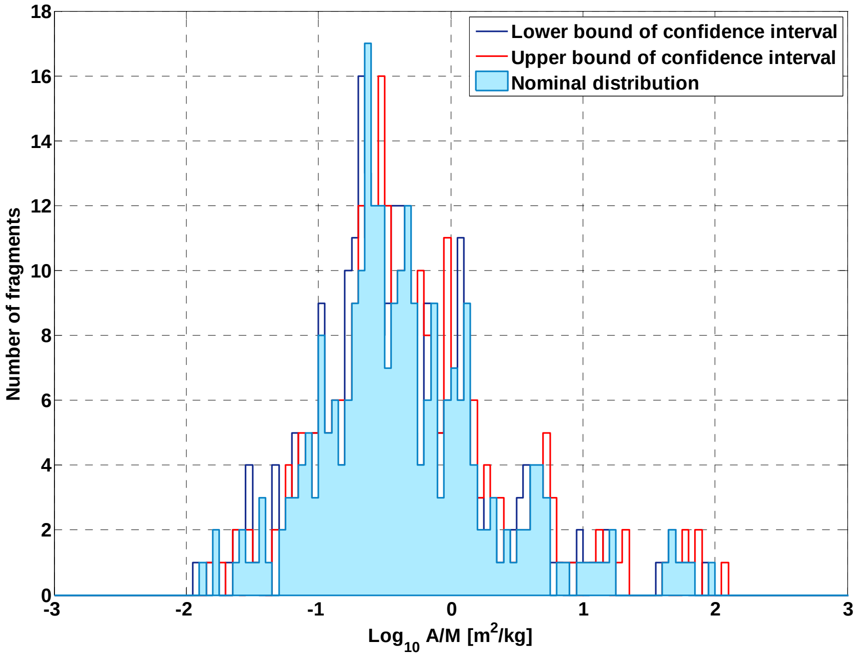

Fig. 11. Comparison of the *A/M* distributions of the Iridium 33 cataloged fragments obtained by considering the lower, medium and upper values of the 99% confidence intervals of the mean and the standard deviation.

By merging the various populations, three for Cosmos 2251 and two for Iridium 33, the distributions of the rescaled ballistic parameters were then obtained relative to the average scaling factor and standard deviation (nominal case), as well as to the bounds of their 99% confidence intervals. Figs. 10 and 11 show, for Cosmos 2251 and Iridium 33, respectively, the shift with respect to the nominal average *A/M* distribution of the two distributions obtained by using the lower and upper bounds of the 99% confidence intervals of the mean and the standard deviation. It should be noted that there is no appreciable difference between the three distributions. Therefore, from a statistical point of view, the nominal rescaled ballistic parameters seem to be appropriate for characterizing the aerodynamic properties of the Cosmos 2251 and Iridium 33 debris clouds.

3. DEBRIS CLOUDS EVOLUTION

The cataloged fragments of the collision between Cosmos 2251 and Iridium 33, for which a rescaled ballistic parameter had been computed, were individually propagated with the last version of a numerical code [14], taking into account the most important perturbations, namely the Earth's gravity field harmonics, up to the 5th order and degree, air drag, luni-solar third body attraction and solar radiation pressure with eclipses. To estimate the effects of air drag, the Jacchia-Roberts 1971 density model was adopted, together with the National Oceanic and Atmospheric Administration (NOAA)/Space Weather Prediction Center (SWPC) forecasts of the planetary geomagnetic index and the 10.7 cm solar flux proxy [15]. The solar flux predictions were based on an average of the International Space Environment Service (ISES) panel forecasts for solar cycle 24, as of 6 April 2009, valid until 31 December 2015. Fig. 12 shows the predicted 10.7 cm solar flux. Besides the nominal cycle, the maximum and minimum forecasts, both based on the predictions of the ISES solar cycle 24 panel, are also represented.

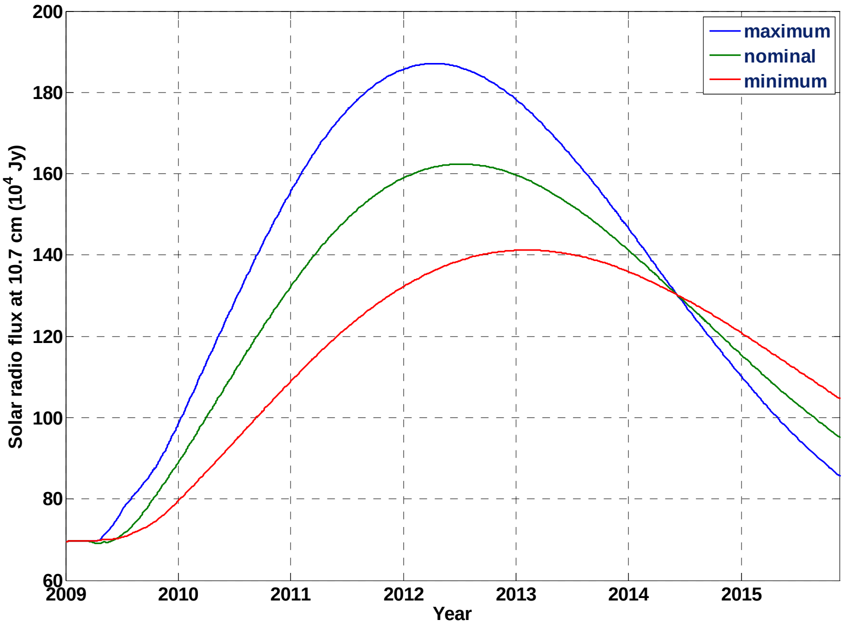

Fig. 12. Solar radio flux at 10.7 cm predictions for cycle 24.

The results obtained in the time span covered by the current solar cycle 24 forecasts are presented in Figs. 13 and 14, for the debris clouds of Cosmos 2251 and Iridium 33, respectively. The evolution, in terms of percentage of fragments left in orbit, will depend, of course, on the expected solar flux (minimum, nominal or maximum) and the actual average *A/M* distribution. However, the uncertainty associated with the solar flux predictions affected the Iridium 33 cloud evolution significantly more than the uncertainty associated with the *A/M* distribution, while their mutual impact was roughly comparable in the case of the Cosmos 2251 cloud. Anyway, it was found that, by the end of 2015, the percentage of Cosmos 2251 cataloged fragments still in orbit will be in between 42% and 70%, while the percentage of Iridium 33 cataloged fragments in space will be in between 21% and 52%, confirming the higher decay and reentry rate of the Iridium 33 debris, generally characterized by a greater area-to-mass ratio (Figs. 10 and 11).

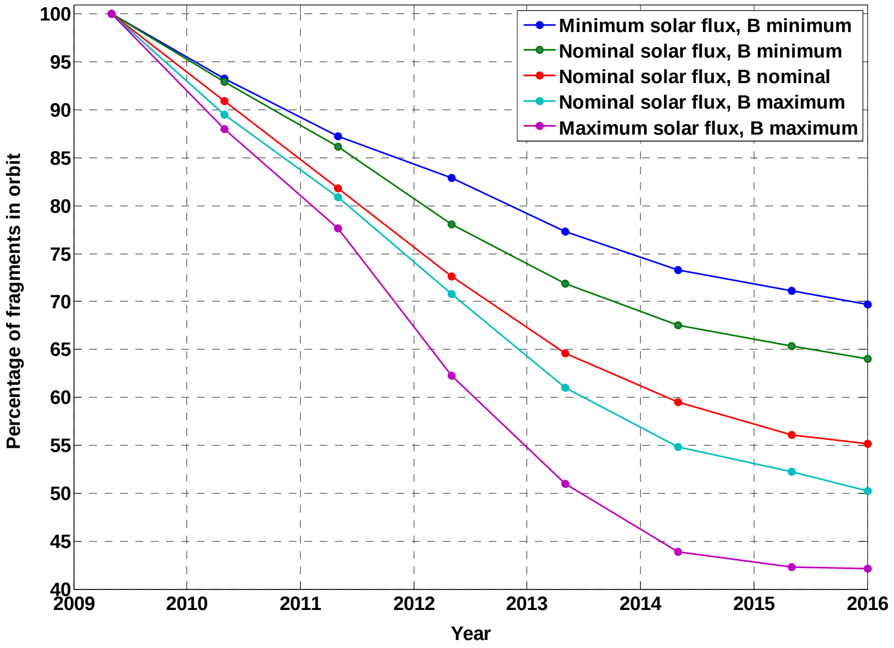

Fig. 13. Evolution of the Cosmos 2251 debris cloud during solar cycle 24, as a function of solar flux prediction (Fig. 12) and ballistic parameter distribution (lower, medium and upper values of the 99% confidence intervals of the mean and the standard deviation).

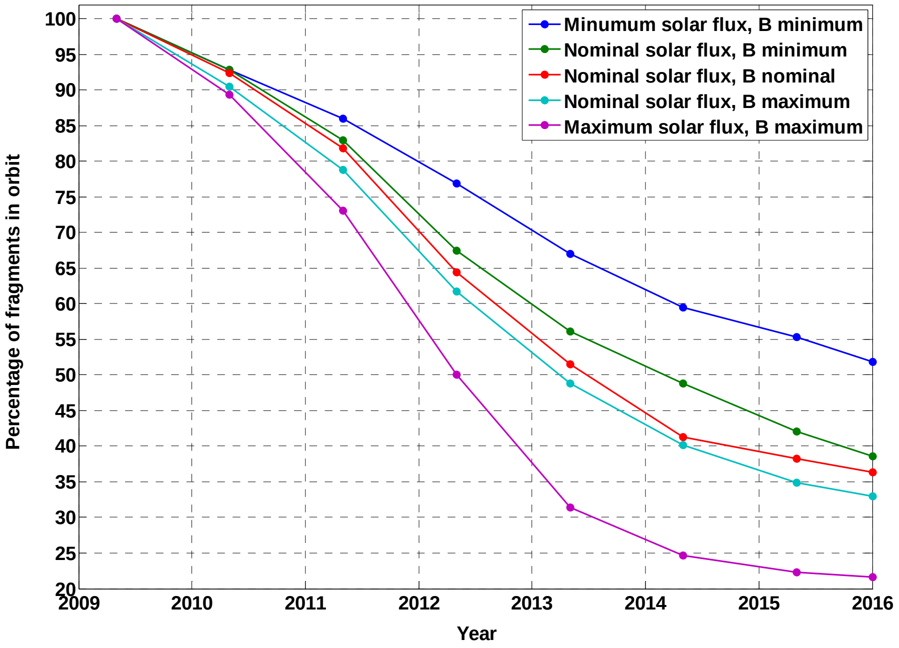

Fig. 14. Evolution of the Iridium 33 debris cloud during solar cycle 24, as a function of solar flux prediction (Fig. 12) and ballistic parameter distribution (lower, medium and upper values of the 99% confidence intervals of the mean and the standard deviation).

In order to evaluate the debris clouds evolution during one century, all the cataloged fragments were individually propagated for 100 years, with the same models and assumptions previously described. However, in this case the predicted solar flux available on the Inter-Agency Space Debris Coordination Committee (IADC) Common Database [16] was adopted (Fig. 15) and only the mean ballistic parameter distributions for the Cosmos 2251 and Iridium 33 fragments were considered.

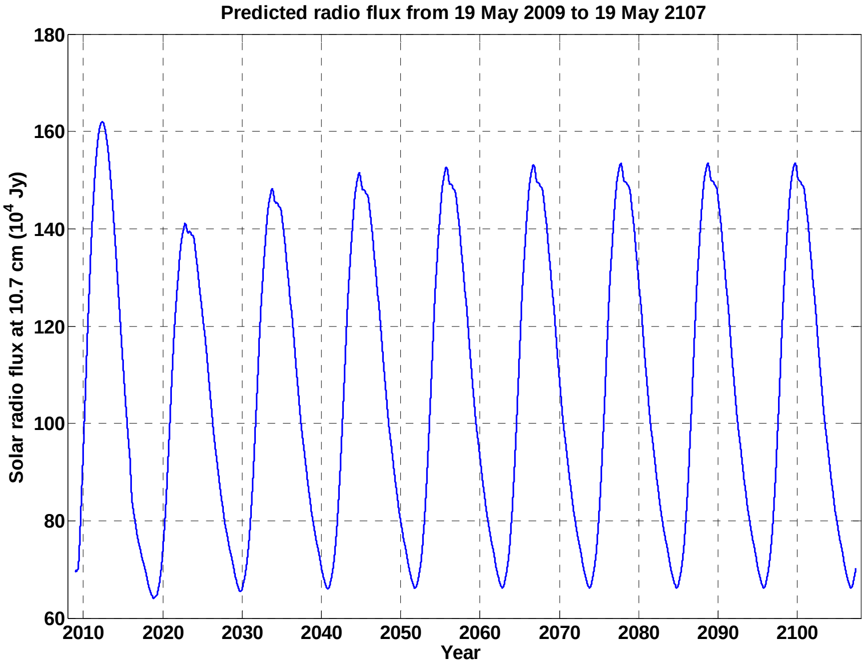

Fig. 15. Solar radio flux predictions for one century.

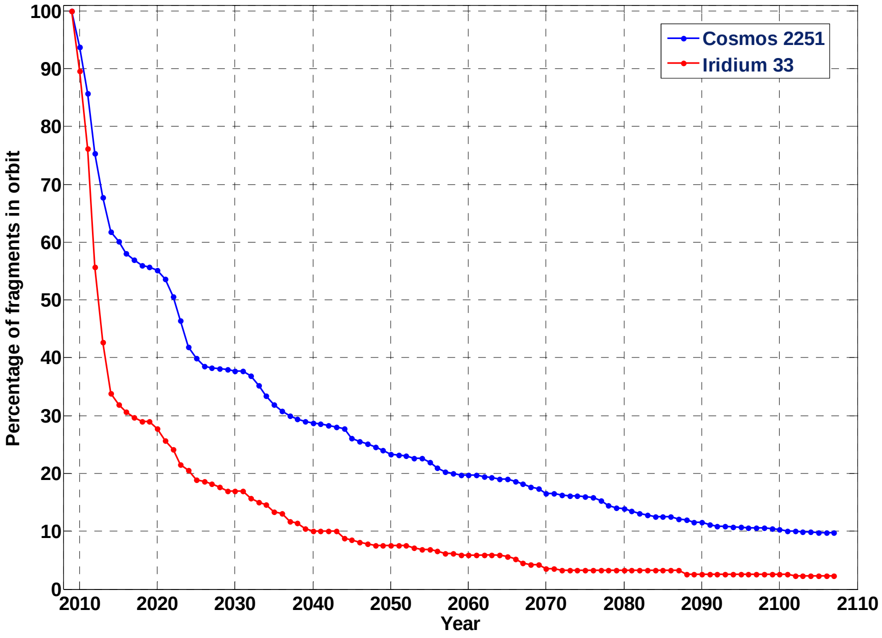

Fig. 16. Evolution of the Cosmos 2251 and Iridium 33 debris clouds during one century, with nominal solar flux prediction and mean ballistic parameter distributions.

The results obtained, again in terms of percentage of fragments left in orbit, are presented in Fig. 16. They confirmed the quite faster decay of the Iridium 33 debris cloud, with 90% of the cataloged fragments left in orbit in 2010, 50% in 2013, 10% in 2040 and 3% after one century. Concerning the Cosmos 2251 debris cloud, the corresponding figures were 90% of the cataloged fragments left in orbit in 2011, 50% in 2022 and 10% after one century. Therefore, the adverse effects of the accidental satellite collision on the LEO environment will be felt for several decades, being needed approximately one century to sweep most of the wreckage from orbit.

4. IMPACT RISK ASSESSMENT FOR THE ASI SATELLITES IN LEO

A software tool specifically developed for orbital debris impact risk assessment [17] [18] was used to estimate the additional impact flux of the Cosmos 2251 and Iridium 33 cataloged debris on the spacecraft of the Italian Space Agency in LEO, at the reference epoch of 29 June 2009. The satellites were: AGILE, an astrophysical spacecraft in low equatorial orbit (altitude: 522 × 551 km; inclination: 2.47°) and COSMO-SkyMed 1, 2 and 3, three sun-synchronous remote sensing spacecraft (of a constellation of four), put on the same orbital plane (altitude: 622 × 623 km; inclination: 97.86°).

Ignoring the objects generated by the collision, the flux of cataloged debris on AGILE was found to be 1.62×10^{-6} m^{-2} per year, with an average collision velocity of 10.234 km/s. The inclusion of the Cosmos 2251 and Iridium 33 cataloged debris increased the flux by 9.5%, to 1.78×10^{-6} m^{-2} per year. The average collision velocity slightly decreased, instead, to 10.186 km/s, due to the relative geometry of the new flux. This is made clear in Fig. 17, showing the cross-sectional area flux as a function of the relative velocity of the incoming debris. Due to the orbit geometry and debris distribution, the collisional flux is dominated by objects in high inclination orbits crossing the equatorial region where AGILE resides.

Concerning the three satellites of the COSMO-SkyMed constellation, the flux of cataloged debris was found to be 5.01×10^{-6} m^{-2} per year, with an average collision velocity of 13.088 km/s, disregarding the objects generated by the collision among Cosmos 2251 and Iridium 33. The inclusion of the cataloged collisional debris increased the flux by 8.6%, to 5.44×10^{-6} m^{-2} per year. On the other hand, even in this case the average collision velocity slightly decreased to 12.895 km/s, due to the relative geometry of the new flux. Fig. 18, showing the cross-sectional area flux as a function of the relative velocity of the incoming debris, confirms this fact. It is clear that, due to the orbit geometry (sun-synchronous) and debris distribution, the collisional flux is dominated by objects in high inclination orbits moving approximately in the opposite direction to the spacecraft. This explains the high value of the average collision velocity.

In conclusion, at the end of June 2009, the wreckage of Cosmos 2251 and Iridium 33 had increased by less than 10% the collision probability with cataloged debris of the AGILE and COSMO-SkyMed satellites of the Italian Space Agency.

5. CONCLUSIONS

The first accidental catastrophic collision in orbit between two intact objects led to the formation of two sizable debris clouds in the circumterrestrial region already most affected by previous launch activity and breakups. This event significantly increased the amount of debris in LEO and a substantial fraction of it will remain in space for several decades. Approximately one century of atmospheric drag will be needed to remove most of the wreckage from orbit.

An obvious consequence of the collision was to significantly increase the probability of collision between intact objects, i.e. spacecraft and upper stages, and man-made debris. However, for the four ASI satellites operational in LEO, the collision probability with cataloged objects had been increased by less than 10%, as of the end of June 2009.

Having no specific information on the physical properties of the fragments resulting from the collision, it was necessary to introduce a number of assumptions to simulate the evolution of the resulting debris clouds. The ballistic parameter, based on decay calibrations, was estimated for five random samples of the fragments, three for Cosmos 2251 and two for Iridium 33, and the statistical inference method was then applied to infer the characteristics of the whole populations.

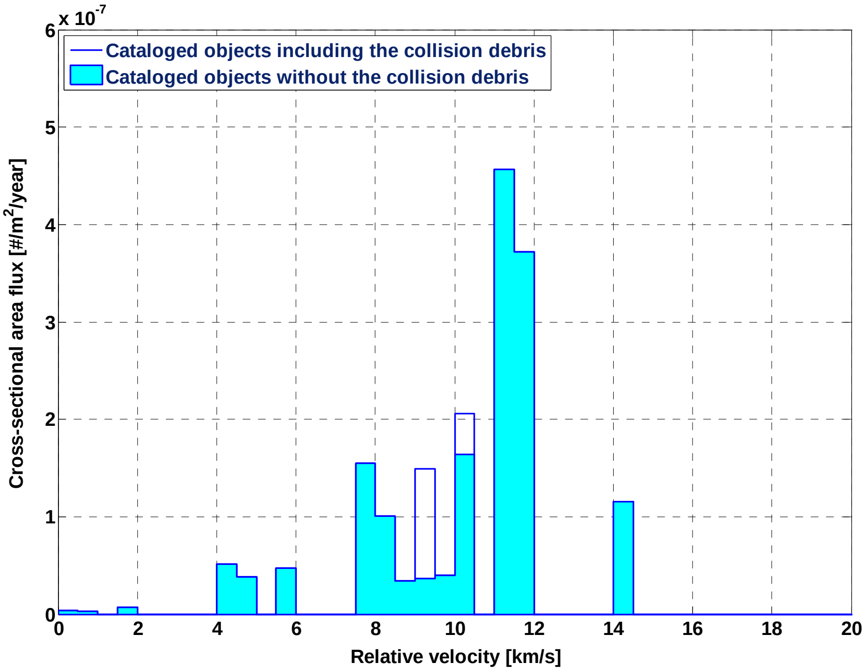

Fig. 17. AGILE: cross-sectional area flux as a function of the incoming debris relative velocity.

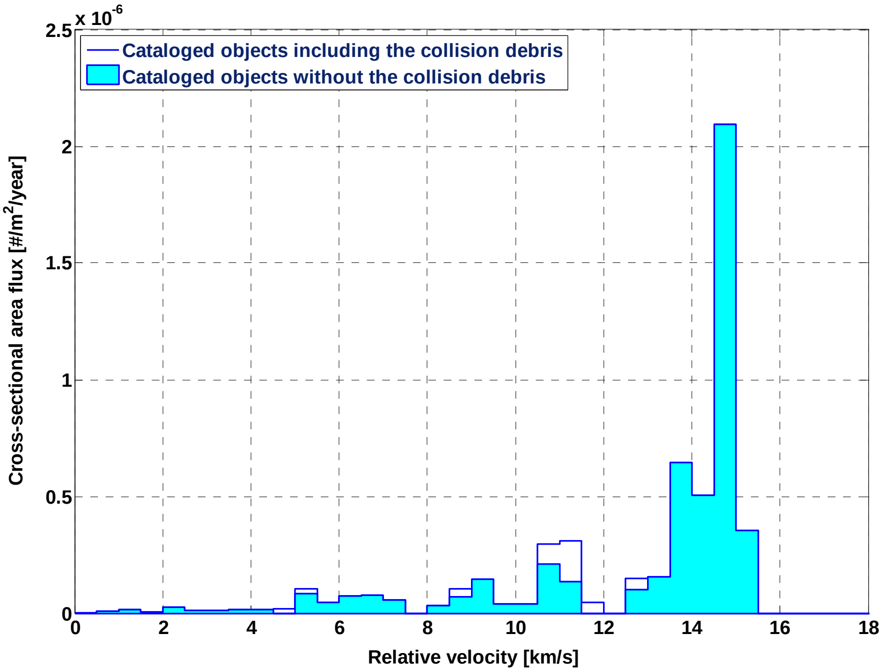

Fig. 18. COSMO-SkyMed constellation: cross-sectional area flux as a function of the incoming debris relative velocity.

In particular, it was found that both clouds presented a significant fraction of cataloged fragments with very high area-to-mass ratios, leading to the conclusion, supported by previous analyses, that the generation of trackable orbital debris with average *A/M* hundreds or thousands of times greater than those of intact satellites might be more common than formerly supposed, being one of the standard consequences of fragmentation events, both at high and low energy.

6. ACKNOWLEDGMENTS

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