# EVOLUTION OF THE DEBRIS CLOUD GENERATED BY THE FENGYUN-1C FRAGMENTATION EVENT

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***ABSTRACT*** *– The cloud of cataloged debris produced in low earth orbit by the fragmentation of the Fengyun-1C spacecraft was propagated for 15 years, taking into account all relevant perturbations. Unfortunately, the cloud resulted to be very stable, not suffering substantial debris decay during the time span considered. The only significant short term evolution was the differential spreading of the orbital planes of the fragments, leading to the formation of a debris shell around the earth approximately 7-8 months after the breakup, and the perigee precession of the elliptical orbits. Both effects will render the shell more "isotropic" in the coming years. The immediate consequence of the Chinese anti-satellite test, carried out in an orbital regime populated by many important operational satellites, was to increase significantly the probability of collision with man-made debris. For the two Italian spacecraft launched in the first half of 2007, the collision probability with cataloged objects increased by 12% for AGILE, in equatorial orbit, and by 38% for COSMO-SkyMed 1, in sun-synchronous orbit.*

## INTRODUCTION

On 11 January 2007, the 880 kg (958 kg at launch) weather spacecraft Fengyun-1C, launched on 10 May 1999 into a sun-synchronous orbit with a CZ-4B booster from the Taiyuan Satellite Launch Center, was destroyed over central China as a result of the first successful Chinese anti-satellite weapon test. It was carried out with a direct ascent interception with a kinetic energy kill vehicle launched by an SC-19 missile, fired from a mobile ground platform close to the Xichang Satellite Launch Center (Songlin, approximately 28 deg N, 102 deg E). While the technical details of the test, probably the third attempt, and the characteristics of the weapon used remain shrouded in secrecy, the intentional breakup in polar orbit of the aging weather spacecraft, fully functional until 2005, produced a huge amount of debris in one of the orbital regimes already most affected by past fragmentation events. At present, the US Space Surveillance Network has cataloged about 2000 objects larger than 5 cm, but the final tally might exceed 2200, even disregarding centimeter sized objects, many thousands of which have been probably generated as well.

After two decades of substantial international progress in the field of orbital debris mitigation, in order to preserve the low earth and geosynchronous environments for future space missions, the Chinese anti-satellite test and other unfortunate accidental breakups, like that over Australia, on 19 February 2007, of the derelict Briz-M rocket stage used for the failed launch of the satellite Arabsat-4A, on 28 February 2006, represented a serious turnabout. In fact, in less than six weeks at the beginning of 2007, the two worst documented fragmentations in 50 years of space operations, both tallying more than 1000 pieces larger than 10 cm, considerably boosted the number of cataloged debris in orbit. To give a rough idea of the impact of such events on the circumterrestrial environment, it is sufficient to realize that the Chinese anti-satellite test alone, in numerical terms, increased the number of cataloged orbital debris by an amount comparable to the previous 14 years of space activity.

## BREAKUP ANALYSIS

By propagating backward in time the first 32 cataloged fragments, it was possible to estimate, through the analysis of the pinch point of the trajectories, the approximate time of the satellite breakup: $22^h25^m40^s$ UTC, on 11 January 2007. Before the interception, the orbit of Fengyun-1C (1999-025A) had a perigee altitude of 855 km, an apogee altitude of 876 km, an inclination of 98.65 deg and a revolution period of about 102 minutes.

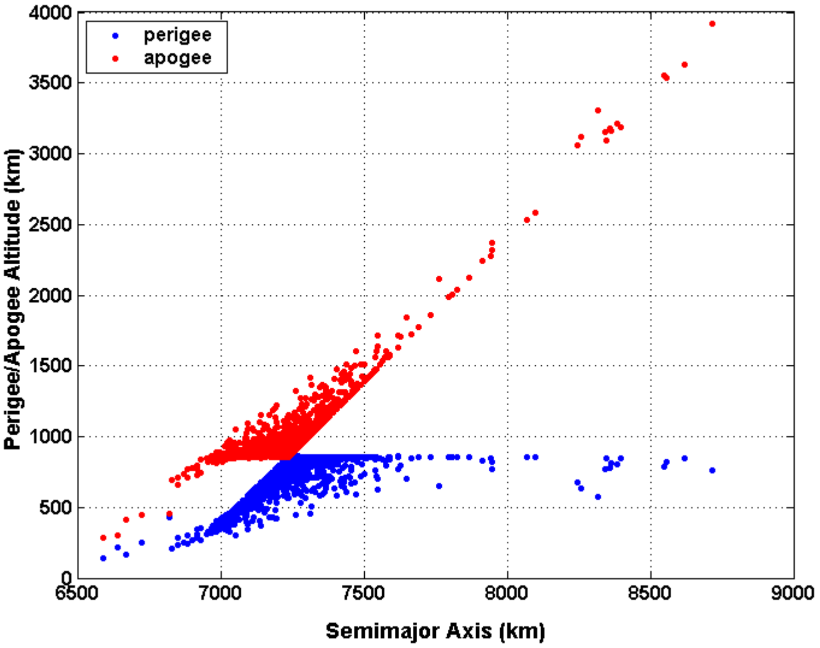

**Fig. 1. Perigee and apogee distribution, as a function of semimajor axis, of the first 1800 cataloged fragments.**

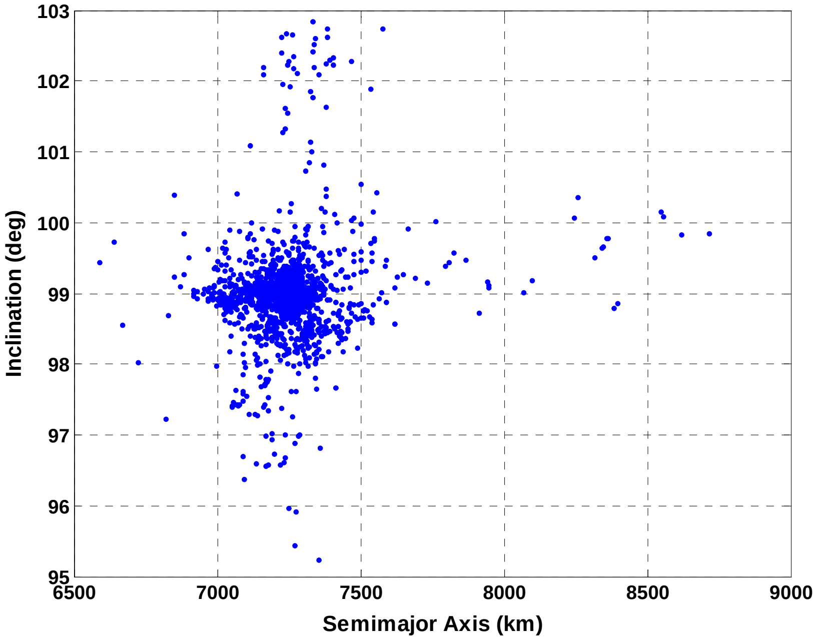

**Fig. 2. Inclination and semimajor axis distribution of the first 1800 cataloged fragments.**

The fragmentation occurred at an altitude of about 863 km over central China (~ 35 deg N, ~ 100 deg E), spreading the resulting fragments between 200 and 4000 km, with maximum concentration around the breakup height (see the Gabbard diagram in Fig. 1). From the distribution of debris inclination and semimajor axis (see Fig. 2), the maximum velocity variation applied by the kinetic energy kill vehicle to the observed fragments was ~ 600 m/s.

Fig. 3 shows how the fragmentation event affected the objects spatial density in low earth orbit, i.e. below the altitude of 2000 km. At the original height of Fengyun-1C the cataloged debris object density increased by more than 60%, but the environmental impact was significant in all the altitude range between 700 and 1000 km, where the debris density due to past space activities was already at worrisome levels. Considering the inclination, nearly polar, and the height of the target, such a deliberate act of debris generation was therefore one of worst conceivable with current technology and its consequences will unfortunately be felt by satellite operators for many decades to come.

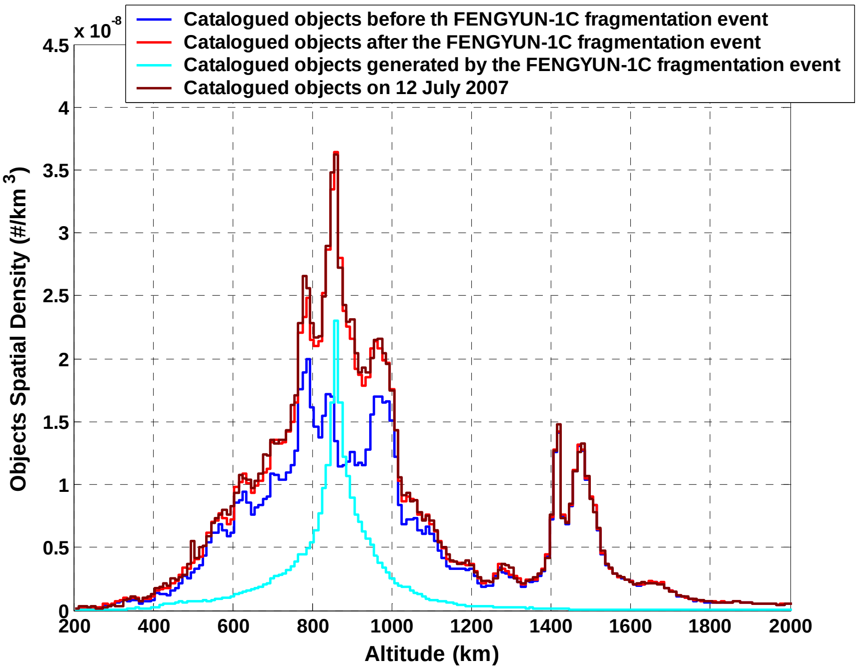

**Fig. 3. Spatial density of cataloged objects before and after the Fengyun-1C breakup.**

## DEBRIS CLOUD EVOLUTION

The cataloged debris for which a reasonable orbit and ballistic parameter were available (about 1800, on 15 June 2007) were propagated with a numerical code, taking into account the most important perturbations: the earth gravity field harmonics, up to the 16th order and degree, air drag, luni-solar third body attraction and solar radiation pressure with eclipses [1][2]. To estimate the effects of air drag during the next 15 years, the Jacchia-Roberts 1971 density model was adopted, together with the NASA Marshall Space Center 50% percentile prediction for the 10.7 cm solar flux proxy and the planetary geomagnetic index (available until February 2022).

The ballistic parameter, defined here as the product between the drag coefficient and the object area-to-mass ratio, was obtained from the "BSTAR" value provided for each object in the two-line elements issued by the US Space Surveillance Network [3][4]. The distribution of the values obtained is presented in Fig. 4, as a function of semimajor axis, in Fig. 5, as a function of eccentricity, and in Fig. 6, as a function of inclination. Some correlation is evident in the figures, as expected if selection effects are taken into account to describe the fragmentation dynamics and the debris radar detection. In fact, lighter objects may be affected by greater velocity variations and larger objects may be easily detected at greater distances, both selection effects concurring in explaining why typically higher values of the ballistic parameter – or, in practice, of the area-to-mass ratio – were found at greater altitudes and/or eccentricities (see Figs. 4 and 5).

The Chinese anti-satellite test dispersed the radar trackable fragments into a broad altitude interval, as shown in Fig. 1, but unfortunately most of the objects will have a substantial orbital lifetime. As of the end of July 2007, only 13 cataloged pieces of debris associated to the event had re-entered into the densest layers of the atmosphere and the mid term propagations carried out showed that the decay rate will remain very small in the next 15 years.

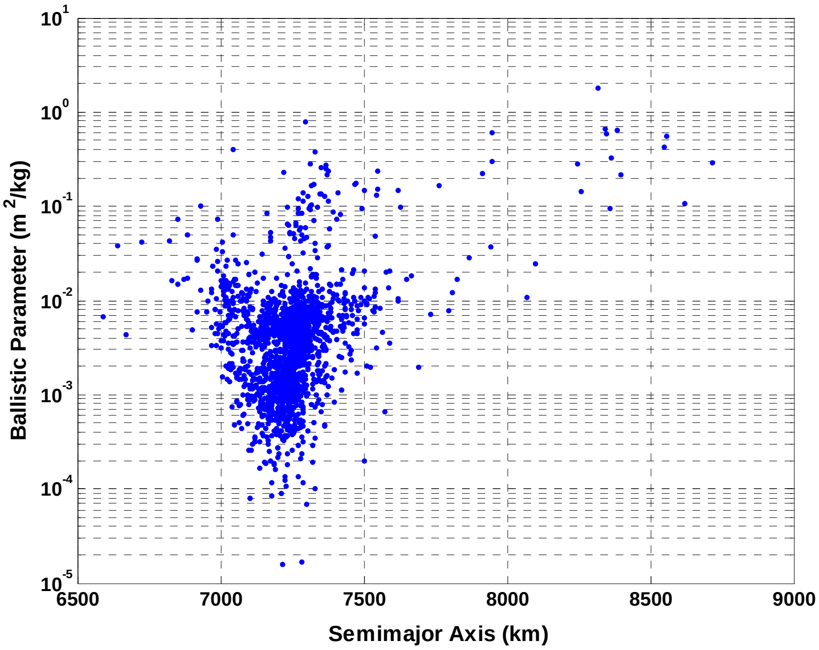

**Fig. 4. Distribution of the debris ballistic parameter, defined as the product between the drag coefficient and the area-to-mass ratio, as a function of the semimajor axis.**

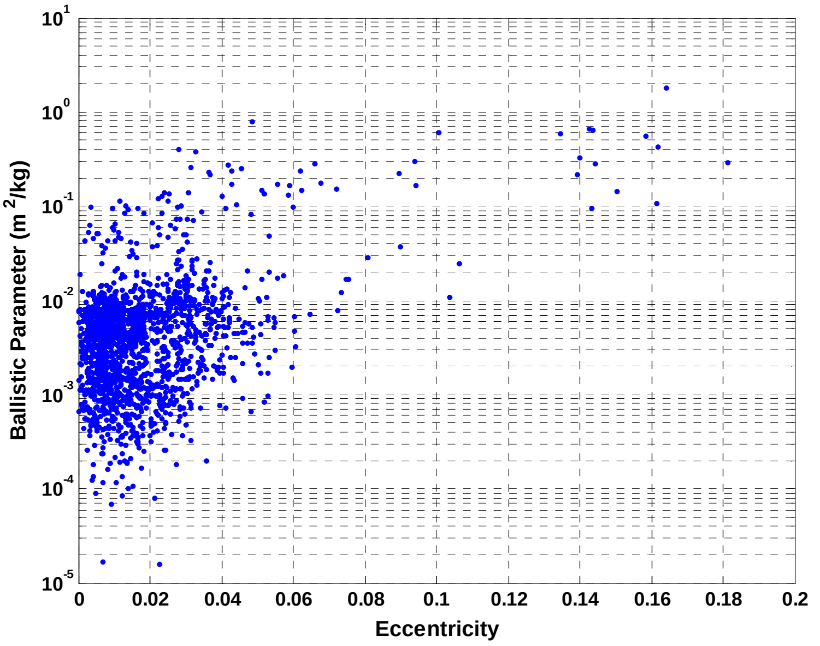

**Fig. 5. Distribution of the debris ballistic parameter, defined as the product between the drag coefficient and the area-to-mass ratio, as a function of the eccentricity.**

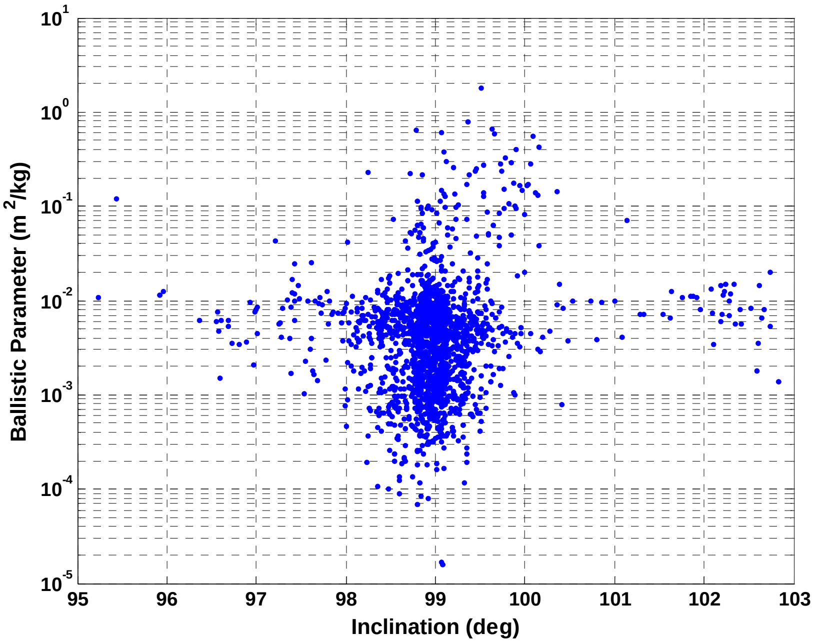

**Fig. 6. Distribution of the debris ballistic parameter, defined as the product between the drag coefficient and the area-to-mass ratio, as a function of the inclination.**

The results obtained from the detailed orbital propagation of the debris cloud over 15 years are summarized in the following plots. Figs. 7, 8 and 9 show the evolution in the elements space (semimajor axis, eccentricity and inclination), which remains quite limited in the time span considered. In other words, the cloud will basically maintain the same distribution in altitude and inclination. Concerning the orientation of the debris orbital planes in the inertial space, the situation is represented in Figs. 10 and 11 during the first 12 months, and Figs. 12 and 13 during the first 5 years after the breakup.

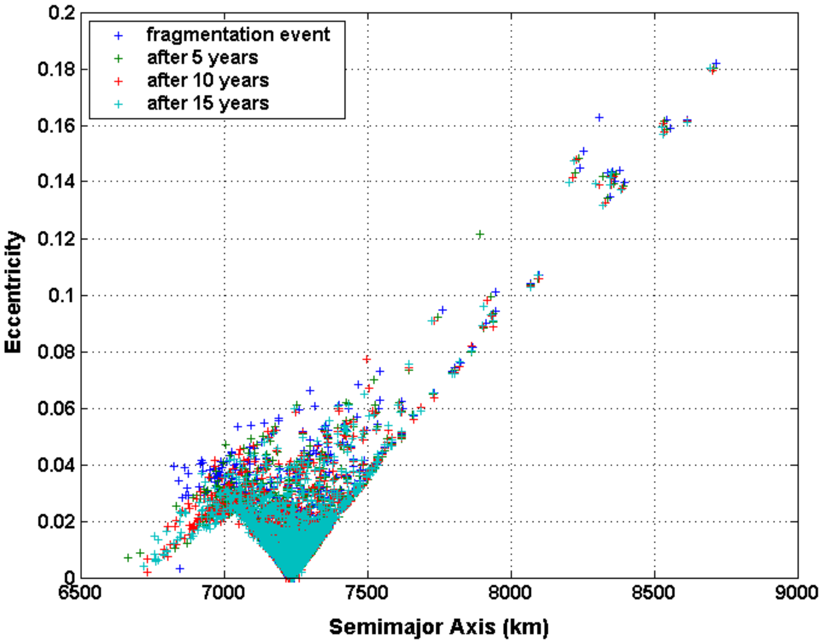

**Fig. 7. Debris cloud evolution, over 15 years, in the eccentricity-semimajor axis elements space.**

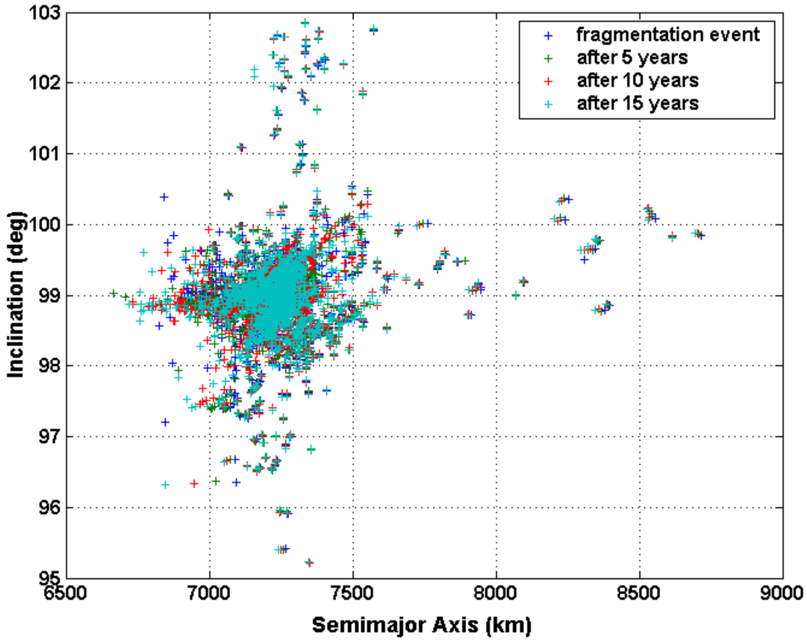

**Fig. 8. Debris cloud evolution, over 15 years, in the inclination-semimajor axis elements space.**

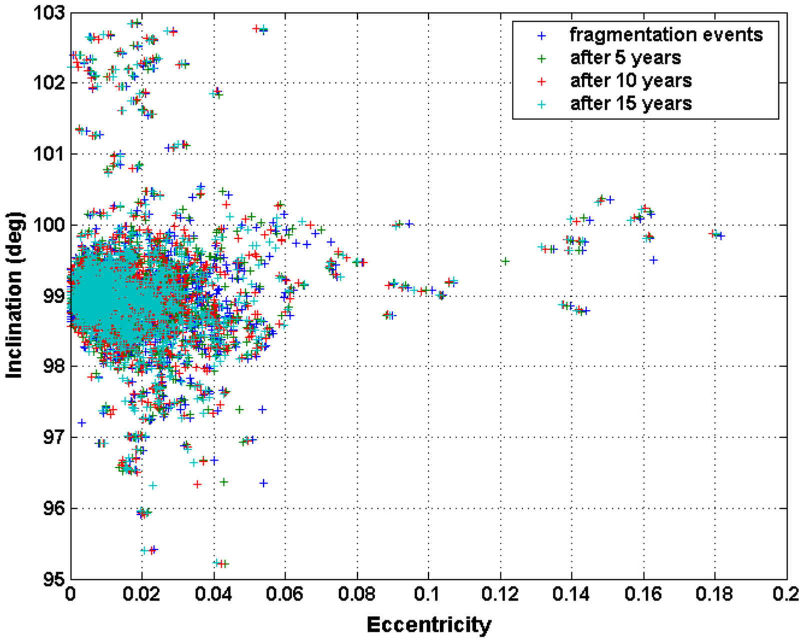

**Fig. 9. Debris cloud evolution, over 15 years, in the inclination-eccentricity elements space.**

Immediately after the fragmentation event, all the objects were practically in the same orbital plane, with a right ascension of the ascending node close to 0 deg. However, the differential precession of the node, induced by the zonal harmonics of the geopotential on orbits with different[1] semimajor axis, eccentricity and inclination, progressively resulted in a dispersion of the orbital planes of the cloud. Two months after the anti-satellite test,

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[1] Due to the action of air drag, semimajor axis and eccentricity were also subjected to a slight secular decrease as a function of ballistic parameter.

the ascending node dispersion of the debris orbital planes was about 50 deg, it became 150 deg after 6 months and in about 7-8 months the near polar orbits completely enveloped the earth with a shell of varying debris density (see, in particular, Fig. 10). Of course, this debris shell will become more evenly distributed in the coming years (see Figs 12 and 13).

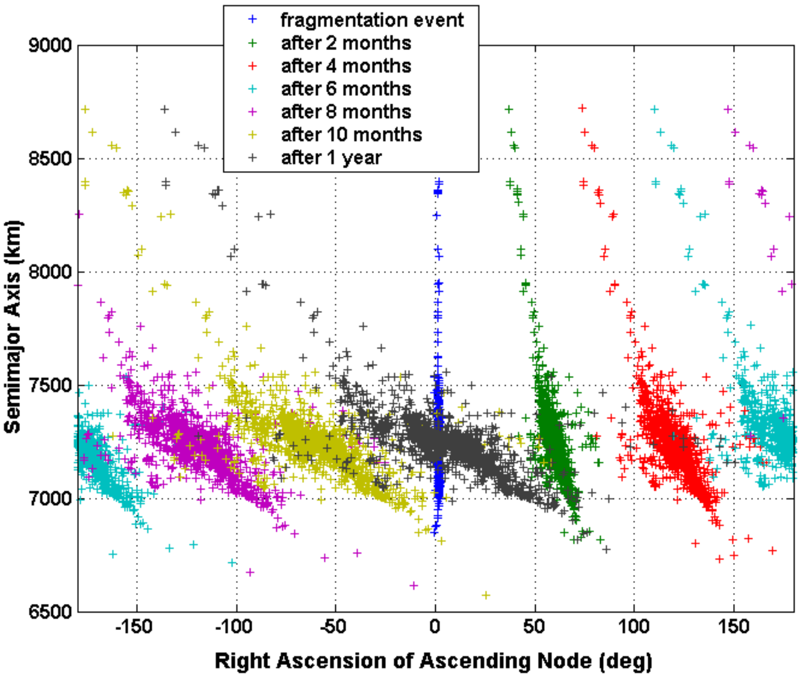

**Fig. 10. Spreading of the debris cloud orbital planes during the first year after the breakup as a function of semimajor axis.**

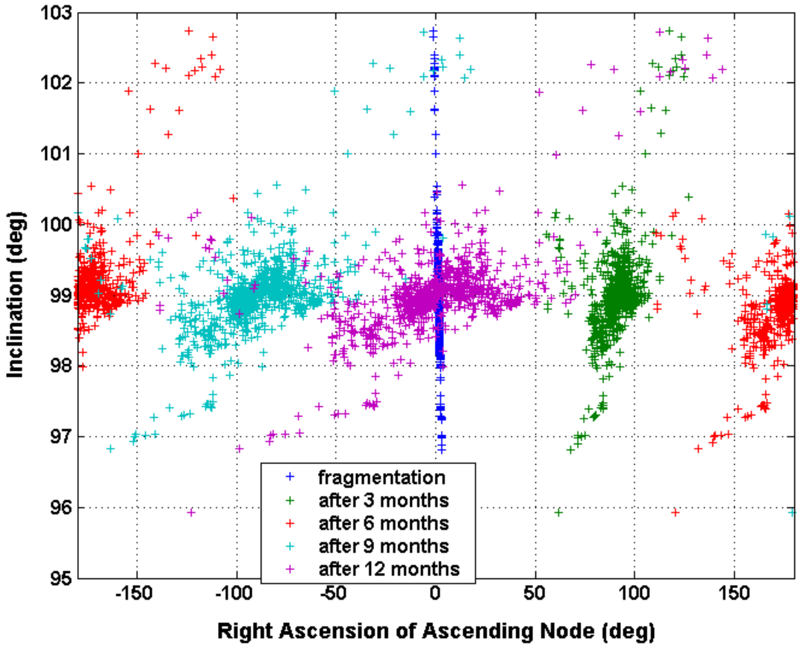

**Fig. 11. Spreading of the debris cloud orbital planes during the first year after the breakup as a function of inclination.**

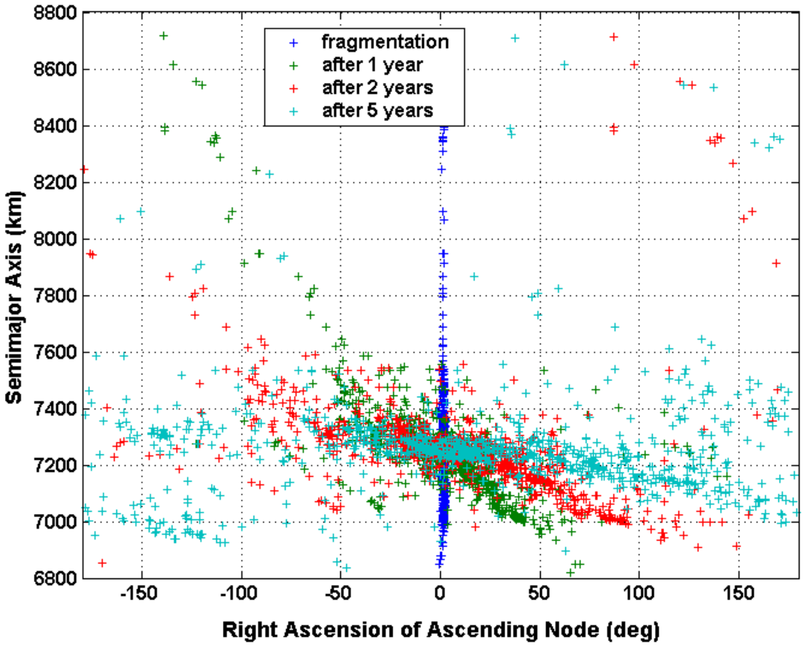

**Fig. 12. Spreading of the debris cloud orbital planes during the first five years after the breakup as a function of semimajor axis.**

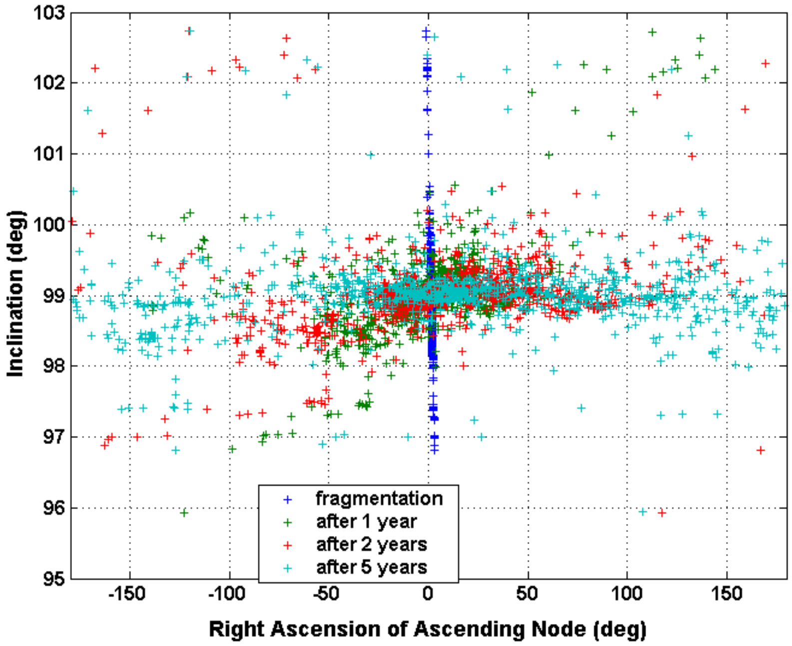

**Fig. 13. Spreading of the debris cloud orbital planes during the first five years after the breakup as a function of inclination.**

During the time span considered for the propagation of the cloud of 1800 cataloged objects, only a few fragments decayed from orbit: 0.50% after 1 year, 0.72% after 2 years, 1.61% after 5 years, 2.00% after 10 years and 2.89% after 15 years. The cloud was, therefore, extremely stable, apart from the progressive spreading and mixing of the orbital planes around the earth and the perigee precession of elliptical orbits. This picture is confirmed by Fig. 14, in which the evolution of the debris spatial density as a function of altitude is represented. Aside from small changes at very low and high altitudes, due to semimajor axis decay and apogee shrinkage, the average density of fragments remained practically the same during the time interval investigated, in particular in the critical orbital regime were the probability of collision was already maximum before the anti-satellite test. The adverse impact of the cloud on the circumterrestrial environment will be, accordingly, enduring.

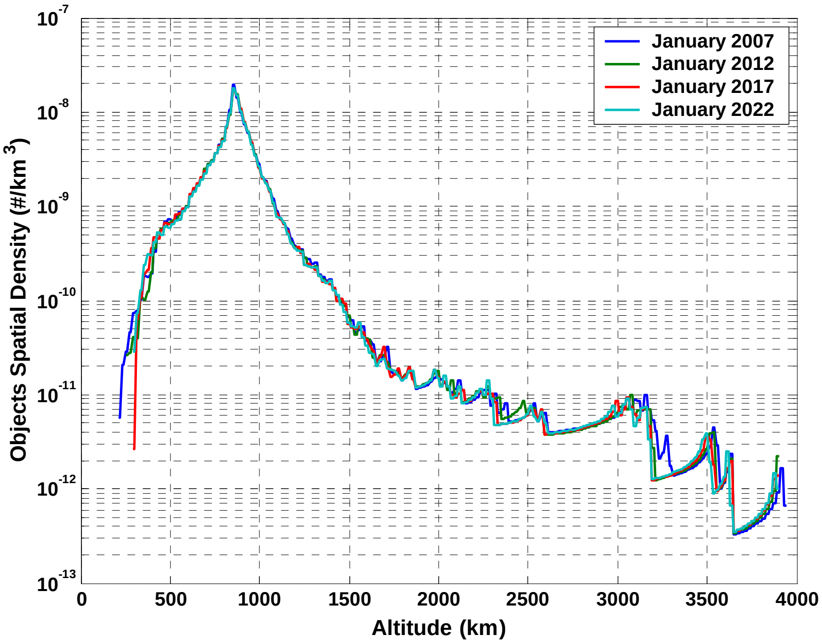

**Fig. 14. Evolution of the spatial density of the fragments generated by the anti-satellite test.**

Due to the orbital characteristics of the fragments, such a conclusion is not substantially affected by a possible systematic underestimation of the ballistic parameters. The underlying orbital theory leading to the generation of the two-line orbital elements considers an atmospheric model with fixed density, fitting the observed orbital decay with an appropriate value of the parameter “BSTAR” [3][4]. During periods of low solar activity, as the cycle minimum in 2007, the values of “BSTAR” are, consequently, smaller than average and the ballistic parameters obtained from it may be systematically underestimated, for instance by a factor ~ 2 at an altitude of 200 km.

However, for any given debris piece, the value of “BSTAR” may change a lot, even by one order of magnitude, between different two-line elements issued a few days – or even a few hours – apart. The intrinsic uncertainties are therefore considerable anyway and the propagation results must be considered reasonably accurate globally, in a statistical sense, but not looking at the behavior of specific objects. In any case, even taking into account these error sources, the basic conclusion of the analysis remains the same: the Fengyun-1C debris cloud is here to stay and for many decades the perturbations will not be able to sweep a substantial amount of the cataloged fragments.

## IMPACT RISK ASSESSMENT FOR SELECTED SATELLITES

A software tool specifically developed for orbital debris impact risk assessment [5][6] was used to estimate the additional impact risk on selected spacecraft due to the Fengyun-1C debris cloud. The satellites chosen for the analysis, all launched after the Fengyun-1C breakup, were: AGILE, an Italian astronomical spacecraft in equatorial orbit, COSMO-SkyMed 1, an Italian remote sensing spacecraft in sun-synchronous orbit, and TerraSAR-X, a German remote sensing spacecraft in sun-synchronous orbit. The reference epoch for the evaluation was 12 July 2007 and the mean orbital elements of the satellites are given in Table 1.

Ignoring the objects generated by the Fengyun-1C fragmentation event, the flux of cataloged debris on AGILE was found to be $1.16 \times 10^{-5}$ $m^{-2}$ $yr^{-1}$, with an average collision velocity of 9.839 km/s. The inclusion of the

Chinese cloud of cataloged debris did not change the directionality of the flux, but increased its magnitude by 12%, to 1.30 × $10^{-5}$ $m^{-2}$ $yr^{-1}$. The average collision velocity increased as well, to 9.871 km/s. Fig. 15 shows the cross sectional area flux as a function of the incoming debris relative velocity. Due to the orbit geometry and debris distribution, the collisional flux is dominated by objects in high inclination orbits crossing the equatorial region were AGILE resides.

**Table 1**

**Mean Orbital Elements of the Satellites Selected for the Impact Risk Assessment**

| Mean Orbital Elements | AGILE | COSMO-SkyMed 1 | TerraSAR-X |
|---|---|---|---|
| **Orbit Epoch** | 12 July 2007 | 13 July 2007 | 13 July 2007 |
| **Orbit Time** | 22:20:46.30 UTC | 04:31:58.04 UTC | 05:08:05.88 UTC |
| **Semimajor Axis** | 6922.406 km | 6997.665 km | 6883.494 km |
| **Eccentricity** | 0.00098 | 0.00123 | 0.0 |
| **Inclination** | 2.47 deg | 97.86 deg | 97.45 deg |
| **R.A. of Ascending Node** | 55.35 deg | 24.00 deg | 200.71 deg |
| **Argument of Perigee** | 66.01 deg | 91.63 deg | 346.87 deg |
| **Mean Anomaly** | 294.28 deg | 268.56 deg | 108.78 deg |

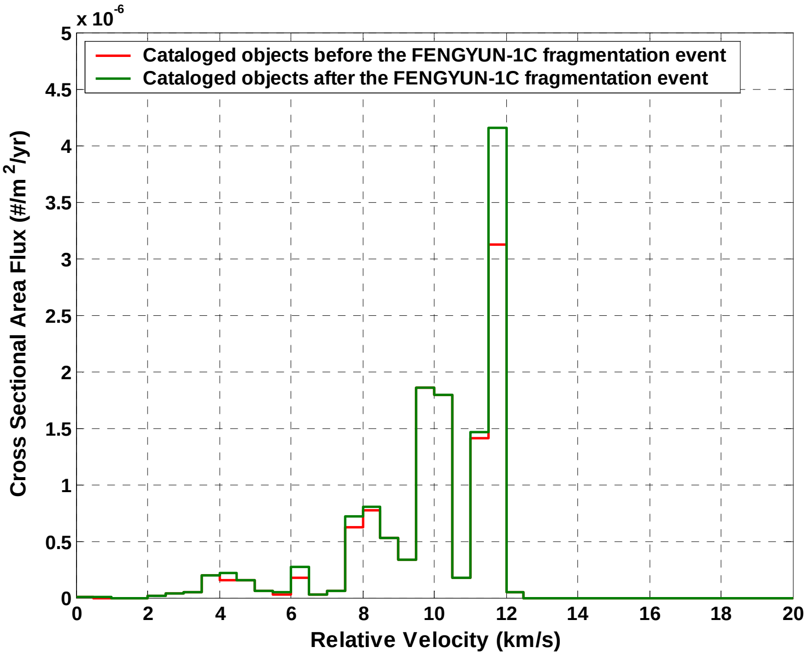

**Fig. 15. AGILE: cross sectional area flux as a function of the incoming debris relative velocity.**

Concerning COSMO-SkyMed 1, the flux of cataloged debris was found to be 2.32 × $10^{-6}$ $m^{-2}$ $yr^{-1}$, with an average collision velocity of 12.917 km/s, disregarding the objects generated by the Fengyun-1C fragmentation event. Even in this case, the inclusion of the Chinese cloud of cataloged debris did not change the directionality of the flux, but increased its magnitude by 38%, to 3.20 × $10^{-6}$ $m^{-2}$ $yr^{-1}$. The average collision velocity increased as well, to 13.410 km/s. Fig. 16 shows the cross sectional area flux as a function of the incoming debris relative velocity. It is clear that in this case, 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 (this explains the elevated value of the average collision velocity).

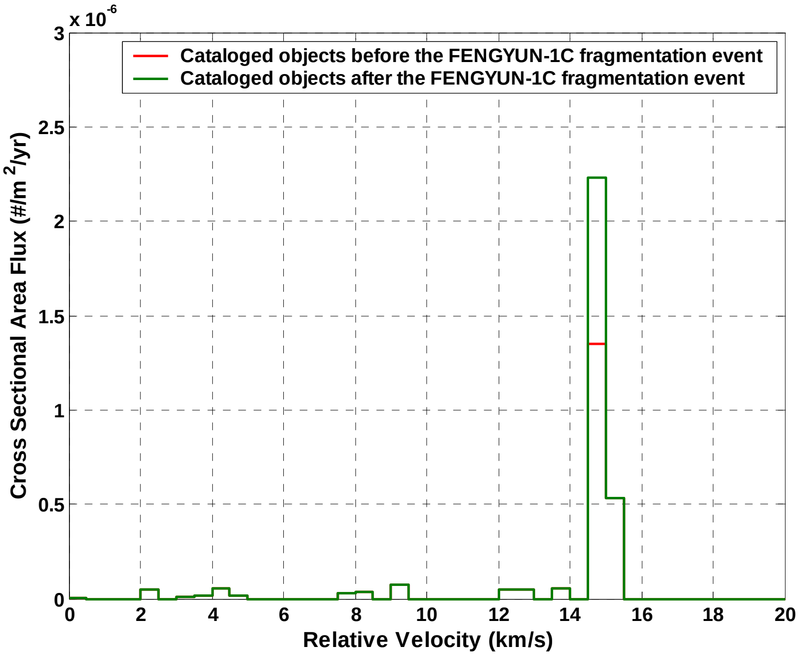

**Fig. 16. COSMO-SkyMed 1: cross sectional area flux as a function of the incoming debris relative velocity.**

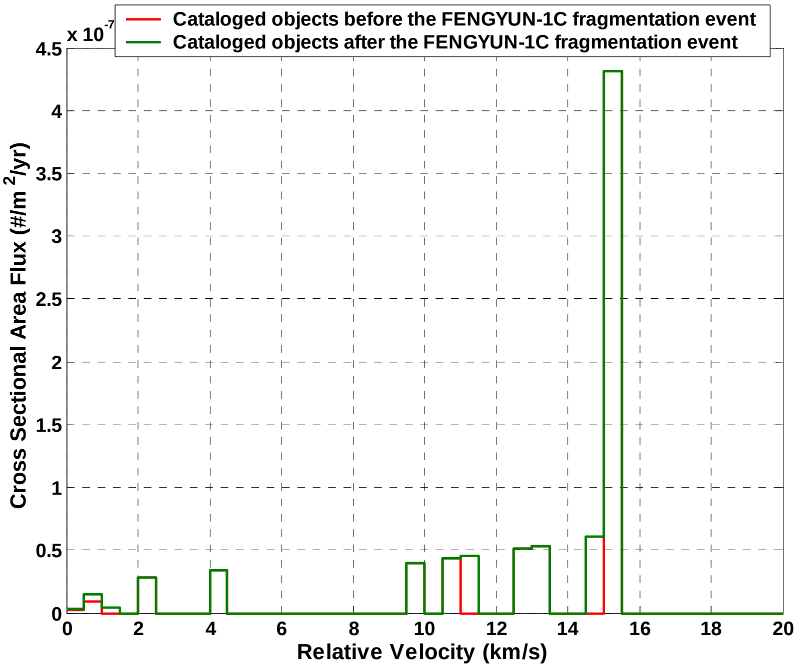

**Fig. 17. TerraSAR-X: cross sectional area flux as a function of the incoming debris relative velocity.**

Finally, as far as TerraSAR-X was concerned, the flux of cataloged debris was found to be $6.93 \times 10^{-7}$ $m^{-2}$ $yr^{-1}$, with an average collision velocity of 12.952 km/s, neglecting the objects generated by the Fengyun-1C fragmentation event. As in the previous cases, the inclusion of the Chinese cloud of cataloged debris did not change the directionality of the flux, but increased its magnitude by 17%, to $8.10 \times 10^{-7}$ $m^{-2}$ $yr^{-1}$. However, the average collision velocity decreased a little bit in this case, to 12.797 km/s. Fig. 17 shows the cross sectional area flux as a function of the incoming debris relative velocity. As in the COSMO-SkyMed 1 case, 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 (explaining, again, the elevated value of the average collision velocity).

In conclusion, the Fengyun-1C breakup significantly increased the collision probability with cataloged debris for the satellites (AGILE and COSMO-SkyMed 1) of the Italian Space Agency (ASI) operational in low earth orbit, but this is true, in general, for any other spacecraft, like the German TerraSAR-X, residing in the same orbital regime. Unfortunately, as discussed in the previous section, this worsened environmental situation is here to stay for a long time, negatively affecting future space operations.

## CONCLUSIONS

The untimely and ill-conceived anti-satellite test leading to the destruction of the aging meteorological satellite Fengyun-1C produced the worst debris cloud of the space age, reversing more than two decades of mitigation efforts, in order to preserve the circumterrestrial space for future generations. Unfortunately, the detailed propagations carried out showed that the cloud is very stable and will not suffer substantial debris decay during the next 15 years. As a matter of fact, natural perturbations alone will not be able to remove from orbit most of the cataloged fragments for centuries. The only significant short term evolution was the differential spreading of the orbital planes of the fragments, leading to the formation of a debris shell around the earth in about 7-8 months since the breakup, and the precession of the perigees of the elliptical orbits. Both effects will render the shell more “isotropic”, as seen from the center of the earth, in the coming years.

The obvious immediate consequence of the Chinese anti-satellite test, carried out in an orbital regime populated by many important operational satellites, was to increase significantly the probability of collision with man-made debris. For the two Italian spacecraft launched in low earth orbit in the first half of 2007, the collision probability with cataloged objects increased by 12% for AGILE, in equatorial orbit, and by 38% for COSMO-SkyMed 1, in sun-synchronous orbit, as of 12 July 2007.

Even though the adverse environmental effects of the Fengyun-1C breakup will be felt in low earth orbit for many decades, the recent approval, during the 6-15 June 2007 session, of a set of space debris mitigation guidelines by the United Nations’ Committee on the Peaceful Uses of Outer Space (COPUOS) represented a ray of hope for the future. Derived from the *Space Debris Mitigation Guidelines* issued in 2002 by the Inter-Agency Space Debris Coordination Committee (IADC), the COPUOS guidelines consist of a set of seven high level mitigation principles covering space system design, launch, operation and disposal. In particular, Guideline 4, titled “Avoid intentional destruction and other harmful activities” says: “Recognizing that an increased risk of collision could pose a threat to space operations, the intentional destruction of any on-orbit spacecraft and launch vehicle orbital stages or other harmful activities that generate long-lived debris should be avoided”. It is therefore reasonable to expect a more responsible behavior in the future from all the countries actively involved in space exploration and exploitation, especially after the approval of the COPUOS guidelines by the United Nations General Assembly.

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