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The Short-Term Impact of the Cosmos 1408 Fragmentation on Neighboring Space Regions: From Inhabited Space Stations to Large Satellite Constellations

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Abstract

In terms of cataloged debris produced, the anti-satellite test carried out by Russia, in November 2021, at an altitude of about 480 km, leading to the destruction of the old satellite Cosmos 1408, was the second worst to date and represented the third worse fragmentation in orbit. It generated more than 1/4 of the cataloged debris produced over 55 years by all such tests and almost twice as many as were produced by all previous Soviet tests. After placing this event in its historical context, this paper analyzes in detail how the evolution of the Cosmos 1408 debris cloud impacted the environment below 600 km in the first seven months, focusing on the two operational space stations and the Starlink mega-constellation of satellites. For the International Space Station, the Cosmos 1408 cloud of fragments increased the flux of cataloged objects, on average, by nearly 80%, while for the Tiangong Space Station the increase was almost 65%. Immediately after the test, the Starlink mega-constellation saw as well an increase in the flux of cataloged objects, of the order of 20% on average. Some orbital planes, the "counter-rotating" ones with respect to the Cosmos 1408 debris cloud, were more affected than others, and the affected planes gradually changed over time, due to the differential precession of cloud and constellation nodes. However, being the Starlink constellation 70 km higher up, the flux of Cosmos 1408 cataloged debris steadily decreased over the period analyzed, due to the cloud orbital decay, more than halving after seven months.

Keywords: ASAT tests, space debris, fragmentation cloud, debris flux, space stations, Starlink constellation.

1. Introduction

The Soviet electronic intelligence (ELINT) satellite Cosmos 1408 (1982-092A), launched in low Earth orbit (LEO) on 16 September 1982, was destroyed in a Russian anti-satellite (ASAT) weapon test on 15 November 2021. The abandoned spacecraft, belonging to the Tselina-D class, with a mass around 1750 kg, traveled through an orbit of high inclination (82.56°) and its intentional fragmentation, which occurred in a decaying orbit with a semi-major axis of 6852.7 km and an eccentricity of 0.00186, led to the generation of a debris cloud comprising more than 1700 trackable pieces – about 1300 of which larger than 10 cm –, as well as about 60,000 fragments greater than 1 cm. The altitudes of the cataloged pieces were scattered between 200 and 1500 km, then crossing the most populated regions in LEO [1-2].

The ASAT test took place in a region of space hosting crewed assets, such as the International and Chinese space stations, as well as large constellations of satellites, like the SpaceX's Starlink around 550 km. As a matter of fact, the debris cloud immediately posed a threat to the International Space Station (ISS) and its crew, forcing astronauts and cosmonauts to undertake safety procedures in the first couple of days following the event. The threat also increased for the Tiangong Chinese Space Station (CSS) and its taikonauts, and also for the numerous satellites that orbit, or will be placed, in those regions of space crossed by the Cosmos 1408 evolving debris cloud.

After a review of the ASAT tests carried out so far, to place the intentional destruction of Cosmos 1408 in the proper context, the purpose of this paper is to assess how the average flux of cataloged objects increased and evolved during the first 7 months at the heights of the International and Chinese space stations, as well as for the Starlink large constellation, operating in orbits with an altitude of 547 km and an inclination of 53°. Finally, the paper concludes with a discussion of the consequences of this kind of tests, recommending their immediate discontinuation as an additional measure to foster the sustainability of space activities and the safeguarding of the circumterrestrial environment.

2. ASAT weapons as a source of orbital debris

A good overview of the history of anti-satellite weapon programs can be find in [3]. The purpose of ASAT weapons is to incapacitate or destroy satellites. China, India, Russia and the United States have currently this capacity, recently demonstrated by intercepting and destroying their own satellites, but several other countries possess the needed knowhow and technology as well [4-6].

Concerning the space debris problem, a functioning satellite rendered inoperative by an ASAT system obviously represents a further object to be added to the list of abandoned spacecraft [7]. However, what matters most are the ASAT weapons that can knock out so many satellites in one shot, or destroy a target satellite by generating hundreds or thousands of trackable fragments. An example of the former is the detonation of nuclear warheads in space, a crazy practice fortunately now prohibited by the enactment of the Partial Test Ban Treaty (PTBT) of 1963 [8]. Examples of the latter, instead, are systems using the explosion of conventional explosives near their target, or vehicles without explosives that destroy the target by impacting it at high relative speed. Therefore, in the following, only the above mentioned ASAT systems are discussed, thus ignoring those that can damage or render satellites inoperative with laser beams, radio interference, or cyberattacks, just to give some examples [3-6].

In the late 1950s and early 1960s, both the United States and the Soviet Union began the development of the first ASAT weapons, often stretching the residual operational capabilities of systems conceived for other missions. Due to the limitations of the guidance and navigation devices of the time, no system was able to get closer to its target than several kilometers away, requiring the use of interceptors armed with nuclear warheads.

In 1958, the United States tested three 1.5 kiloton nuclear bombs at the height of 480 km, in order to inject electrons into the Van Allen radiation belts, but the experiment did not live up to expectations. In 1962, a thermonuclear bomb a thousand times more powerful was exploded at a height of 400 km above Johnston Island, in the Pacific Ocean, knocking out several satellites, but also triggering an electric and telephone blackout in the Hawaii Islands, 1300 km away. The Soviet Union carried out four nuclear tests in space: two in 1961, of 1.2 kilotons, and two in 1962, of 300 kilotons.

With the signature of the Partial Test Ban Treaty (PTBT), in 1963, these tests were fortunately discontinued, and in any case ASAT systems involving nuclear weapons had many serious disadvantages, such as being indiscriminate and unpredictable in their effects, felt at great distances and even after a few weeks. Since then the effort has therefore shifted to approaches that could limit the immediate damage to a specific target, a progress made gradually possible by the development of increasingly accurate and reliable guidance and navigation devices.

During the 1960s, the Soviet Union developed a "co-orbital" ASAT system, in which a chaser spacecraft carrying on board conventional explosives is launched into the same orbital plane of the target satellite. After a fast rendezvous phase, the chaser spacecraft moves near enough to its target in order to fatally damage it with the shrapnel produced by the explosion of the conventional charge.

From 1968 to 1982, 9 chaser spacecraft (Cosmos 249, 252, 374, 375, 397, 462, 886, 970 and 1174) and 4 target satellites (Cosmos 248, 839, 880 and 1375) have suffered breakup over the course of the ASAT system development program [9], producing a total of 916 cataloged debris in LEO, 409 (about 45%) of which still in orbit as of 20 June 2022. 730 pieces, of which 282 (about 39%) still in orbit, were generated by the explosions of the interceptors, while 186, of which 127 (about 70%) still in orbit, resulted from the damage suffered by the target satellites. Since 1982, the Soviet Union, and then Russia, have not destroyed any other satellites in the framework of ASAT activities for nearly 40 years, that is, until the destruction of Cosmos 1408 – the subject of this paper – in 2021.

The United States focused instead on a different system, which was used only once in the past century against a satellite. It consisted of a two-stage missile launched at high altitude by an F-15 fighter jet. The missile was to intercept its target orbiting in low LEO with a direct ascent trajectory, releasing a miniature homing vehicle for destroying the satellite not with an explosion, but by crashing into it at great speed. In October 1985, this new ASAT weapon was successfully tested targeting Solwind (also known as P78-1), an aging scientific spacecraft for the study of solar physics with degrading batteries. With a dry mass of 850 kg, it orbited at an altitude of about 525 km, with an inclination of 97.6° with respect to the Earth's equator. The destruction of Solwind produced 285 cataloged fragments, the last of which decayed in the atmosphere in 2004.

Even though not conceived as an ASAT test, but rather as a development step under the Strategic Defense Initiative, for the purposes of this paper also deserves to be mentioned the Delta 180 mission [10], carried out in September 1986 in an orbit of 220 km with an inclination of 28.5°. In fact, at the end of the mission, the payload (USA 19), after having maneuvered to a distance of 200 km from the second stage of the Delta rocket used to launch it, was commanded to intercept the upper stage, colliding with it at a relative velocity of 2.9 km/s. The impact also ignited the self-destruction charge, leading to the complete fragmentation of the two bodies. Only 18 fragments were cataloged, the last of which entered the densest layers of the atmosphere in April 1987.

After this event, no further ASAT tests leading to the destruction of satellites in orbit were conducted for more than 20 years, encouraging the hope that an increasingly widespread and shared awareness of the fragility of the circumterrestrial environment had led the major space powers to decide on an indefinite moratorium. Unfortunately, in the new century, these hopes have proved premature, instead observing a resurgence of ASAT tests, which, in some cases, have had a negative impact on the environment like never before.

3. ASAT tests at the beginning of the XXI century

The long 20-year moratorium of destructive ASAT tests came to an abrupt end in January 2007, when the defunct weather spacecraft Fengyun 1C, in a sun-synchronous orbit at the altitude of about 865 km, was destroyed by a Chinese kinetic energy kill vehicle launched into a direct ascent intercept trajectory by an SC-19 missile [3,11,12]. The catastrophic breakup of the 880 kg spacecraft generated – as of 20 June 2022 – 3533 cataloged fragments, 2829 (i.e. 80%) of which still in orbit. Even today, it yet represents the most severe fragmentation ever occurred in orbit. Alone, as of 20 June 2022, it has produced more cataloged debris (+8%) than all other tests combined, both before and after, and the fragments still in orbit are more than 2.3 times those attributable to all other tests. Moreover, due to the initial orbit of the target satellite, a significant fraction of the debris will remain in space for several decades, adversely affecting the environment in a LEO region already especially crowded [13].

The second ASAT weapon of the XXI century was used by the United States a little over a year later, in February 2008 [3,14]. The move was justified by the need to destroy a 1-meter spherical propellant tank filled with about 450 kg of toxic hydrazine on board the failed satellite USA 193, reentering uncontrolled from a low orbit with an inclination of 58.5° [15]. The hydrazine, needed for orbit maintenance, had never been used, due to the failure of the spacecraft immediately after its launch, and was now frozen inside the tank, then representing a considerable reentry casualty risk, according to NASA estimates [14].

USA-193, with an estimated mass of about 2400 kg [14], was destroyed by the high velocity impact with a lightweight exo-atmospheric projectile kinetic warhead launched into a direct ascent intercept trajectory with a modified SM-3 missile, fired from an Aegis cruiser stationed west of the Hawaii Islands. The interception, occurred at a geodetic altitude of just 249 km, produced 175 cataloged fragments. However, being the engagement height so low, most of the debris decayed from orbit within a few months and the last cataloged piece entered the atmosphere at the end of October 2009.

The Chinese and American satellite destructions, separated from each other by only one year, were then followed by 11 years without further events of the same kind. Nevertheless, this apparent calm was abruptly interrupted at the end of March 2019, when India joined the exclusive club of nations that had destroyed an orbiting spacecraft with an ASAT weapon [16]. Once again, repeating a choreography now distinctive of the latest generation of ASAT systems, the interceptor was launched from the ground, targeting an Indian satellite, Microsat-R, designed for this very purpose. The spacecraft, placed at an altitude of about 278 km, on an orbit inclined 96.6° to the Earth's equator, had a mass of 740 kg. Its fragmentation, as a result of the impact, at the relative speed of 9.8 km/s, with a kinetic energy kill warhead launched with a Prithvi Delivery Vehicle Mark-II missile [17], generated 130 cataloged debris. Due to the relatively low altitude in which the test was conducted, 69% of the fragments decayed from orbit during the first 6 months, and 82% during the first 9 months. 19 pieces entered the atmosphere in 2020, 3 in 2021 and the last one finally decayed in June 2022.

4. The destruction of Cosmos 1408

According to the detailed reconstruction described in [18], Cosmos 1408 was destroyed at 02:47:31.5 UTC on 15 November 2021. The kinetic kill interceptor, launched minutes earlier from Plesetsk Cosmodrome with a Nudol missile, that inserted it into a suborbital direct ascent trajectory, impacted the old Tselina-D spacecraft with a relative velocity of 4.6 km/s [18], completely destroying the satellite at a geodetic altitude of 479.5 km, above the geographical coordinates of 68.558° N and 46.611° E.

As of 20 June 2022, the US space surveillance network has cataloged 1764 objects, of which 806 are still in orbit. These numbers make the destruction of Cosmos 1408 the second worst ASAT test recorded to date, preceded only by the Chinese one in 2007. It also represents the third worst fragmentation in orbit, with the second place occupied by the accidental collision between Iridium 33 and Cosmos 2251 in 2009 [13,18]. However, the debris cloud generated by the Russian ASAT test will last much less than those of the couple of catastrophic events just mentioned. In fact, according to the predictions outlined in [18], more than 95% of the cataloged debris will enter the atmosphere in less than 2 years after the breakup, while all remaining pieces will decay in less than 10 years.

Table 1. Cataloged debris produced by ASAT tests and still in orbit, as of 20 June 2022. The first phase (I) ended in 1986, while the second phase (II) began in 2007. The two worst fragmentations recorded to date are explicitly reported as well.

ASAT Tests Phase/Target	Total Cataloged Debris	Total Cataloged Debris in Orbit
I (XX Century)	1214	409
II (XXI Century)	5602	3635
I+II (All ASAT)	6816	4044
Fengyun 1C	3533	2829
Cosmos 1408	1764	806

Table 1 summarizes the contribution of ASAT tests to the orbital debris environment. The first phase, ended in 1986, produced 18% of the debris cataloged so far, while 82% of the cataloged debris were generated, since 2007, during the second phase, when mitigation principles and guidelines, also formally supported by the countries involved, were already in place, for example the *Space Debris Mitigation Guidelines* of the Inter-Agency Space Debris Coordination Committee (IADC), whose first version dates back to 15 October 2002, or the Resolution 62/217 of 22 December 2007, by which the General Assembly of the United Nations endorsed the *Space Debris Mitigation Guidelines* of the Committee on the Peaceful Uses of Outer Space (COPUOS).

The ASAT test fragments still in orbit, as of 20 June 2022, represent 1/3 of all cataloged fragmentation debris and 30% have been produced in the last 15 years. Concerning the destruction of Cosmos 1408, it accounts for more than 1/4 of the cataloged debris generated by ASAT tests. All the cataloged fragments produced by the Soviet Union from 1968 to 1982, during the first phase of ASAT testing, involving 13 spacecraft, were only slightly more than half of those produced by the breakup of Cosmos 1408 alone. The same proportion is reflected in the number of objects still in orbit, which, in the case of Cosmos 1408, also account for 20% of ASAT test debris and approximately 7% of fragmentation debris.

5. Cosmos 1408 debris cloud evolution

The Gabbard plot of the cataloged debris produced by the intentional destruction of Cosmos 1408 is shown in Figure 1. The fragments large enough to be tracked have been hurled into orbits with heights between the lower limits of outer space and nearly 1500 km, thus traversing the most densely populated regions of the LEO environment. However, the highest concentration of fragments was distributed between 350 and 600 km, as shown in Figure 2.

The evolution of the debris cloud is summarized, for the first seven months, in Figures 3-7. In each of them, as well as in the Gabbard plot (Figure 1), the orbital decay due to atmospheric drag is evident, both directly and indirectly, because of the relatively low altitude in which the breakup occurred. This is particularly true for Figure 3, showing how the debris spatial density has evolved over time, causing a significant contraction of the cloud, both in terms of number of debris and altitude ranges significantly affected. As of 20 June 2022, 54% of the cataloged debris had already entered the atmosphere and, according to preliminary assessments, the cloud is destined to disappear within a couple of years after the ASAT test [18].

Figures 4 and 5, on the other hand, tell us primarily how the fragmentation energy was distributed among the fragments, imparting velocity changes that modified their orbit, both in-plane (semi-major axis, eccentricity and argument of perigee) and out-of-plane (inclination and right ascension of ascending node). A uniform and isotropic distribution of velocity changes imparted to the fragments by the breakup would imply that larger in-plane variations correspond, on average, to smaller out-of-plane variations, and vice versa. Although actual fragmentations always deviate from this idealized model, Figures 4 and 5 show anyway a certain degree of anti-correlation between in-plane and out-of-plane changes. The maximum velocity change imparted to cataloged debris was estimated to be around 260 m/s, even though some tracked objects with velocity changes up to 450 m/s were identified in [18].

Figures 6 and 7 are particularly interesting, because they show how the orbit plane spreading of the fragments progressed during the first seven months following the breakup. This orbit plane dispersion, beyond the initial few degrees (2°-3°) caused by the velocity changes imparted to some of the fragments by the breakup process itself, is caused by the differential rate of node precession induced by the zonal harmonics of geopotential on debris placed in orbits with different – and varying, due to atmospheric drag – semi-major axes. However, being the inclination of the parent object close to 90°, where the precession of the node cancels out, the differential rate of node precession is quite slow, and the orbit plane spreading rate for the extreme limits of the cloud of cataloged objects is just 0.28° per day, much less ($\approx 0.05°$ per day) for the core of the cloud.

This explains why the distribution of the nodes of the cloud remained so compact in seven months. Considering the relatively short orbital lifetime of the cloud, roughly two years, this also means that the Cosmos 1408 fragments will not be able to form a roughly uniform debris shell around the Earth, as happened instead to the fragments of Fengyun 1C and Cosmos 2251. Moreover, regarding the potential collisional risk represented by the Cosmos 1408 debris, for the time to come it can never be regarded as part of an almost uniform background, being the cloud concentrated in a relatively narrow range of nodes.

6. Increase of debris flux on space stations

The increased collision risk in low LEO due to the Cosmos 1408 debris cloud was analyzed in [18], focusing the attention on the first days and months following the ASAT intercept and describing in detail the augmented spacecraft operator workload for the Planet's fleet of small Earth observation satellites, the largest to date for such a purpose. In this paper the attention is concentrated on how the debris flux evolved, during the first seven months, considering as targets the two permanently crewed space stations and the SpaceX's Starlink mega-constellation of satellites, by far the largest deployed to date.

For this aim we have resorted to the Space Debris Impact Risk Analysis Tool (SDIRAT), developed by us since 1998 [19-21]. Conceived as a practical space engineering software program completely independent of the debris model used, it is able to incorporate and process any orbital debris population, provided it includes, at the very least, the orbital state vector for each representative object.

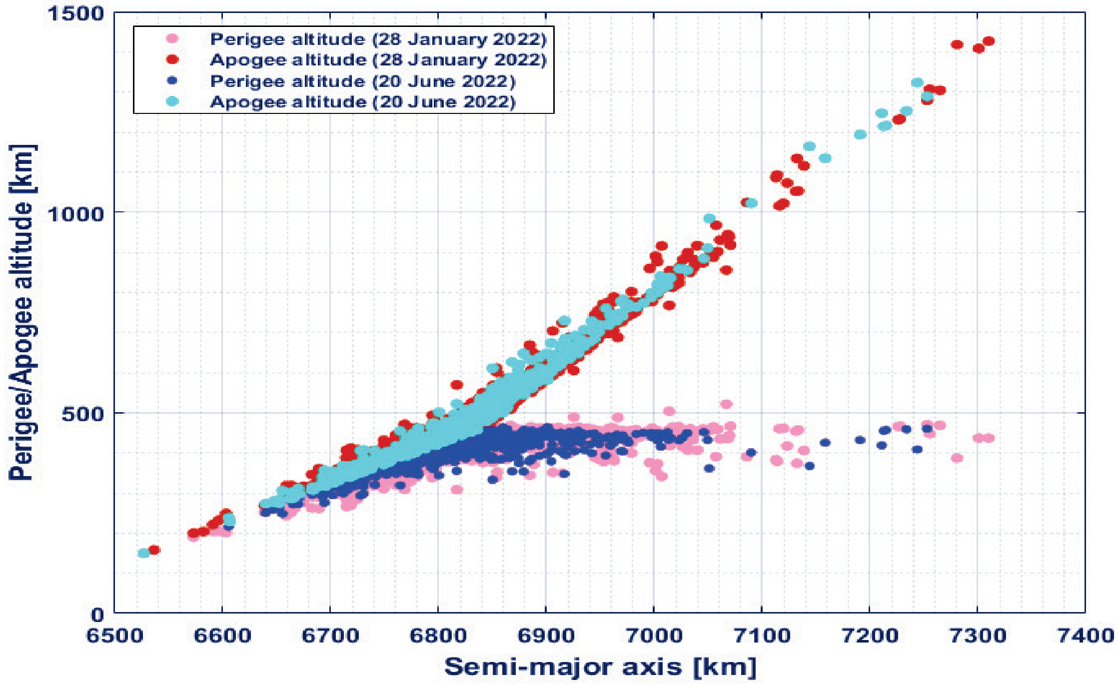

Fig. 1. Gabbard plot of the cataloged debris produced by the intentional destruction of Cosmos 1408. The progressive orbital decay due to atmospheric drag intervened in approximately 5 months, between 28 January and 20 June 2022, is evident.

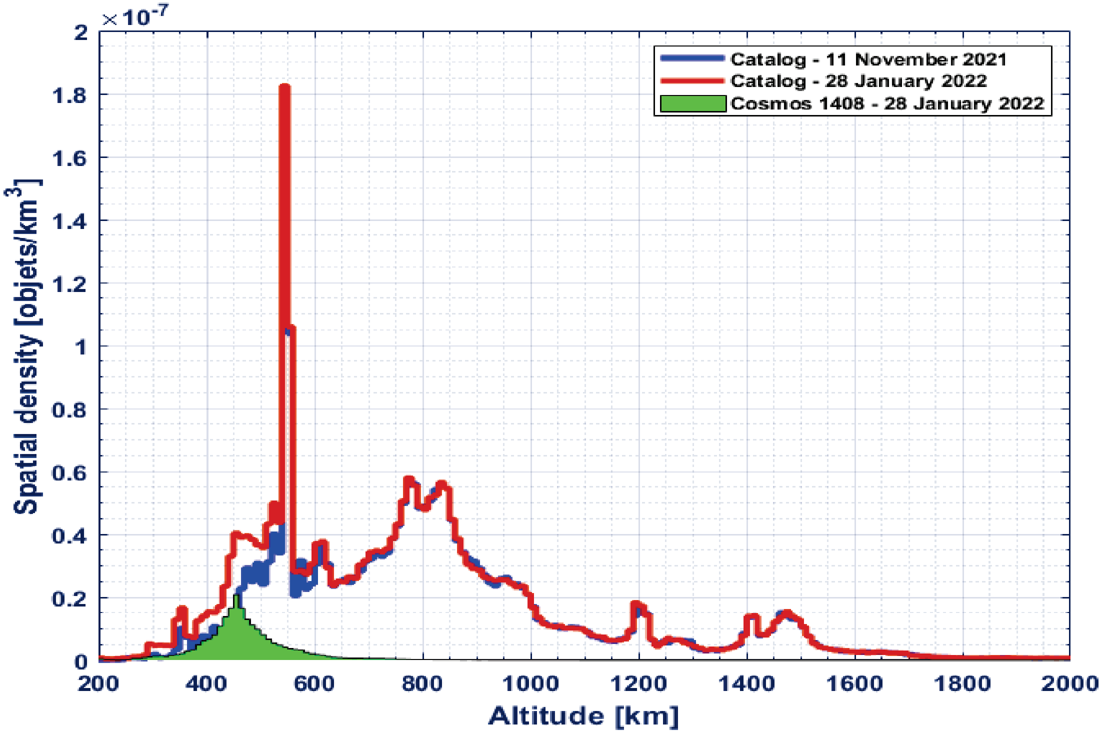

Fig. 2. Spatial density of cataloged objects in LEO, over 10 km altitude bins, before and after the Cosmos 1408 ASAT test (the altitude is counted from the mean equatorial Earth's radius). The Cosmos 1408 debris cloud mainly affected the altitude range between 350 and 600 km.

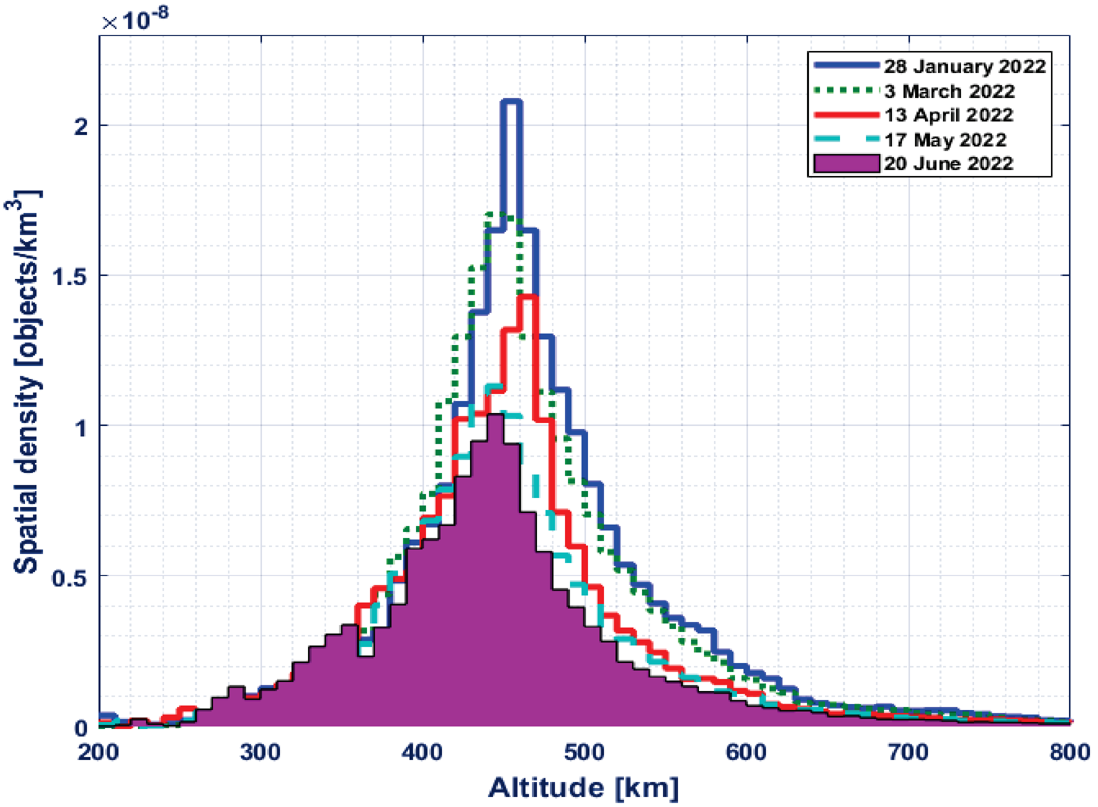

Fig. 3. Evolution of the spatial density of the Cosmos 1408 cataloged debris cloud, from 28 January to 20 June 2022. The shrinkage of the cloud due to atmospheric drag, both in the number of objects and in altitude distribution, is evident. The cloud is destined to disappear within a couple of years after the ASAT test.

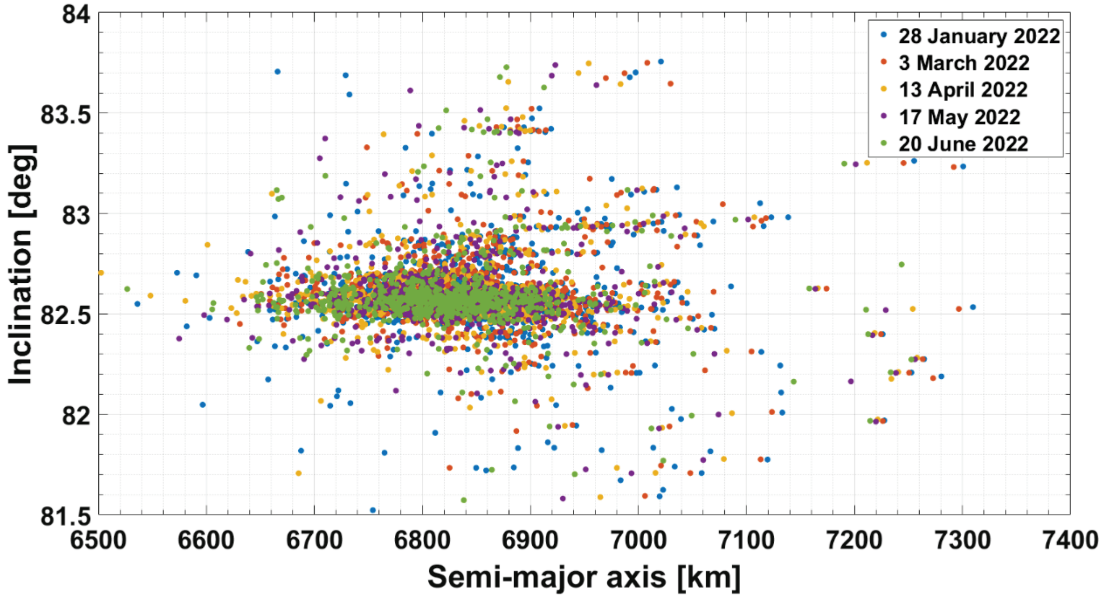

Fig. 4. Distribution of inclination vs. semi-major axis (mean elements in the True Equator Mean Equinox reference frame) of the Cosmos 1408 cataloged debris.

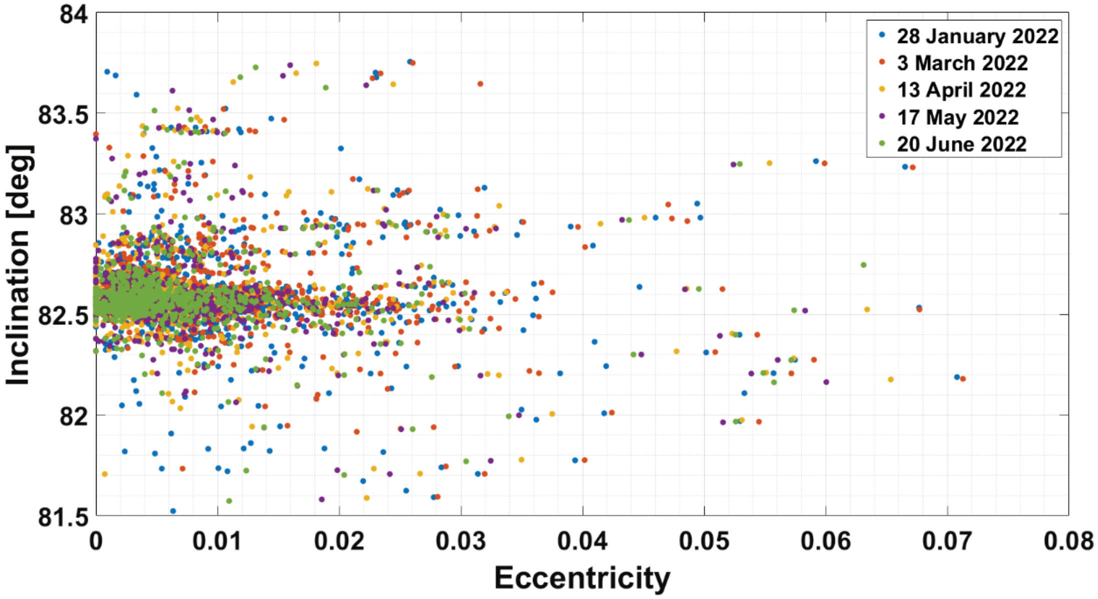

Fig. 5. Distribution of inclination vs. eccentricity (mean elements in the True Equator Mean Equinox reference frame) of the Cosmos 1408 cataloged debris.

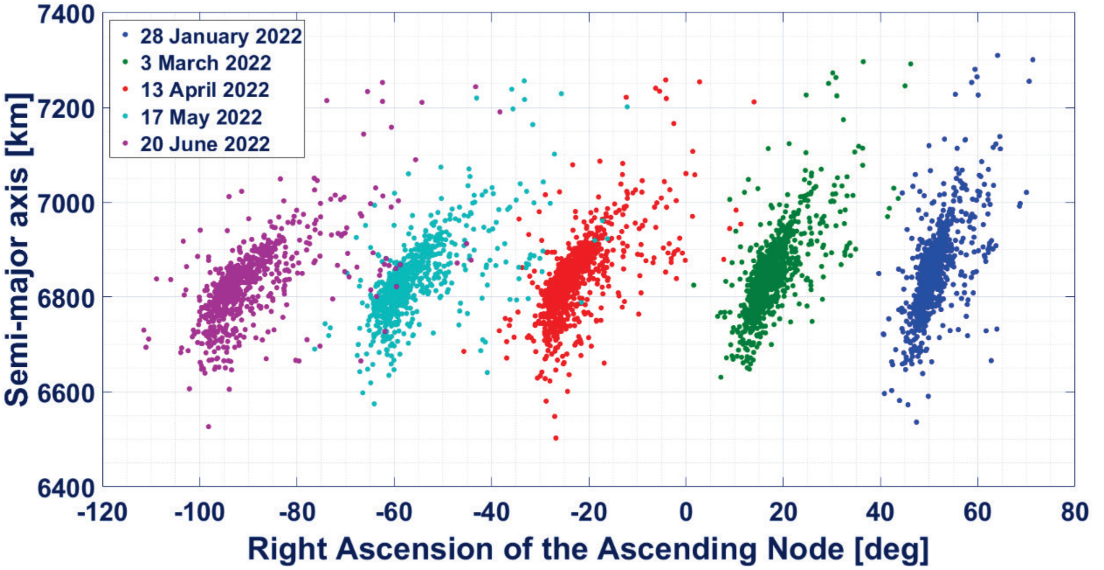

Fig. 6. Distribution evolution of semi-major axis vs. right ascension of ascending node (mean elements in the True Equator Mean Equinox reference frame) of the Cosmos 1408 cataloged debris. The line of nodes of the core of the cloud is subject to a node regression of one degree per day.

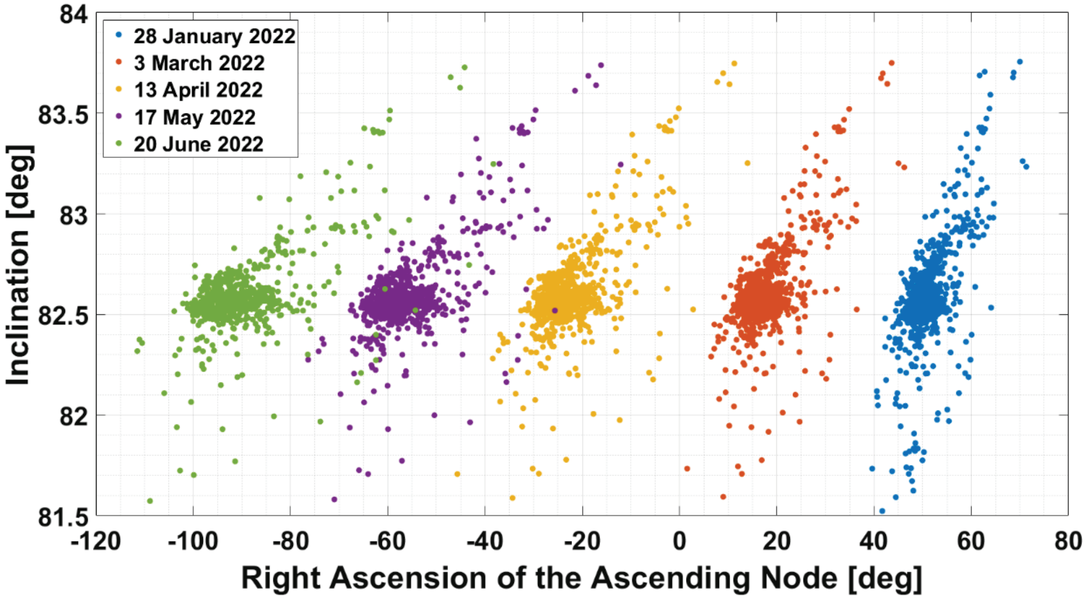

Fig. 7. Distribution evolution of inclination vs. right ascension of ascending node (mean elements in the True Equator Mean Equinox reference frame) of the Cosmos 1408 cataloged debris. The line of nodes of the core of the cloud is subject to a node regression of one degree per day.

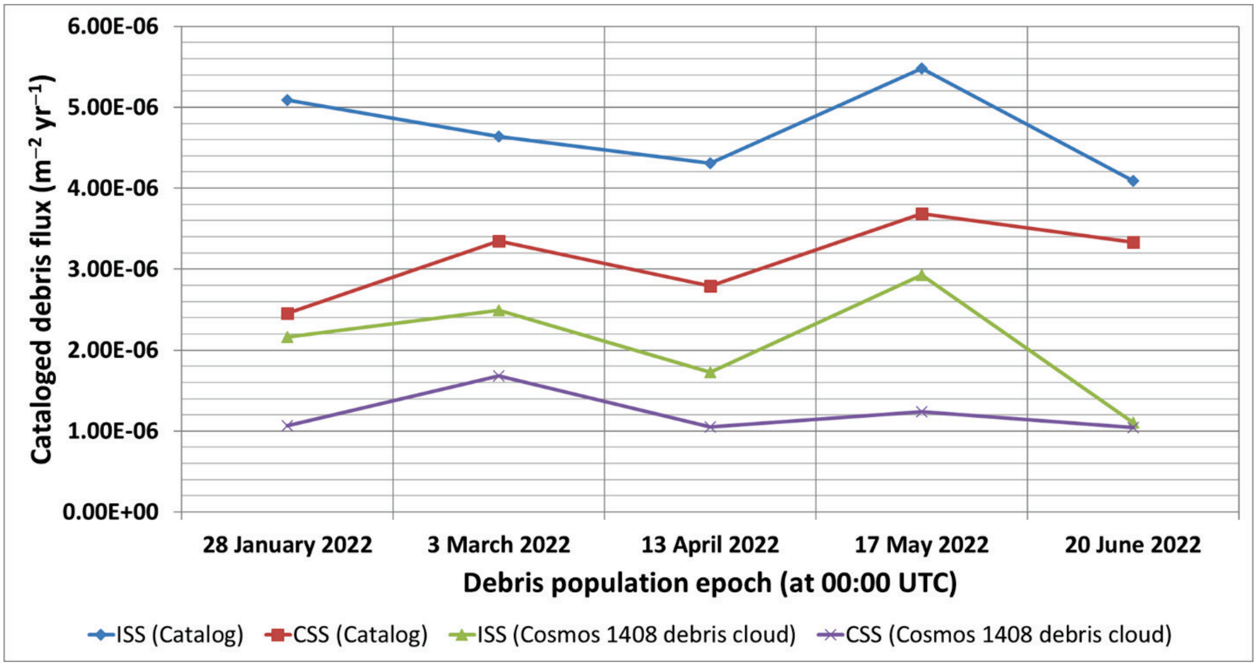

Fig. 8. Evolution of the flux of cataloged objects on the International (ISS) and Chinese (CSS) space stations, up to seven months after the Cosmos 1408 ASAT test. The catalog includes the Cosmos 1408 fragments as well.

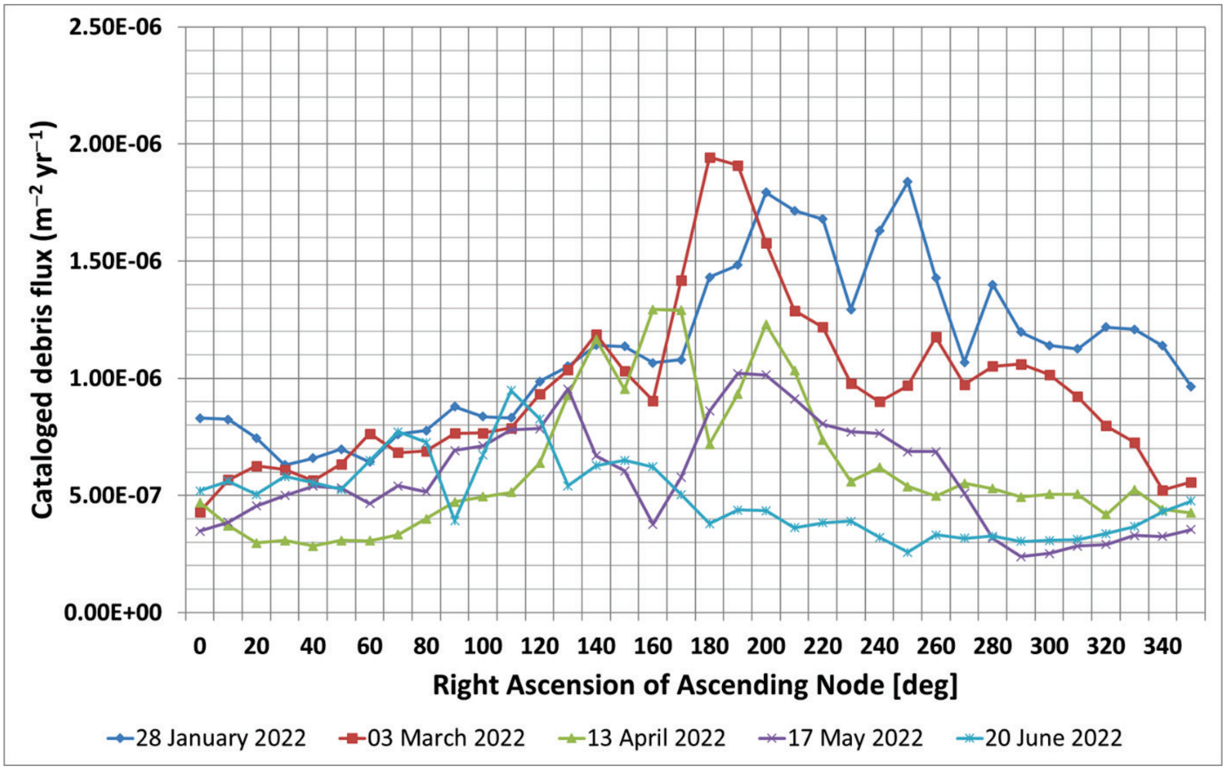

Fig. 9. Evolution of the flux of the Cosmos 1408 cataloged fragments at the operational altitude and inclination of Starlink, as a function of the right ascension of the ascending node of the constellation satellites. The epochs are at 00:00 UTC.

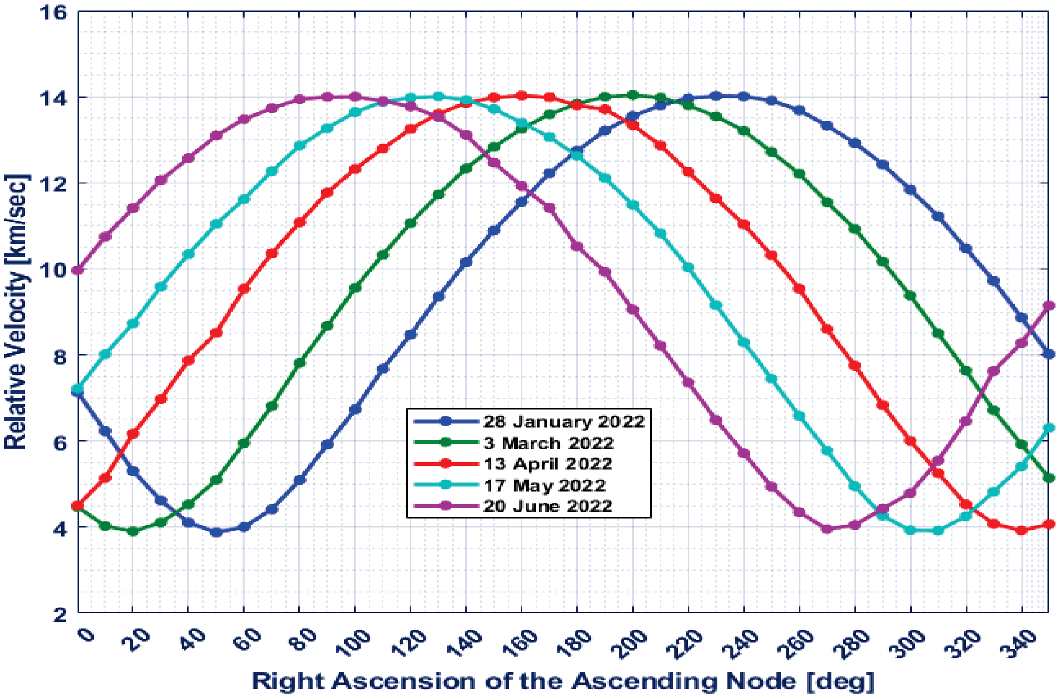

Fig. 10. Mean relative velocity of the Cosmos 1408 cataloged fragments with respect to the Starlink operational orbit planes, as a function of time and right ascension of the ascending node of the constellation satellites. The epochs are at 00:00 UTC.

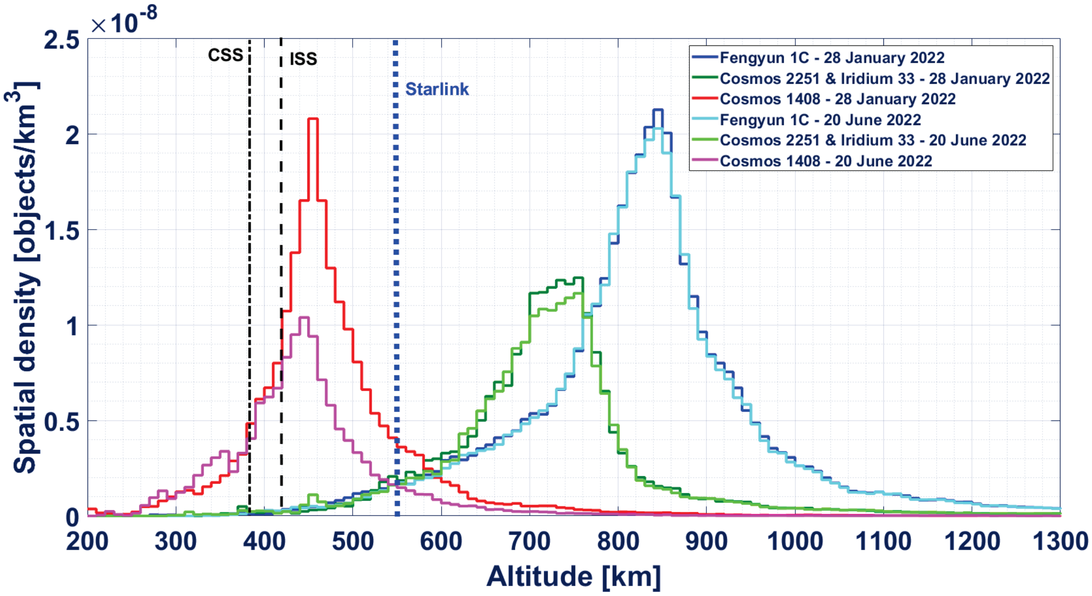

Fig. 11. Spatial density distribution of the cataloged debris clouds generated by the Fengyun 1C and Cosmos 1408 ASAT tests, and by the accidental collision between Cosmos 2251 and Iridium 33. The epochs, 28 January and 20 June 2022, are at 00:00 UTC.

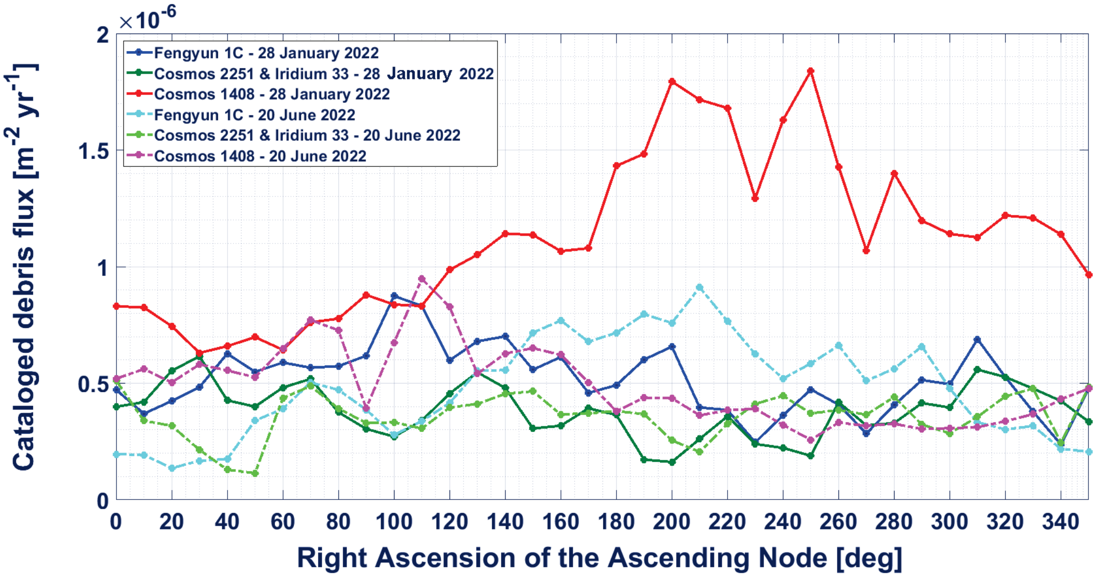

Fig. 12. Comparison of the cataloged debris flux, as a function of the right ascension of the ascending node of the constellation satellites, at the operational altitude and inclination of Starlink, due to the clouds generated by the Fengyun 1C and Cosmos 1408 ASAT tests, and by the accidental collision between Cosmos 2251 and Iridium 33. The epochs, 28 January and 20 June 2022, are at 00:00 UTC.

If available, the sampling factor, mass, area, and diameter for each representative object can be included as well and used for specific analyses needing this kind of information. On the basis of the selected reference population, which can be, for example, the output of a model, the entire population of cataloged objects, or even a single cloud of debris produced by a fragmentation event, SDIRAT can calculate, with a deterministic approach, the magnitude and direction of the incident debris flux experienced by an object on an arbitrary orbit around the Earth, the distribution of the relative velocity between debris and target, and the spatial debris density, as a function of altitude and latitude.

First of all, we focused our attention on the two space stations currently in orbit: the ISS and the CSS. During the first half of 2022, the former was at an average altitude of 418 km. With an inclination of 51.64°, the orbit plane right ascension of the ascending node preceded by –4.0° per day. The CSS, on the other hand, was at an average altitude of 385 km. With an inclination of 41.47°, the orbit plane right ascension of the ascending node preceded by –5.1° per day.

Considering the much greater inclination of the Cosmos 1408 debris cloud (between 81.5° and 84°), and the fact that the right ascension of the ascending node of the core of the cloud preceded by approximately –1° per day, the relative geometry of the debris cloud orbit planes with respect to the orbit planes of the ISS and CSS has changed continuously, alternating between periods of maximum and periods of minimum debris flux. The results obtained with SDIRAT for the first seven months after the breakup are summarized in Tables 2-5 and in Figure 8.

Regarding the ISS, the breakup of Cosmos 1408 approximately doubled the flux of cataloged objects on the station during the first six months, with fractional contributions varying between 40% and 54% of the total. On 28 January 2022, the orbit plane of the ISS was nearly perpendicular to that of the core of the Cosmos 1408 debris cloud, implying two critical crosses per orbit at a relative velocity of 11 km/s. On 3 March, the changing relative orientation of the orbital planes led to a further increase of the mean relative velocity and to a corresponding increase of the debris flux. On 13 April, on the other hand, the orientation of the planes led to a significant reduction of the relative velocity and flux. The opposite situation, from a geometric point of view, occurred on 17 May, when the mean relative velocity exceeded 14 km/s and the flux from the Cosmos 1408 cataloged debris accounted for more than 53% of the total. Finally, on 20 June, the flux decreased again, to 27% of the total, both for the changing plane orientation and for the decline of cloud fragments, due to orbital decay.

Concerning the CSS, the consequences of the Cosmos 1408 breakup were lower in both absolute and relative terms. In absolute terms, the resulting debris flux was approximately 60% of that on the ISS, while in relative terms oscillated between 31% and 50% of the total. However, the impact was still very significant. As in the case of the ISS, the varying debris flux was mainly the result of the changing orbit plane relative geometry, leading to considerable variations of the mean relative velocity of the Cosmos 1408 fragments with respect to the CSS.

As a matter of fact, the destruction of Cosmos 1408 increased significantly the collision risk for the two crewed space stations in orbit. Over the first seven months, it increased, on average, by nearly 80% the flux of cataloged objects on the ISS, and by almost 65% the flux on the CSS. And it will take at least another year for these fluxes to return to the values before the ASAT test.

Table 2. International Space Station: mean relative velocity and flux of cataloged objects, from before the destruction of Cosmos 1408 to just over seven months later.

Epoch (at 00:00 UTC)	Mean Relative Velocity (km/s)	Debris Flux (m^{-2} yr^{-1})
2021-11-11	5.786	2.43×10^{-6}
2022-01-28	8.412	5.09×10^{-6}
2022-03-03	7.292	4.64×10^{-6}
2022-04-13	4.993	4.31×10^{-6}
2022-05-17	7.825	5.48×10^{-6}
2022-06-20	6.851	4.09×10^{-6}

Table 3. International Space Station: mean relative velocity and flux of the cataloged debris of Cosmos 1408 up to just over seven months after the ASAT test.

Epoch (at 00:00 UTC)	Mean Relative Velocity (km/s)	Debris Flux (m^{-2} yr^{-1})
2022-01-28	11.043	2.16×10^{-6}
2022-03-03	12.715	2.49×10^{-6}
2022-04-13	5.837	1.73×10^{-6}
2022-05-17	14.070	2.93×10^{-6}
2022-06-20	7.570	1.10×10^{-6}

Table 4. Chinese Space Station: mean relative velocity and flux of cataloged objects, from before the destruction of Cosmos 1408 to just over seven months later.

Epoch (at 00:00 UTC)	Mean Relative Velocity (km/s)	Debris Flux (m^{-2} yr^{-1})
2021-11-11	6.484	1.48×10^{-6}
2022-01-28	7.118	2.45×10^{-6}
2022-03-03	8.054	3.35×10^{-6}
2022-04-13	5.750	2.79×10^{-6}
2022-05-17	8.516	3.68×10^{-6}
2022-06-20	7.026	3.34×10^{-6}

Table 5. Chinese Space Station: mean relative velocity and flux of the cataloged debris of Cosmos 1408 up to just over seven months after the ASAT test.

Epoch (at 00:00 UTC)	Mean Relative Velocity (km/s)	Debris Flux (m^{-2} yr^{-1})
2022-01-28	7.951	1.07×10^{-6}
2022-03-03	12.471	1.68×10^{-6}
2022-04-13	9.624	1.05×10^{-6}
2022-05-17	11.356	1.24×10^{-6}
2022-06-20	8.568	1.04×10^{-6}

7. Impact at the height of the Starlink constellation

SDIRAT was also used to analyze in detail the impact of the Cosmos 1408 destruction on the Starlink mega-constellation of satellites. While the ISS and the CSS orbited the Earth below the altitude of the Soviet satellite, by about 60 km and 90 km, respectively, the operational satellites of the Starlink mega-constellation were located just over 70 km above, with a semi-major axis of about 6925.5 km and an inclination of 53°. The results obtained are summarized in Tables 6-9 and in Figures 9 and 10.

According to the analysis carried out with SDIRAT, before the Russian ASAT test in November 2021, and obviously excluding the functional Starlink satellites, the average background flux of cataloged objects on the operational orbits of the mega-constellation was 6.55×10^{-6} m^{-2} yr^{-1}, with a mean relative velocity of 9.739 km/s. Then, the destruction of Cosmos 1408 increased the average flux of cataloged objects on the Starlink constellation by 17%. However, due to the progressive decay of the debris cloud, the mean flux of the Cosmos 1408 fragments has steadily declined over the first seven months, more than halving between 28 January and 20 June 2020 (Table 6).

The mean relative velocity of the Cosmos 1408 fragments with respect to the Starlink satellites has remained relatively stable at just under 10 km/s (Table 6 and Figure 10), with maximum mean relative velocities of 14 km/s for the Starlink satellites moving approximately "against" the cloud (Table 8 and Figure 10), and minimum mean relative velocities just under 4 km/s for the constellation satellites moving approximately in the same direction of the cloud (Table 9 and Figure 10). Figure 10 shows clearly how the mean relative velocity of the cloud fragments changes as a function of the relative spatial orientation of the constellation orbital planes.

The compactness of the cloud, in terms of node dispersion, and the regression of the nodes, by one degree per day in the core of the cloud, has led to a "modulation" of the debris flux, as a function of time and right ascension of the ascending nodes most affected, as can be clearly seen in Figure 9 and in Tables 7-9. On average, in each epoch, the most unfavorable nodes had about 4 times more debris flux than the most favorable ones, roughly placed ~ 180° apart. This means that, at any moment, there have been constellation planes much more affected than others.

Even in the case of the Starlink mega-constellation, therefore, the breakup of Cosmos 1408 has appreciably increased the flux of cataloged objects, progressively affecting mostly specific orbit planes, depending on the relative regression between the nodes of the cloud and those of the constellation satellites. However, the relatively rapid decay of the cloud fragments resulted over the months in a significant improvement of the situation, with the average additional flux at seven months from the ASAT test reduced to just 7% more than before the destruction of the Soviet satellite. And even this modest increase is set to practically disappear between the end of September and the end of December 2022.

Table 6. Starlink mega-constellation of satellites: mean relative velocity and flux of the cataloged debris of Cosmos 1408 up to just over seven months after the ASAT test.

Epoch (at 00:00 UTC)	Mean Relative Velocity (km/s)	Mean Debris Flux (m^{-2} yr^{-1})
2022-01-28	9.708	1.12×10^{-6}
2022-03-03	9.649	9.44×10^{-7}
2022-04-13	9.702	6.14×10^{-7}
2022-05-17	9.632	5.80×10^{-7}
2022-06-20	9.721	4.91×10^{-7}

Table 7. Maximum and minimum flux of the Cosmos 1408 cataloged fragments at the operational altitude and inclination of the Starlink mega-constellation.

Epoch (at 00:00 UTC)	Maximum Debris Flux (m^{-2} yr^{-1})	Minimum Debris Flux (m^{-2} yr^{-1})
2022-01-28	1.84×10^{-6}	6.30×10^{-7}
2022-03-03	1.94×10^{-6}	4.30×10^{-7}
2022-04-13	1.29×10^{-6}	2.84×10^{-7}
2022-05-17	1.02×10^{-6}	2.39×10^{-7}
2022-06-20	9.48×10^{-7}	2.58×10^{-7}

Table 8. Starlink mega-constellation of satellites: spatial evolution of the maximum mean relative velocity of the Cosmos 1408 cataloged fragments.

Epoch (at 00:00 UTC)	Maximum Mean Relative Velocity (km/s)	Right Ascension of Ascending Node (°)
2022-01-28	14.019	230
2022-03-03	14.041	200
2022-04-13	14.027	160
2022-05-17	14.007	130
2022-06-20	13.999	100

Table 9. Starlink mega-constellation of satellites: spatial evolution of the minimum mean relative velocity of the Cosmos 1408 cataloged fragments.

Epoch (at 00:00 UTC)	Minimum Mean Relative Velocity (km/s)	Right Ascension of Ascending Node (°)
2022-01-28	3.878	50
2022-03-03	3.902	20
2022-04-13	3.922	340
2022-05-17	3.918	310
2022-06-20	3.953	270

8. Discussion

To further contextualize the environmental impact of the Russian ASAT test in November 2021, one can compare its effects with those of the major debris clouds already in LEO, namely that resulting from the Chinese ASAT test that destroyed Fengyun 1C, and those resulting from the accidental collision between Cosmos 2251 and Iridium 33. The cataloged debris densities of the clouds are shown in Figure 11, a couple of months after the Cosmos 1408 destruction and seven months later.

As evident from the figure, the Russian ASAT test mostly affected the low LEO regime, below 600 km, while the effects of the other clouds are more pronounced at higher altitudes. The Starlink constellation, being at a height crossed by the ascending tail of the Cosmos 1408 cloud and by the descending tails of the other clouds, certainly experienced an increase in flux immediately after the test, but this average increase was not dramatic, being comparable to the combined flux of the other higher clouds. Moreover, after seven months, the density and the mean flux of the Cosmos 1408 debris have more than halved, reaching the level of the Fengyun 1C and Cosmos 2251 + Iridium 33 clouds, and thus half of their total contribution to the background, on average.

This general trend is confirmed, but in greater detail, by Figure 12, were the debris fluxes are plotted as a function of the right ascension of the ascending node of the constellation satellites. As of 28 January 2022, the flux of the Cosmos 1408 debris on the Starlink constellation clearly prevailed compared to that of each of the other clouds over a wide range of orbital planes, but seven months after the ASAT test the effect blended with that of the other main clouds.

Concerning the two crewed space stations, the impact of the Russian ASAT test, at least in the short term, has been instead quite significant, as detailed in Section 6, for three reasons: 1) the test altitude was too close, in particular to that of the ISS; 2) the debris were raining down on the stations from the higher region of maximum concentration, due to atmospheric drag; and 3) the contribution of the other main clouds (Figure 12) and of the background (Figure 2) was relatively small.

From the beginning of January 1999 to the end of July 2022, the ISS performed 32 debris avoidance maneuvers [22]. Of these, 3 involved fragments of Fengyun 1C, 3 fragments of Iridium 33 and 2 fragments of Cosmos 2251. The first avoidance maneuver to dodge a fragment of Cosmos 1408 was executed on 16 June 2022. Adding to this the safety procedures implemented by the crew of the ISS during the first couple of days following the destruction of Cosmos 1408, it is evident that the Russian ASAT test has already had an actual impact on the operations of the space station, even ignoring the additional workload to monitor the new fragments and identify the hazardous ones.

In terms of frequency of potential close approaches of cataloged objects at less than 1 km, before the Russian ASAT test it was 7.6 per year for the ISS and 4.6 per year for the CSS. After the test, and during the following seven months, these values practically doubled to 14.8 and 9.8 per year, respectively, for the ISS and the CSS.

Regarding the Starlink mega-constellation, the flux of cataloged objects was already quite significant before the Cosmos 1408 breakup. Each operational satellite had, on average, 0.2 close approaches at less than 100 m per year, corresponding to more than one close approach per day for a constellation of 2000 spacecraft. After the Russian ASAT test, the cataloged debris cloud of Cosmos 1408 increased the frequency of close approaches at less than 100 m by 0.035 per year and per satellite, corresponding to a further close approach every 5 days for 2000 spacecraft. However, after 7 months, the frequency of close approaches attributable to the Cosmos 1408 debris cloud had already reduced to 0.015 per year and per satellite, corresponding to an additional close approach every 12 days, always for 2000 spacecraft. Therefore, even though far from negligible, the operational impact of the Cosmos 1408 breakup was not particularly severe compared to normal operations that were already quite burdensome.

9. Conclusions

This is a particularly critical time for the preservation of the circumterrestrial space environment for future generations and for the adoption of sustainable space activities over the long term. The so-called New Space Economy seems to be undermining all the orbital debris mitigation measures that have been painstakingly developed over the past two decades and the pace of change is so rapid as to appear incompatible with the long time frames associated with international negotiation processes, the only ones that can deeply involve all the most relevant countries.

This makes it more important than ever to avoid the intentional destruction of objects in orbit. Space around Earth is now so crowded that even ASAT tests conducted at relatively low altitudes can pose an unacceptable risk to astronauts and operational spacecraft, some of which extremely complex, expensive and critical for specific applications. The Russian ASAT test conducted on 15 November 2021, although probably conceived with the idea of causing a limited impact, turned out to be instead quite problematic in low LEO, that is below 600 km altitude, where space activities have grown so much in the last decade. The ISS itself, half made up of Russian modules and also crewed by Russians citizens, was put at risk by the test and even had to perform an evasive maneuver to dodge debris from the destroyed satellite. During the first months following the test, the flux of cataloged objects has nearly doubled for both the ISS and the CSS, and other satellite systems in low LEO have been heavily affected from the operational point of view [18]. Even the mega-constellation Starlink, 70 km higher up, saw an increase in the flux of cataloged objects, at least initially, of the order of 20%.

In light of these facts, the recent announcement, on 18 April 2022, of the U.S. government's commitment to stop testing anti-satellite weapons can only be warmly welcomed. Subsequently, both Canada and New Zealand have joined the U.S.-led moratorium. At this point one can only hope that this path will be followed by as many space powers as possible, preferably within the framework of the United Nations. An excellent opportunity might be represented by the United Nations-chartered Open-Ended Working Group (OEWG) on responsible space behaviors, which should develop norms and rules of conduct possibly leading to binding agreements.

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