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# REVISITING THE CATALOGED DEBRIS COLLISION RISK FOR THE IRIDIUM AND COSMO-SKYMED SATELLITE CONSTELLATIONS

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**Abstract**

After two decades of slightly declining growth rate, the population of cataloged debris around the Earth increased by more than 56% in just a couple of years, from January 2007 to February 2009, due to two collisions in space involving the catastrophic destruction of three intact satellites (Fengyun 1C, Cosmos 2251 and Iridium 33) in high inclination orbits. Both events had occurred in the altitude range already most affected by previous launch activity and breakups. In 2011 a detailed analysis had been carried out to analyze the consequences of these fragmentations, in particular concerning the evolution of the collision risk for the Iridium and COSMO-SkyMed satellite constellations. Five years after such first assessment, the cataloged debris environment affecting the two constellations was revisited to evaluate how the situation had evolved due to the varying contribution of the above mentioned breakup fragments and the space activities carried out in the meantime. Being distributed, at 778 km, over six nearly polar orbit planes separated by just 30° at the equator, the Iridium satellites represent a very good gauge for checking the evolution of the debris environment in the most critical low Earth region. In approximately five years, from May 2011 to June 2016, the average debris flux on the Iridium satellites increased by about 14%, to 1.59 $\times$ $10^{-5}$ $m^{-2}$ per year. The cataloged fragments of Fengyun 1C, Cosmos 2251 and Iridium 33 still accounted for, on average, 54% of the total flux. More than 39% of the latter was associated with the Fengyun 1C fragments, about 11% with the Cosmos 2251 fragments and less than 4% with the Iridium 33 fragments. Specifically concerning the mutual interaction among the Iridium 33 debris and the parent constellation, the progressive dispersion and rather fast decay of the fragments below the Iridium operational altitude, coupled with a slow differential plane precession and low average relative velocities with respect to four of the six constellation planes, determined in five years, on average, a decline of the flux by about 31%, i.e. to about 5.75 $\times$ $10^{-7}$ $m^{-2}$ per year. The decrease occurred in each constellation plane, even though with different rates and percentages, due to the varying relative orbit geometry. From May 2011 to June 2016, the mean debris flux on the COSMO-SkyMed satellites, at 623 km, increased by about 26%, to 7.24 $\times$ $10^{-6}$ $m^{-2}$ per year. The Fengyun 1C, Cosmos 2251 and Iridium 33 cataloged fragments accounted for, on average, about 1/4 of the total, with 12% due to Fengyun 1C, 8% to Cosmos 2251 and 4% to Iridium 33.

**Keywords:** Iridium and COSMO-SkyMed satellite constellations; Cataloged debris flux; Collisional debris clouds evolution; Fengyun 1C; Cosmos 2251; Iridium 33.

## 1. Introduction

After two decades of slightly declining growth rate, thanks also to the advancing implementation of mitigation measures, the population of cataloged debris around the Earth increased by more than 56% in just a couple of years, from January 2007 to February 2009, due to two collisions in space involving the catastrophic destruction of three intact satellites (Fengyun 1C, Cosmos 2251 and Iridium 33) in high inclination orbits [1–5]. Both events had occurred in the altitude range already most affected by previous launch activity and breakups.

In 2010-2011 a detailed analysis had been carried out to analyze the consequences of these fragmentations, in particular concerning the evolution of the collision risk for the Iridium and COSMO-SkyMed satellite constellations [6,7]. Five years after such first assessment, the cataloged debris environment affecting the two constellations was revisited to evaluate how the situation had evolved due to the varying contribution of the above mentioned breakup fragments and the space activities carried out in the meantime. The results obtained are the subject of this paper.

## 2. Evolution of cataloged debris

As of 8 June 2016, reference epoch of this study, there were 15,890 cataloged objects in orbit for which Two-Line Elements (TLEs) were publicly available, of

which 18% were fragments of the Fengyun 1C intentional destruction and 9% were fragments of the accidental collision between Cosmos 2251 (7%) and Iridium 33 (2%), as summarized in Fig. 1.

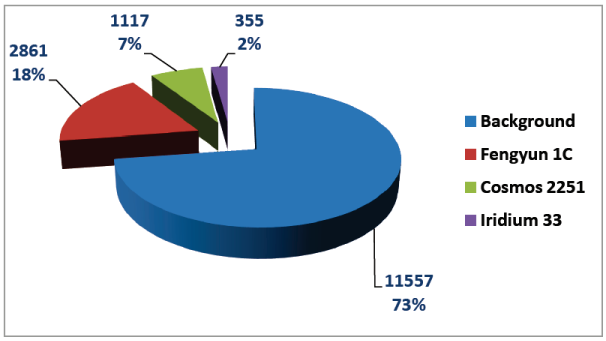


Fig. 1. Cataloged debris in orbit with publicly available TLEs (15,890), as of 8 June 2016, showing the contribution of the Fengyun 1C, Cosmos 2251 and Iridium 33 fragments.

The evolution of the cataloged objects spatial density in low Earth orbit (LEO), from 1 May 2011 to 8 June 2016, is shown in Figs. 2 and 3, where also the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds are represented. The total spatial density evolution was the combined result of five processes: (1) the orbit changes, leading often to objects decay, due to natural perturbations, in particular air drag; (2) the end-of-life re-orbiting or de-orbiting involving a relatively small number of controlled spacecraft and upper stages; (3) the new launches placing in orbit spacecraft, rocket bodies and mission related objects; (4) the new fragmentations, in particular accidental explosions; and (5) the addition to the catalog of old and smaller debris thanks to the performance improvement of the US Space Surveillance Network (SSN). The latter was particularly true for the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds, whose evolution, during the five years considered, is shown better in Fig. 4.

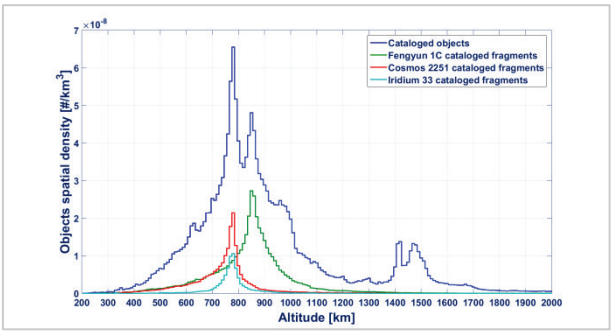


Fig. 2. Spatial density of cataloged debris in LEO with publicly available TLEs on 1 May 2011, showing also the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds.

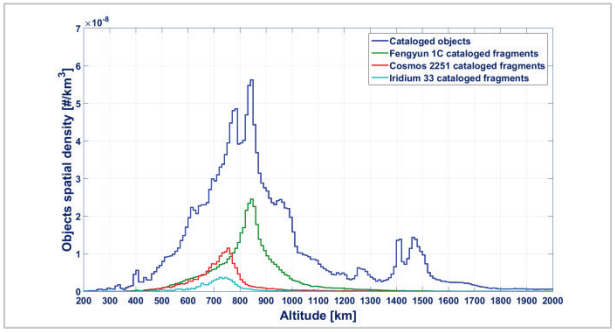


Fig. 3. Spatial density of cataloged debris in LEO with publicly available TLEs on 8 June 2016, showing also the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds.

Even though the solar activity cycle 24 was one of the weakest ever recorded, its maximum, occurring just in the 2011-2016 time interval, was relatively effective in checking the overall debris population in LEO (Figs. 2 and 3), due to the consequent increase of thermospheric density, drag on satellite motion and orbit decay rate, in particular on objects lower in altitude or with a relatively high area-to-mass ratio. This outcome was especially evident in the case of the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds (Fig. 4), more enhanced on the last two, being characterized by a significantly lower average altitude.

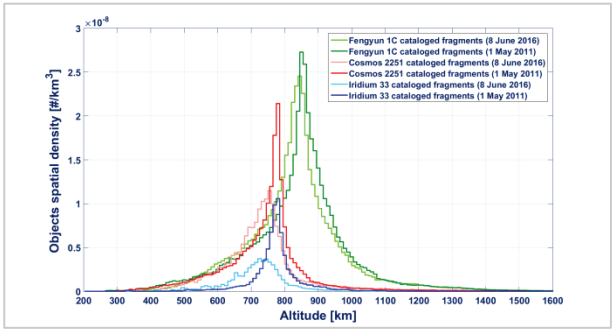


Fig. 4. Evolution of the spatial density of the cataloged debris belonging to the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds during about five years, from 1 May 2011 to 8 June 2016. The discovery and cataloging of new fragments during that period were more than compensated by the secular orbital decay induced by thermospheric drag.

The fragments decayed up to 8 June 2016 had been 16.4% for Fengyun 1C, 32.8% for Cosmos 2251 and 43.3% for Iridium 33 (Table 1). These decay percentages were in qualitative agreement with the predictions of Pardini and Anselmo [5], but were smaller than anticipated (about 20%, 43% and 54%, respectively), due to the extremely feeble maximum of solar activity cycle 24.

 

Table 1. Basic statistics of the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds as of 8 June 2016.

| Objects | Fengyun 1C | Cosmos 2251 | Iridium 33 |
|---|---|---|---|
| Cataloged | 3428 | 1668 | 628 |
| Decayed | 563 | 547 | 272 |
| In orbit | 2861 | 1117 | 355 |
| Lost (no TLE) | 4 | 4 | 1 |

Concerning the distribution around the Earth of the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds, it evolved according to the predictions of Pardini and Anselmo [5], due to the differential precession of the nodes induced by the perturbations. The orbits of the Fengyun 1C debris had already completely enveloped the Earth in 2011 and still formed a quite symmetrical shell in 2016, excluding just the polar regions, with approximately uniform density in longitude, increasing density from the equator to the highest overflown latitudes and maximum density around the height of 850 km (Fig. 5). In 2011, the Cosmos 2251 debris had still not achieved an evenly distribution around the Earth, but after five additional years, in 2016, a nearly symmetrical shell of fragments had clearly emerged, as for the Fengyun 1C cloud (Fig. 6). Regarding the Iridium 33 cloud, on the other hand, the nearly polar initial inclination prevented an effective differential precession of the nodes induced by the perturbations (Fig. 7). So, even in 2016, more than seven years after the breakup, the cloud of fragments was far from symmetrically enveloping the Earth and, due to the relatively rapid debris decay caused by thermospheric drag, a symmetric shell around our planet will not likely be ever created [5].

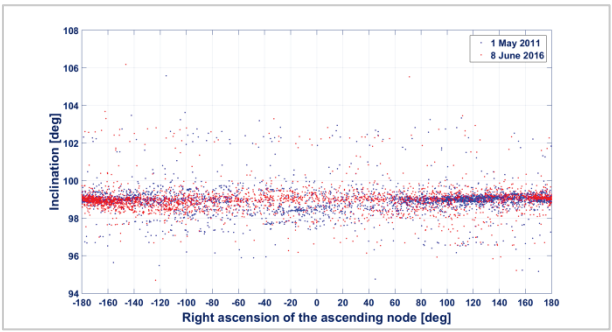


Fig. 5: Evolution of the nodal distribution of the Fengyun 1C debris cloud.

## 3. Debris flux estimation

The flux of cataloged debris on the Iridium and COSMO-SkyMed satellite constellations was estimated with the Space Debris Impact Risk Analysis Tool (SDIRAT), developed and implemented at ISTI/CNR to assess the orbital debris impact risk on user specified targets in Earth orbit in terms of flux, relative velocity, impact velocity, direction of the incoming particles, debris mass and diameter [8–10]. For this study, the population of cataloged objects provided by the US Space Track Organization was used by SDIRAT to represent the debris distribution at the reference epochs of the analysis.

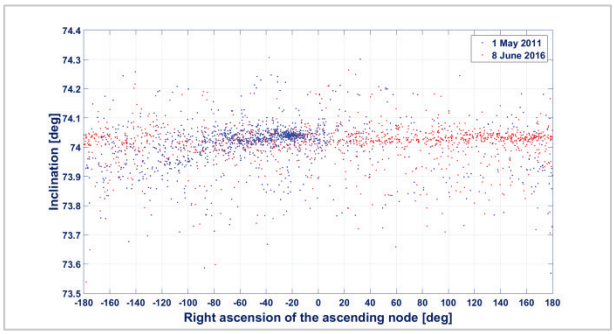


Fig. 6: Evolution of the nodal distribution of the Cosmos 2251 debris cloud.

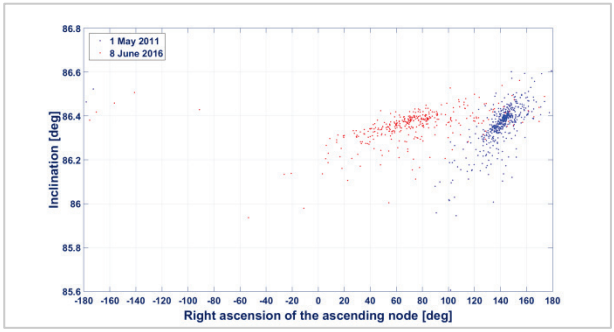


Fig. 7: Evolution of the nodal distribution of the Iridium 33 debris cloud.

The orbit of the target objects, belonging either to the Iridium or the COSMO-SkyMed constellations, was split into a user-specified number of orbital cells, each centered on a fictitious target, to analyze the risk of impact. The global results were therefore obtained once a 360° scan in mean anomaly of the target orbit was completed, and the mean debris flux ($F$) was computed by averaging the contributions of all the cells along the orbit as follows [8,9]:

$$F = \frac{\sum_{j=1}^{C} \sum_{i=1}^{N(j)} \left( \left| \vec{v}_{RT}(i,j) \right| / Vol(j) \right)}{C}, \qquad (1)$$

being $\vec{v}_{RT}(i,j)$ the relative velocity vector of the $i^{\text{th}}$ cataloged object with respect to the $j^{\text{th}}$ fictitious target, $N(j)$ the number of cataloged objects inside the $j^{\text{th}}$ cell, $C$ the number of cells considered along the target orbit ($C$ = 360°/$\Delta M$, being $\Delta M$ the mean anomaly increment in degrees) and $Vol(j)$ the volume of the $j^{\text{th}}$ cell.

 

## 4. Debris flux evolution on the Iridium constellation

Being distributed, at 778 km, over six nearly polar orbit planes (inclination ≈ 86.4°) separated by just 30° at the equator, the Iridium satellites represent a very good gauge for checking the evolution of the debris environment in the most critical LEO region (Fig. 8). With the environment of 8 June 2016, the results obtained for each Iridium constellation plane are detailed in Tables 2–6. In about five years, from 1 May 2011 to 8 June 2016, the average debris flux on the Iridium constellation orbital planes passed from $1.39 \times 10^{-5}$ m$^{-2}$ per year [6,7] to $1.59 \times 10^{-5}$ m$^{-2}$ per year, meaning that the combination of new space missions, solar activity, mitigation measures and debris evolution led to an increase of about 14%. Three planes (0, −1, −2) experienced a flux increase, up to 60% for the latter, while the other three (+1, +2, +3) experienced an overall flux decrease, down to −9% for the first one (Table 2).

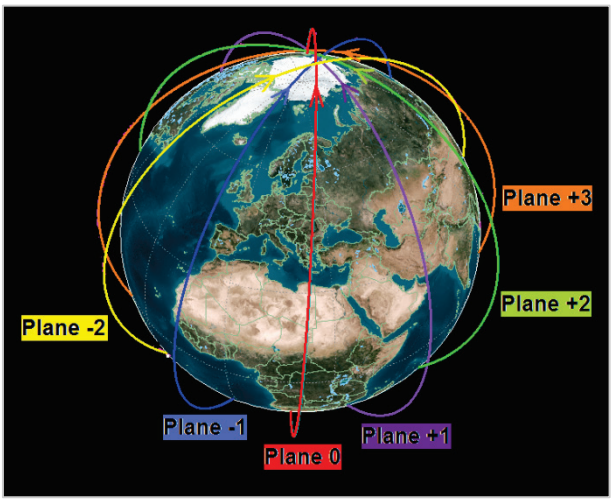


Fig. 8: Distribution of the orbit planes of the Iridium constellation, referred counterclockwise with respect to the Iridium 33 original plane (Plane 0).

Table 2. Flux of cataloged objects on the Iridium constellation planes, as of 8 June 2016, and percentage variation with respect to 1 May 2011, in square brackets.

| Iridium plane | Cross-sectional area flux [m$^{-2}$/year] | Average relative velocity [km/s] | Average collision velocity [km/s] |
|---|---|---|---|
| −2 | $2.17 \times 10^{-5}$ [+60%] | 10.99 | 13.19 |
| −1 | $1.99 \times 10^{-5}$ [+36%] | 10.08 | 12.98 |
| 0 | $1.46 \times 10^{-5}$ [+2%] | 8.34 | 11.94 |
| +1 | $1.32 \times 10^{-5}$ [−9%] | 7.70 | 11.22 |
| +2 | $1.23 \times 10^{-5}$ [−4%] | 7.15 | 10.88 |
| +3 | $1.33 \times 10^{-5}$ [−3%] | 7.38 | 11.15 |

Table 3. Flux of background cataloged objects (i.e. excluding the Fengyun 1C, Cosmos 2251 and Iridium 33 debris) on the Iridium constellation planes, as of 8 June 2016, and percentage variation with respect to 1 May 2011, in square brackets.

| Iridium plane | Cross-sectional area flux [m$^{-2}$/year] | Average relative velocity [km/s] | Average collision velocity [km/s] |
|---|---|---|---|
| −2 | $9.23 \times 10^{-6}$ [+74%] | 10.36 | 13.11 |
| −1 | $1.12 \times 10^{-5}$ [+96%] | 10.66 | 13.22 |
| 0 | $6.02 \times 10^{-6}$ [+29%] | 9.02 | 11.97 |
| +1 | $5.46 \times 10^{-6}$ [+21%] | 7.13 | 10.91 |
| +2 | $5.48 \times 10^{-6}$ [−9%] | 6.71 | 10.79 |
| +3 | $6.18 \times 10^{-6}$ [−11%] | 7.54 | 11.43 |

Disregarding the fragments from Fengyun 1C, Cosmos 2251 and Iridium 33, the average flux of cataloged objects on the Iridium planes passed from $5.53 \times 10^{-6}$ m$^{-2}$ per year [6,7] to $7.26 \times 10^{-6}$ m$^{-2}$ per year, with an increase of 31%. Four planes (+1, 0, −1, −2) experienced a flux increase, up to 96% for plane −1, while the remaining two (+2, +3) experienced an overall flux decrease, down to −11% for the latter (Table 3).

After more than five years, in June 2016, the cataloged debris associated with the Fengyun 1C intentional destruction and the accidental collision between Cosmos 2251 and Iridium 33 accounted for, on average, 54% of the overall flux on the Iridium satellite constellation (Fig. 9). Certainly there was a decrease from the 60% value in May 2011 [6,7], but the fragments generated by the two above mentioned breakup events still represented, five years later, more than half of the averaged collision risk for the Iridium spacecraft.

Table 4. Flux of Fengyun 1C cataloged debris on the Iridium constellation planes, as of 8 June 2016, and percentage variation with respect to 1 May 2011, in square brackets.

| Iridium plane | Cross-sectional area flux [m$^{-2}$/year] | Average relative velocity [km/s] | Average collision velocity [km/s] |
|---|---|---|---|
| −2 | $9.03 \times 10^{-6}$ [+137%] | 12.43 | 13.82 |
| −1 | $6.40 \times 10^{-6}$ [+99%] | 11.84 | 13.56 |
| 0 | $6.40 \times 10^{-6}$ [+133%] | 10.91 | 12.85 |
| +1 | $5.94 \times 10^{-6}$ [+81%] | 10.83 | 12.79 |
| +2 | $4.84 \times 10^{-6}$ [+77%] | 9.52 | 12.04 |
| +3 | $4.71 \times 10^{-6}$ [+44%] | 8.32 | 11.81 |

However, while in May 2011 the prevailing mean flux was associated with the Cosmos 2251 debris cloud ($4.39 \times 10^{-6}$ m$^{-2}$ per year, compared with $3.18 \times 10^{-6}$

$m^{-2}$ per year of Fengyun 1C and $8.36 \times 10^{-7}$ $m^{-2}$ per year of Iridium 33 [6,7]), in June 2016 the Fengyun 1C fragments alone represented more than 39% of the total flux of cataloged objects on the Iridium constellation. In fact, their average flux had increased, by about 96%, to $6.22 \times 10^{-6}$ $m^{-2}$ per year, affecting by different relative amounts all the Iridium orbit planes (Table 4). This was the result of the progressive orbit decay of the Fengyun 1C debris cloud induced by thermospheric drag (Fig. 4), with a growing number of objects descending at the Iridium constellation altitude and crossing its planes with a relative geometry* leading to high relative velocities and correspondingly higher fluxes (Table 4).

Table 5. Flux of Cosmos 2251 cataloged debris on the Iridium constellation planes, as of 8 June 2016, and percentage variation with respect to 1 May 2011, in square brackets.

| Iridium plane | Cross-sectional area flux [$m^{-2}$/year] | Average relative velocity [km/s] | Average collision velocity [km/s] |
|---|---|---|---|
| –2 | $2.69 \times 10^{-6}$ [–26%] | 11.01 | 12.68 |
| –1 | $1.87 \times 10^{-6}$ [–63%] | 10.15 | 11.84 |
| 0 | $1.74 \times 10^{-6}$ [–72%] | 7.35 | 10.16 |
| +1 | $1.29 \times 10^{-6}$ [–78%] | 4.94 | 7.54 |
| +2 | $1.48 \times 10^{-6}$ [–53%] | 4.70 | 8.07 |
| +3 | $1.71 \times 10^{-6}$ [–30%] | 4.87 | 8.08 |

Table 6. Flux of Iridium 33 cataloged debris on the Iridium constellation planes, as of 8 June 2016, and percentage variation with respect to 1 May 2011, in square brackets.

| Iridium plane | Cross-sectional area flux [$m^{-2}$/year] | Average relative velocity [km/s] | Average collision velocity [km/s] |
|---|---|---|---|
| –2 | $7.39 \times 10^{-7}$ [–17%] | 6.55 | 8.27 |
| –1 | $5.03 \times 10^{-7}$ [–29%] | 2.43 | 4.27 |
| 0 | $4.14 \times 10^{-7}$ [–46%] | 1.55 | 3.75 |
| +1 | $5.17 \times 10^{-7}$ [–28%] | 3.72 | 5.90 |
| +2 | $5.39 \times 10^{-7}$ [–38%] | 4.96 | 7.86 |
| +3 | $7.40 \times 10^{-7}$ [–31%] | 10.36 | 11.66 |

The mean flux of the Cosmos 2251 debris, instead, had decreased by about 59%, to $1.80 \times 10^{-6}$ $m^{-2}$ per year, from May 2011 to June 2016, for the spreading of the cloud around the Earth (Fig. 6) and the substantial decay of the fragments due to air drag (Fig. 4), shifting the peak of the altitude distribution below the Iridium operational height. Combined with the low average relative velocity with respect to three of the Iridium planes (Table 5), the outcome was that the Cosmos 2251 fragments accounted for only about 11% of the cataloged debris flux on the Iridium constellation in June 2016, compared with nearly 32% in May 2011 [6,7].

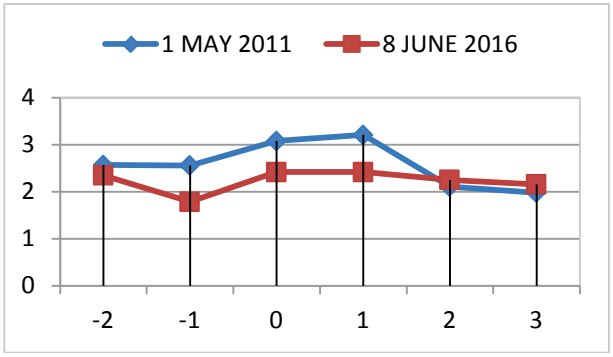


Fig. 9: Ratio of the total flux of cataloged objects to the background flux obtained by excluding the Fengyun 1C, Cosmos 2251 and Iridium 33 debris (in the ordinate) as a function of the Iridium constellation orbit planes (in the abscissa).

Concerning the mutual interaction among the Iridium 33 fragments and the parent constellation, the debris dispersion and rather fast decay below the operational Iridium altitude (Fig. 4), coupled with a slow differential plane precession (Fig. 7) and low average relative velocities with respect to four of the Iridium planes for geometrical reasons (Table 6), determined in five years, on average, a decline of the flux by about 31%, i.e. to $5.75 \times 10^{-7}$ $m^{-2}$ per year, affecting by different relative amounts all the Iridium orbit planes (Table 6). As in May 2011 [6,7], in June 2016 the highest flux had remained focused on the Iridium planes +3 and –2. However, a slow counter-clockwise drift (i.e. in the direction +3 → –2 → –1 → 0 → +1 → +2) of the debris flux peak with respect to the constellation planes was observed, needing about 8 years to move from one plane to the next one of the sequence. But due to the quite rapid cloud decay induced by thermospheric drag, further planes, i.e. –1 and 0, will not be able to experience sizable flux peaks in the future, before the vanishing of the debris cloud.

In June 2016, the Iridium 33 fragments accounted for less than 4% of the cataloged debris flux on the Iridium constellation, compared with 6% in May 2011. Coupled with the previous discussion, it is clear that this intra-constellation breakup was not particularly severe for the constellation itself. In fact, the physical properties of the fragments and the post-event cloud orbital evolution concurred in maintaining the additional collision risk to low values compared with the overall

* The relative geometry is a function of the respective orbital inclinations and right ascensions of the ascending nodes.

evolution of the debris environment in LEO. And it is quite symptomatic that after nearly ten years a totally unrelated breakup, that of Fengyun 1C, resulted in an average flux 10 times that of Iridium 33 and 2.6 times that of the Iridium 33 and Cosmos 2251 fragments combined.

Therefore, contrary to common wisdom, intra-constellation breakups are not necessarily critical for the constellation itself in terms of increased mid and long-term collision probability. Certainly, some events might be more problematic, depending on the constellation geometry and the plane were the breakup would occur, and a case-by-case analysis would be needed to highlight the details of the debris cloud evolution, but in general the outcome would be more benign than usually believed.

A more detailed representation of the debris relative velocity and directional flux on the six planes of the Iridium constellation, as of 8 June 2016, is displayed in Figs. 10–15. On plane –2, the 60% flux increase compared with 1 May 2011 [6,7] was mainly due to a growing number of background and Fengyun 1C objects moving nearly opposite to the Iridium satellites, at relative velocities just below 15 km/s (Fig. 10). The same applied to the 36% flux increase on plane –1 (Fig. 11). On plane 0, the overall flux distribution remained basically the same, but the prevailing contribution of Cosmos 2251 fragments to the very high relative velocity objects [6,7] was nearly completely replaced by Fengyun 1C and background debris (Fig. 12). This occurred also on plane +1, even though the total flux decreased by 9% (Fig. 13). On plane +2, the concomitant decrease of background, Cosmos 2251 and Iridium 33 debris fluxes was nearly completely replaced by an increase of the Fengyun 1C debris flux, still more concentrated in the head-on high relative velocity component (Fig. 14). And basically the same occurred on plane +3 as well (Fig. 15).

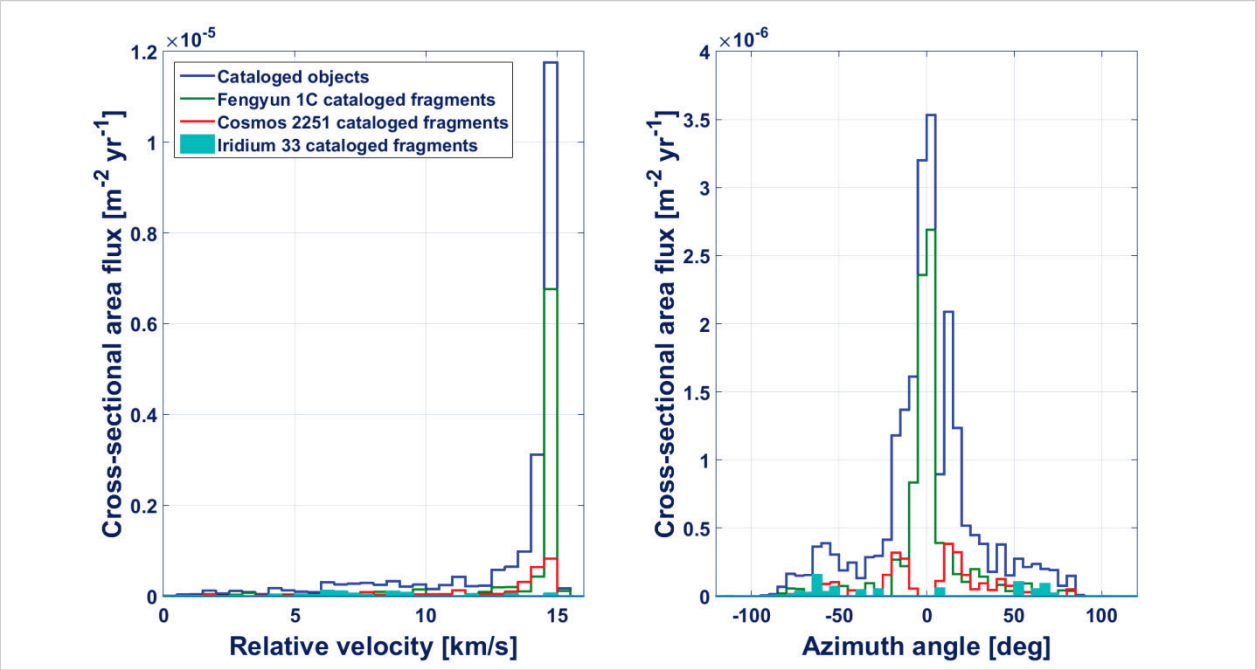


Fig. 10: Cataloged debris relative velocity and directional flux (8 June 2016) on the Iridium operational plane –2. The azimuth angle is measured clockwise from the projection of the velocity vector in the target centered horizon plane. Most of the debris flux exhibits elevation angles $< |5|$ deg with respect to the local horizon.

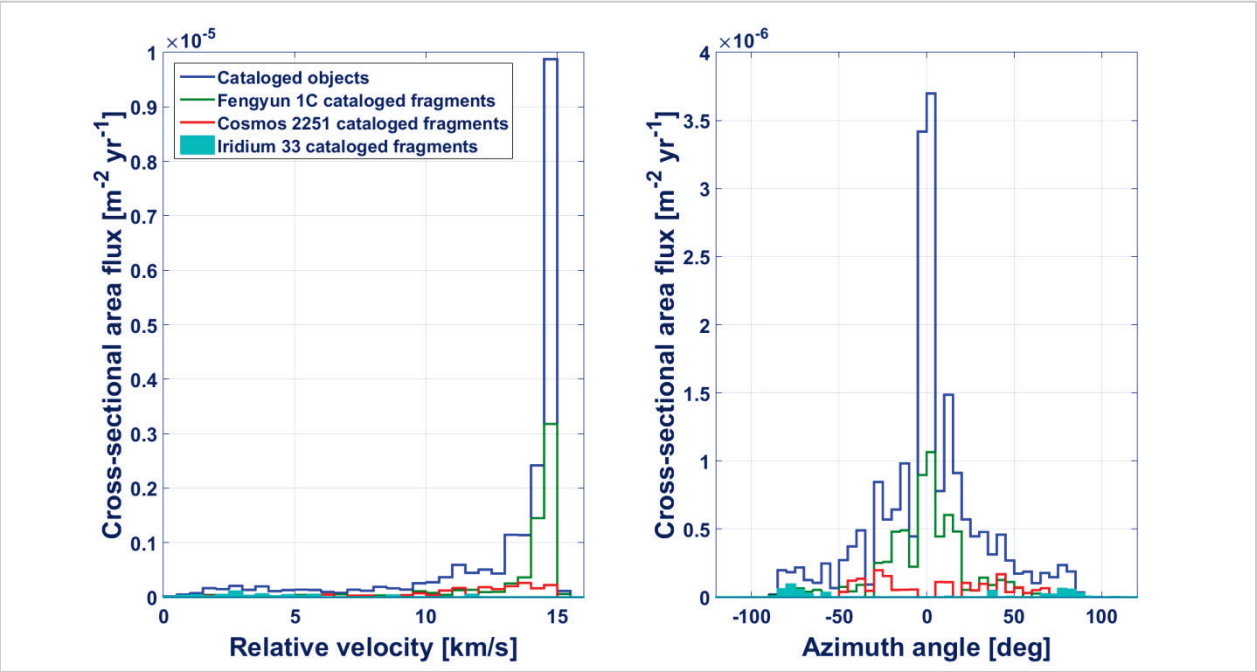


Fig. 11: Cataloged debris relative velocity and directional flux (8 June 2016) on the Iridium operational plane –1.

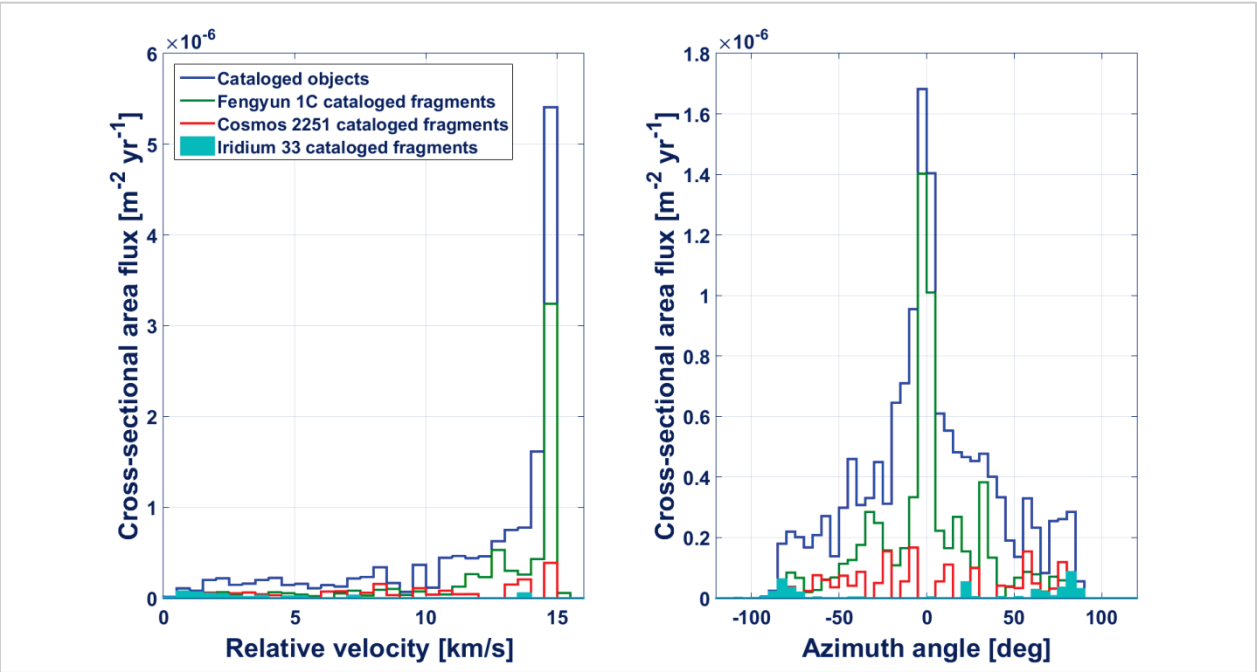


Fig. 12: Cataloged debris relative velocity and directional flux (8 June 2016) on the Iridium operational plane 0.

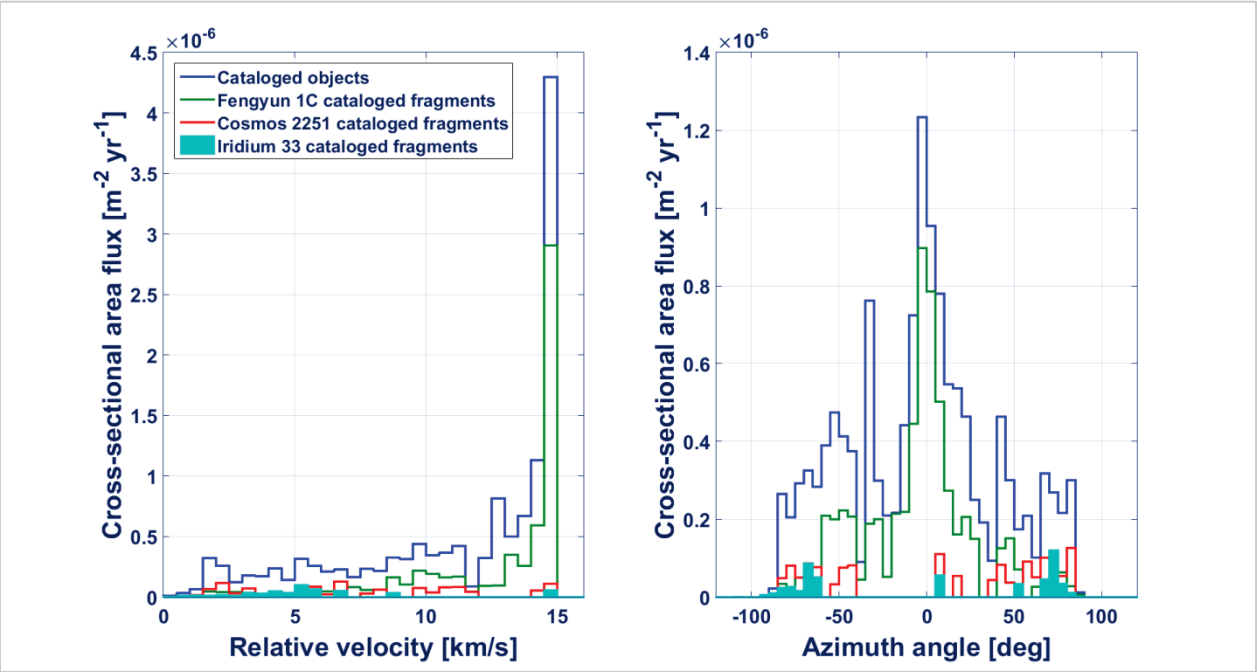


Fig. 13: Cataloged debris relative velocity and directional flux (8 June 2016) on the Iridium operational plane +1.

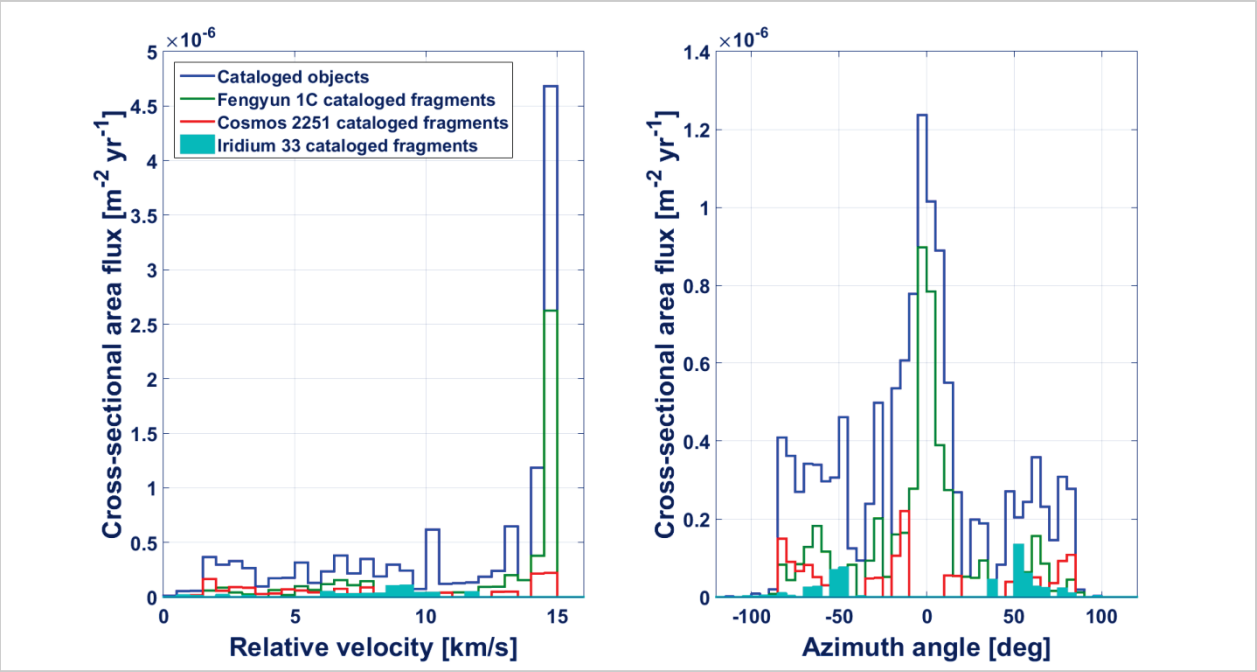


Fig. 14: Cataloged debris relative velocity and directional flux (8 June 2016) on the Iridium operational plane +2.

 

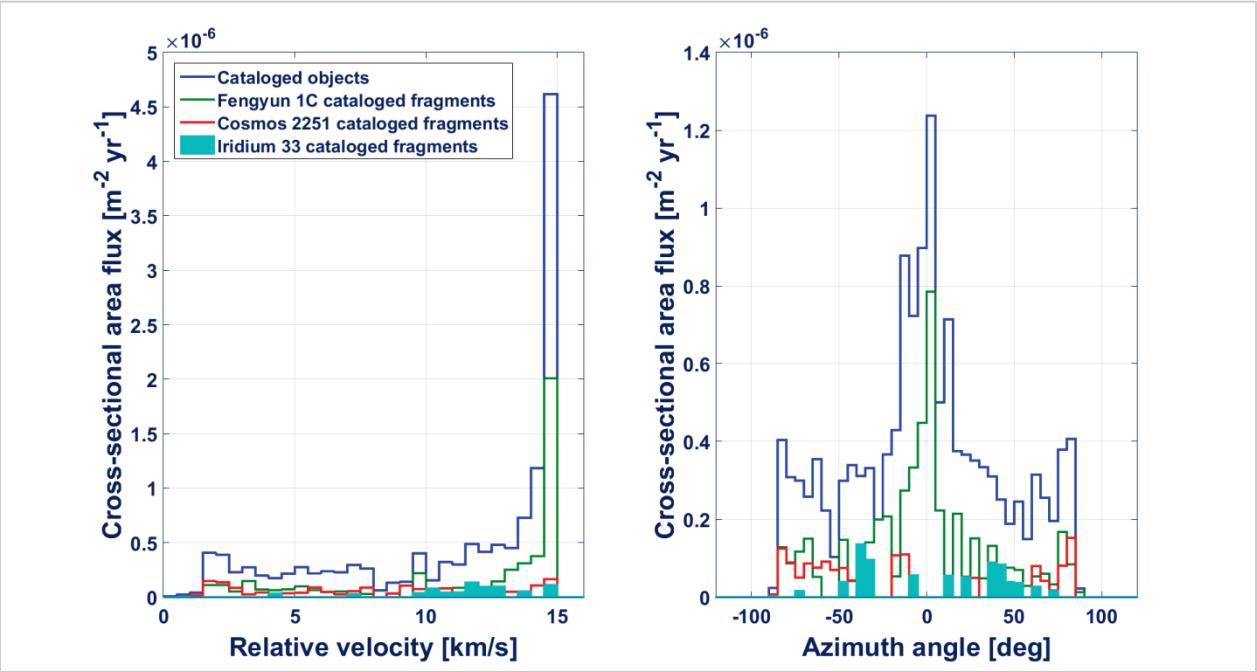


Fig. 15: Cataloged debris relative velocity and directional flux (8 June 2016) on the Iridium operational plane +3.

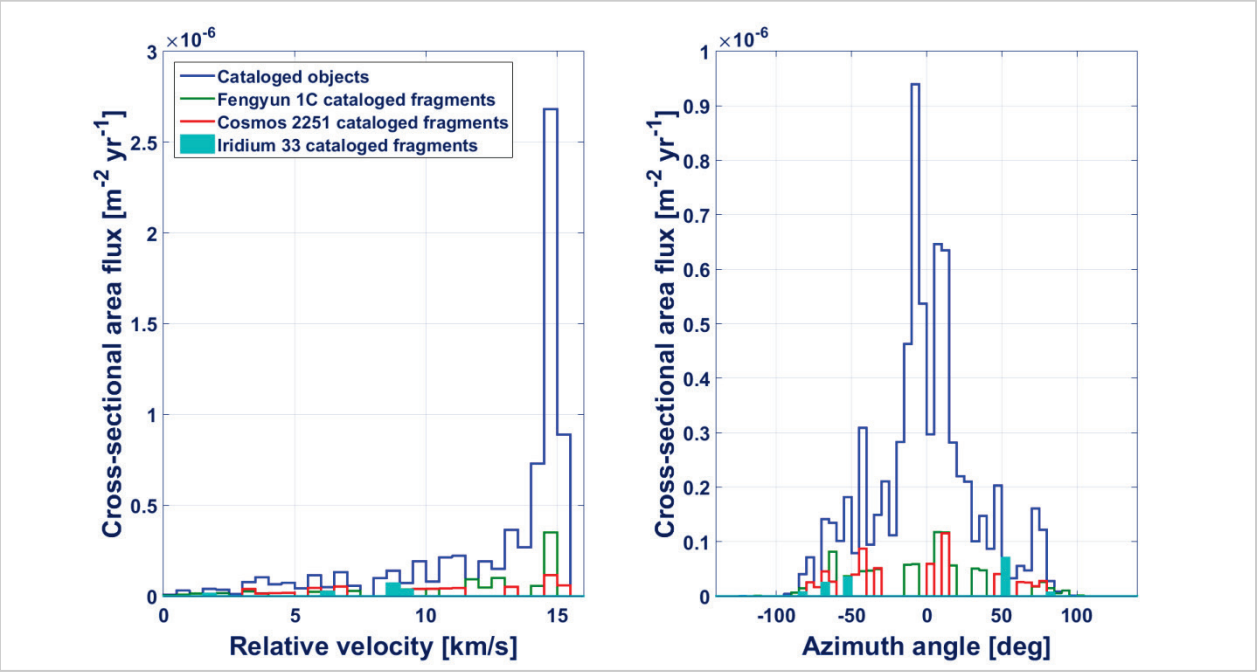


Fig. 16: Cataloged debris relative velocity and directional flux (8 June 2016) on the COSMO-SkyMed constellation.

 

## 5. Debris flux evolution on COSMO-SkyMed

The COSMO-SkyMed constellation, owned by the Italian Space Agency (ASI) and the Italian Ministry of Defense, consists of 4 Earth's observation satellites at a height of approximately 623 km and inclination of 97.9°. The spacecraft are placed on the same orbit plane, phased by 90 deg.

With the environment of 8 June 2016, the results obtained for the COSMO-SkyMed constellation plane are summarized in Table 7 and in Fig. 16. From May 2011 to June 2016, the average debris flux of cataloged objects passed from $5.76 \times 10^{-6}$ m$^{-2}$ per year [6,7] to $7.24 \times 10^{-6}$ m$^{-2}$ per year, with an increase of about 26%. The background flux, excluding the Fengyun 1C, Cosmos 2251 and Iridium 33 debris clouds, passed from $3.91 \times 10^{-6}$ to $5.57 \times 10^{-6}$ m$^{-2}$ per year, with an increase of about 42%. Also the decaying Fengyun 1C and Cosmos 2251 debris clouds, by now symmetrically spread around the Earth, augmented their contribution to the flux, respectively increasing from $7.33 \times 10^{-7}$ to $9.24 \times 10^{-7}$ m$^{-2}$ per year (+26%), and from $4.54 \times 10^{-7}$ to $6.03 \times 10^{-7}$ m$^{-2}$ per year (+33%). The flux of Iridium 33 debris, instead, dropped by 78%, from $6.63 \times 10^{-7}$ to $1.43 \times 10^{-7}$ m$^{-2}$ per year.

Compared with May 2011 [6,7], the debris relative velocity and directional flux distributions remained qualitatively unaffected, with the head-on high relative velocity flux dominated by the background population (Fig. 16). The only relevant difference was the disappearance, on June 2016, of a conspicuous head-on flux of Iridium 33 fragments [6,7], leading also to the significant flux drop previously highlighted.

This evolution cannot be only explained by the progressive dispersion, decay and rarefaction of the Iridium 33 cloud. Conversely, as shown in Fig. 4, the cloud rapid decay had increased the object density at the COSMO-SkyMed altitude, and this debris "rain" will continue for several years in the future. The apparent paradox can be solved by recalling again that the orbit plane spread of the Iridium debris is still moderate, and will remain so for years to come. A consequence of this is that the relative geometry between the COSMO-SkyMed orbit plane and those of the Iridium 33 debris cloud is experiencing a cyclical variation, with a period of approximately 8-9 months, as a result of the differential precession of the nodes [6,7]. Therefore, the COSMO-SkyMed satellites experience periods of Iridium debris head-on fluxes, with average relative velocities around 15 km/s, as on 1 May 2011, followed by decreasing fluxes and relative velocities, down to a minimum (≈ 2 km/s) around 4-5 months later. Then, fluxes and relative velocities increase again, towards a new maximum and head-on trajectories, around 8-9 months after the start of the cycle [6,7].

Table 7. Flux of cataloged debris on the COSMO-SkyMed constellation plane, as of 8 June 2016, and percentage variation with respect to 1 May 2011, in square brackets.

| Debris source | Cross-sectional area flux [m$^{-2}$/year] | Average relative velocity [km/s] | Average collision velocity [km/s] |
|---|---|---|---|
| Catalog | $7.24 \times 10^{-6}$ [+26%] | 9.42 | 12.65 |
| Background | $5.57 \times 10^{-6}$ [+42%] | 10.51 | 13.23 |
| Fengyun 1C | $9.24 \times 10^{-7}$ [+26%] | 6.53 | 11.49 |
| Cosmos 2251 | $6.03 \times 10^{-7}$ [+33%] | 8.07 | 10.16 |
| Iridium 33 | $1.43 \times 10^{-7}$ [−78%] | 6.06 | 7.77 |

On 8 June 2016, the right ascension of the ascending node of the COSMO-SkyMed orbit plane was shifted westward by 88° with respect to the ascending node of the center of the cloud (Fig. 7), so the relative geometry was intermediate between the most and less favorable from a debris flux point of view. In 2016, the maximum flux, $1.12 \times 10^{-6}$ m$^{-2}$ per year, occurred for a COSMO-SkyMed right ascension of the ascending node around 165° eastward with respect to the ascending node of the approximate center of the Iridium 33 cloud, and such a flux was higher by 68% compared with the maximum in 2011 [6,7], due to the cloud orbital decay and the raining down of fragments at the COSMO-SkyMed operational altitude. The minimum flux was instead about $10^{-7}$ m$^{-2}$ per year, or less, while the average flux over a full relative geometry cycle was $3.15 \times 10^{-7}$ m$^{-2}$ per year.

In conclusion, in 2016, the Fengyun 1C fragments accounted for about 12% of the average cataloged debris flux on the COSMO-SkyMed constellation, the Cosmos 2251 fragments accounted for about 8% of the flux and the Iridium 33 fragments accounted for about 4% of the flux. Therefore, the three debris cloud combined represented, on average, approximately 1/4 of the total flux of cataloged debris on the COSMO-SkyMed constellation.

## 6. Conclusions

The two catastrophic breakups occurred in January 2007 (Fengyun 1C) and in February 2009 (Cosmos 2251 and Iridium 33) significantly affected the altitude range already most crowded by orbiting objects, including a large number of operational spacecraft, used mainly for communications and Earth observation. More than five years after a previous analysis, the debris flux associated with the three clouds of collisional

 

fragments was revisited in detail for two important operational satellite constellations, Iridium and COSMO-SkyMed.

For the Iridium constellation, at 778 km, the Fengyun 1C, Cosmos 2251 and Iridium 33 fragments still accounted for 54% of the total flux of cataloged objects in mid-2016. Both the Fengyun 1C and Cosmos 2251 debris clouds were quite uniformly spread around the Earth, while the orbit planes of the Iridium 33 fragments were yet relatively clustered and not much drifted with respect to the original plane of the constellation to which Iridium 33 belonged before the accidental collision with Cosmos 2251. However, looking down from the north pole, a slow counter-clockwise drift of the intra-constellation debris flux peak was observed, needing about 8 years to move from one Iridium operational plane to the next one in the sequence, even though, due to the quite rapid cloud decay induced by neutral atmosphere drag, further planes, aside from the two ones mostly affected since the beginning, will not be able to experience sizable flux peaks in the future before the vanishing of the debris cloud.

From May 2011 to June 2016 the total mean flux of cataloged debris increased by 14%, and by 31% disregarding the Fengyun 1C, Cosmos 2251 and Iridium 33 fragments. This means that during the maximum of the solar activity cycle 24, and in spite of the debris mitigation recommendations of the Inter-Agency Space Debris Coordination Committee [11], the United Nations [12] and several national standards, new space activities and the evolution of what already present in orbit, excluding the Fengyun 1C, Cosmos 2251 and Iridium 33 clouds, led to an average debris flux increase on the Iridium constellation of nearly 1/3.

Regarding the COSMO-SkyMed constellation, at 623 km, from May 2011 to June 2016 the total mean flux of cataloged debris increased by 26%, and by 42% disregarding the Fengyun 1C, Cosmos 2251 and Iridium 33 fragments. The latter three debris clouds, combined, accounted for approximately 1/4 of the total flux in 2016. Due to the above mentioned orbit planes clustering of the Iridium 33 fragments, their relative geometry with respect to the COSMO-SkyMed orbit plane was still experiencing a sinusoidal cyclical variation, with a period of approximately 8-9 months, as a result of the differential precession of the nodes. This affected the Iridium 33 debris flux and relative velocity with the same periodicity.

In conclusion, from May 2011 to June 2016, a significant increase of the flux of cataloged debris was observed in LEO both on the Iridium and COSMO-SkyMed constellations. During this period the relative contribution of the three debris clouds produced by the breakups of Fengyun 1C, Cosmos 2251 and Iridium 33 decreased, but remained substantial. Among the latter three sources, the main flux component was represented by the Fengyun 1C fragments, followed by those of Cosmos 2251. The Iridium 33 cataloged debris, on the other hand, contributed only 4% of the average flux, on both constellations, in 2016.

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