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THE EFFECTS OF SOLAR MAXIMUM ON THE EARTH'S SATELLITE POPULATION AND SPACE SITUATIONAL AWARENESS

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The rapidly approaching maximum of Solar Cycle 24 will have wide-ranging effects not only on the number and distribution of resident space objects, but also on vital aspects of space situational awareness, including conjunction assessment processes. The best known consequence of high solar activity is an increase in the density of the thermosphere, which, in turn, increases drag on the vast majority of objects in low Earth orbit. The most prominent evidence of this is seen in a dramatic increase in space object reentries. Due to the massive amounts of new debris created by the fragmentations of Fengyun 1C, Cosmos 2251, and Iridium 33 during the recent period of solar minimum, this effect will again be pronounced.

However, space surveillance systems are also affected, both directly and indirectly, historically leading to an increase in the number of lost satellites and a decrease in the routine accuracy of the calculation of their orbits. Thus, at a time when more objects are drifting through regions containing exceptionally high-valued assets, such as the International Space Station and remote sensing satellites, their position uncertainties increase. In other words, as the possibility of damaging and catastrophic collisions increases, our ability to protect space systems is degraded. Potential countermeasures include adjustments to space surveillance techniques and the resetting of collision avoidance maneuver thresholds.

I. GENERAL EFFECTS OF INCREASED SOLAR ACTIVITY

Solar activity in terms of sunspot number has been studied for four centuries with detailed data collected for the past 250 years. The presence of an average 11-year solar cycle was deduced in the mid-19th century. With the advent of the space age, the effect of varying solar activity levels on atmospheric density became apparent with corresponding changes in the rates of orbital decay for objects in low Earth orbit.

On 3 November 1960, the U.S. deployed the Explorer 8 spacecraft into an elliptical orbit of 420 km by 2290 km with an inclination of 50 degrees. Although the spacecraft completed its mission after only two months, Explorer 8, with its relatively low perigee and high apogee, was in an ideal orbit to monitor changes in the density of the thermosphere under varying levels of solar activity. Figure 1 illustrates the effect of the periodic solar maxima from the launch of Explorer 8 to its reentry in March, 2012. Clearly, the rate of orbital decay increased in synchronization with high levels of solar activity.

Important atmospheric density changes extend to much higher altitudes as well. During 1964-1965 the U.S. launched three calibration spheres (calspheres), each with a diameter of 36 cm but with individual masses of 1 kg, 2kg, and 10 kg, into nearly circular orbits between 1000 and 1200 km. Consequently, these three satellites possessed area-to-mass ratios of 0.10, 0.05, and 0.01 m^2/kg, respectively. Figure 2 depicts the effects of solar activity, as measured in solar flux units, on these higher altitude objects. Again, the effects of periodic solar maxima are evident.

The area-to-mass ratios of the three calspheres are greater than many spacecraft and orbital stages, but they are not uncommon for smaller debris. In fact, as noted later in this paper, some cataloged debris exhibit area-to-mass ratios of 1.0 m^2/kg or more. This means that these debris, particularly those in orbits below 1000 km, will be highly susceptible to periods of elevated solar activity. Moreover, smaller, uncataloged debris will often have even higher area-to-mass ratios and will be more likely to reenter during a solar maximum.

The satellite population in Earth orbit primarily increases by new space launches and fragmentations and decreases by natural orbital decay. Periods of high solar activity can lead to a net decrease in the population, as seen during the Cycle 22 maximum of 1989-1990 (Figure 3). Such a decrease has also been in effect since June 2010 as the maximum of Cycle 24 approaches. Note that both population decreases have been driven by the reentry of fragmentation debris with their typically higher area-to-mass ratios.

II. SOLAR CYCLE 24

Solar Cycles 21-23 reached smoothed monthly values in 10.7 cm radio flux of approximately 200 solar flux units (sfu or 10^4 janskys). However, in 2006 and 2007 predictions for Cycle 24 were the subject of great debate with one group of specialists forecasting a higher than normal solar maximum and one group envisioning lower than normal solar activity with a peak almost a year later than the competing prediction. With a failure of the scientific community to reach a consensus, the U.S. National Oceanic and Atmospheric Administration’s (NOAA) Space Weather Prediction Center took an unusual decision to publish two separate projections during 2007 and 2008 (Figure 4, upper): one for a nearly normal maximum and one with a markedly lower peak. By 2009 a single forecast based on the lower predicted maximum, but with an even later arrival, was finally adopted (Figure 4, lower).

If the latest forecast proves accurate, the anticipated reduction in the number of objects in Earth orbit, both large and small, will be substantially less than if a “normal” solar maximum were to occur. As an example, in 2008 a study was undertaken to determine the likely rate of reentry of debris from the Fengyun 1C fragmentation using a projected solar maximum of ~190 sfu.[1] This analysis has recently been redone with the current NOAA prediction for Cycle 24 with a maximum of only 140 sfu. Figure 5 compares the two resultant curves and indicates that the debris are now expected to remain in orbit longer than previously calculated. To date, solar activity suggests that a peak of 140 sfu might even be optimistic.

In both exercises, the models above assume a return to normal solar maxima levels for Cycles 25 and beyond. However, some solar specialists believe that solar maxima for the next several cycles might be well below those seen during the past several decades. In such a case, the decay of orbital debris will continue to be impeded, likely resulting in higher net rates of total satellite population growth.

III. IMPORTANCE OF FENGYUN 1C, COSMOS 2251, AND IRIDIUM 33

The detrimental effects of the 2007 intentional destruction of the Chinese Fengyun 1C satellite and the 2009 accidental collision of the Russian Cosmos 2251 and U.S. Iridium 33 satellites are clearly seen in Figure 3. By July 2012, the U.S. Space Surveillance Network had cataloged more than 3300 debris from Fengyun 1C and more than 2200 debris total from the other two spacecraft. All together, these debris accounted for more than a third of the total cataloged satellite population in low Earth orbit (LEO), where approximately 500 operational spacecraft reside or transit daily. The number of potentially hazardous, uncataloged debris is more than an order of magnitude greater than those which have been officially cataloged.

Therefore, the effects of Cycle 24 on the fragments, cataloged and uncataloged, of the aforementioned three satellites are of very great importance. By mid-2012 more than 570 (10%) of the cataloged debris from these two incidents had already fallen out of orbit and with an increasing rate. Many of the remaining cataloged debris had also noticeably experienced the effects of atmospheric drag. The collapse of the apogee arms on the left side of both graphics in Figure 6 is primarily due to drag on the remaining debris with the lowest perigees.

Figure 7 illustrates how the continuing draw-down of the three debris clouds might flow through the end of Cycle 24 and into the beginning of the next century. These curves are based on the official NOAA solar activity prediction for Cycle 24 and an assumption that Cycle 25 and its successors will return to average levels of activity seen during cycles prior to Cycle 24.

The relative rates at which the debris reenter is a function of (1) the altitude of the fragmentation events, (2) the velocity distribution, and (3) the area-to-mass ratio distribution of the debris. The altitude of the Fengyun spacecraft when it was destroyed was higher than that of the Cosmos 2251-Iridium 33 collision. In addition, debris from Iridium 33 on average have higher area-to-mass ratios than debris from Cosmos 2251 (see immediately below). By the end of Cycle 24 (estimated to be about 2020), about one-third of all debris from these three events might have reentered, depending upon the peak and duration of the forthcoming solar maximum.

Unlike the Cosmos 2251 spacecraft with a construction heritage dating back to the 1960's, the Iridium 33 spacecraft built in the 1990's incorporated a significant amount of low-density materials, *e.g*., aluminum honeycomb and graphic epoxy-based structural components. Not surprisingly then, the area-to-mass distributions of their respective fragments, as well as their orbital decay behavior, are noticeably different.[2] As indicated in Figure 7, the debris from Iridium 33 is reentering the atmosphere at a higher rate than the debris from Cosmos 2251, even though the parent spacecraft were in nearly identical orbits (*i.e*., similar perigees and apogees near 800 km) at the time of the collision.

An example of an apparent high area-to-mass ratio fragment from Iridium 33 can be seen in Figure 8. This object was actually thrown into a much higher orbit by the collision with Cosmos 2251, but it decayed in only a little more than three years. The eccentricity variations are indicative of the influence of solar radiation pressure on low density objects.

From a long-term environmental perspective, the combination of the number of debris produced and their respective longevity in Earth orbit is of primary importance. Since the issuance of its first orbital debris mitigation guidelines in 1995, NASA has employed a metric of object-years to evaluate the potential effects of debris, particularly the likelihood of collision with operational spacecraft.[3] Figure 9 illustrates the much greater effect the debris from Fengyun-1C will have on the low Earth orbital region, as a result not only of the greater number of debris produced, but also of their overall longer stays in space.

IV. SOLAR CYCLE EFFECTS ON SSA AND CONJUNCTION ASSESSMENTS

During periods of solar maximum the overall energy output of the Sun leads to a heating of the atmosphere via two ionization processes: photo-ionization of air molecules primarily from short-wavelength radiation and the creation of ions through collisions between solar particles (*e.g*., protons) and particles in the air. Increased ionization of the atmosphere increases the atmospheric temperature and an expansion of the atmosphere, which in turn increases the density of the atmosphere at higher altitudes, creating additional drag on orbital objects. In addition, satellites can experience an ion drag force from an ion wind within the atmosphere.

The two major solar indices which influence the atmospheric density are the 10.7 cm radio flux (often referred to as F10.7 or F_{10}) noted above and the geomagnetic index (A_p). The former is associated with the average level of radiation over the full solar disk, whereas the latter is influenced by solar flares. Changes, particularly rapid changes, in either or both can have significant effects on terrestrial space surveillance systems attempting to monitor the low Earth orbital regime.[4-6]

Changes in atmospheric drag will cause a satellite to penetrate a sensor's coverage volume at a time other than that expected. If the time of arrival falls outside a pre-set window, the sensor might not properly correlate the object with a known object. In such a case additional observations (track time) are normally required and the data are forwarded to a processing center as an unknown. There the data might be properly correlated automatically using additional techniques, or manual intervention might be required. In either case, additional resources are needed. If many objects are affected, *e.g.*, after a sharp change in F10.7 or Ap, then the load on the data processing center can be significant with detrimental effects on the quality of satellite ephemeris.

The first effect noticed is normally a decrease in the accuracy of the satellite's orbit. From a satellite catalog perspective, this accuracy can be measured by the number of objects with orbits known within a specified in-track error, *e.g.*, 2 km or 12 km. Overall satellite accuracy often decreases after marked changes in F10.7 and A_p.

The most severe consequence is the "loss" of the satellite entirely, *i.e.*, a failure to correlate new observations with the object of interest. This problem was clearly apparent during the maximum of Solar Cycle 21 (1979-1980), which was significantly higher than that of Solar Cycle 20 when far fewer satellites were being tracked. Space surveillance operations during the maximum of Solar Cycle 22 (1989-1990) were disrupted even more than during the previous solar maximum. Immediately following a major solar event in March 1989, more than 700 known satellites became lost, bringing the total percentage of lost objects to nearly 20% of the satellite catalog.

Objects in low Earth orbits are normally tracked by large, ground-based radars, operating in a variety of bands: VHF, UHF, C-Band, L-band, X-band, and Ku-band. Increased ionization in the atmosphere can adversely affect the performance of these radars, *e.g.*, by increased range errors. However, typically these increased errors are of lesser importance than the effects on the satellite orbits themselves.

As the maximum of Solar Cycle 24 approaches, the challenges for space situational awareness (SSA) have never been greater. As of July 2012 the total number of officially lost satellites (satellites for which reliable orbital elements were more than 30 days old) reached a record high of nearly 3500. Moreover, another 2700 objects had not been updated for at least 5 days. In total, the orbits of approximately 6250 satellites (28% of the known objects in Earth orbit) were of little value for collision risk assessment purposes.

Exacerbating the problem is a much higher number of very small objects (typically with higher areas-to-mass ratios which are more susceptible to variations in atmospheric density) in the satellite catalog, many originating from the fragmentations of the Fengyun-1C and the Iridium 33 spacecraft. Moreover, thousands of these objects can be detected by only one or a very few sensors, often leading to long periods between observation opportunities and the resultant degradation of their assessed orbital elements.

The conjunction assessment (CA) process for protecting spacecraft in altitudes below 800 km is further complicated by the greater number of objects which are transiting this region due to increased drag. For example, more objects are passing through the altitude regime of the International Space Station, leading to an increase in close approaches.[7] At the same time, the uncertainty of the position of these potential threats at the time of conjunction increases, negatively affecting collision avoidance decision-making.

A number of countermeasures can be applied to mitigate the effects of increased solar activity and specific solar events on the quality of the satellite catalog. An increase in tracking frequency can better maintain orbital element accuracy and reduce the number of objects which might be lost. Of course, more frequent tracking increases the load on both sensors and data processing centers.

Increasing the frequency of official satellite element updates is also needed. The orbits of satellites are normally not automatically updated each time a new observation is made. Updates can occur daily or less often and can involve only partial differential corrections instead of full differential corrections. More accurate and up-to-date orbital elements at the sensors will improve overall satellite catalog accuracy.

Within the data processing centers other actions can be beneficial, including more frequent updates of solar indices, the use of better solar forecast models, more accurate atmospheric density models, and the change of drag multipliers as solar conditions vary. Since 2001 the High Accuracy Satellite Drag Model (HASDM) has been under development for the U.S. Space Surveillance Network (SSN). An improved HASDM, expected to be operational in the U.S. Joint Space Operations Center (JSpOC), might improve in-track accuracies for predictions made 72 hours before a conjunction by as much as 50% in the human spaceflight regime during solar maximum and solar storms.

Finally, spacecraft programs can modify their own collision avoidance processes and procedures to take into account the increased uncertainty (covariance) in calculated conjunction assessments during solar maximum. This might mean adjusting the probability of collision threshold at which avoidance maneuvers are normally made.

SUMMARY

Although the positive effects of the approaching solar maximum on the population of objects in orbit about the Earth have already begun to manifest themselves, as evidenced by the gradual decrease in the number of officially cataloged satellites, the peak in solar activity expected in 2013 might be the lowest in 100 years. Hence, far fewer debris, both large and small, will fall back to Earth compared with a more normal solar cycle. This comes at a time of a record number of known orbital objects. If solar activity does not return to more normal levels during the next solar cycle (Solar Cycle 25), the rate of growth of the Earth orbital population will increase more rapidly than most forecasts now anticipate.

As the world becomes ever more reliant on space situational awareness, critical capabilities will be hampered during solar maximum, especially for the approximately 500 operational spacecraft in low Earth orbits. Modifications to SSA processes will be needed to limit the negative effects of increased and variable solar activity.

ACKNOWLEDGMENTS

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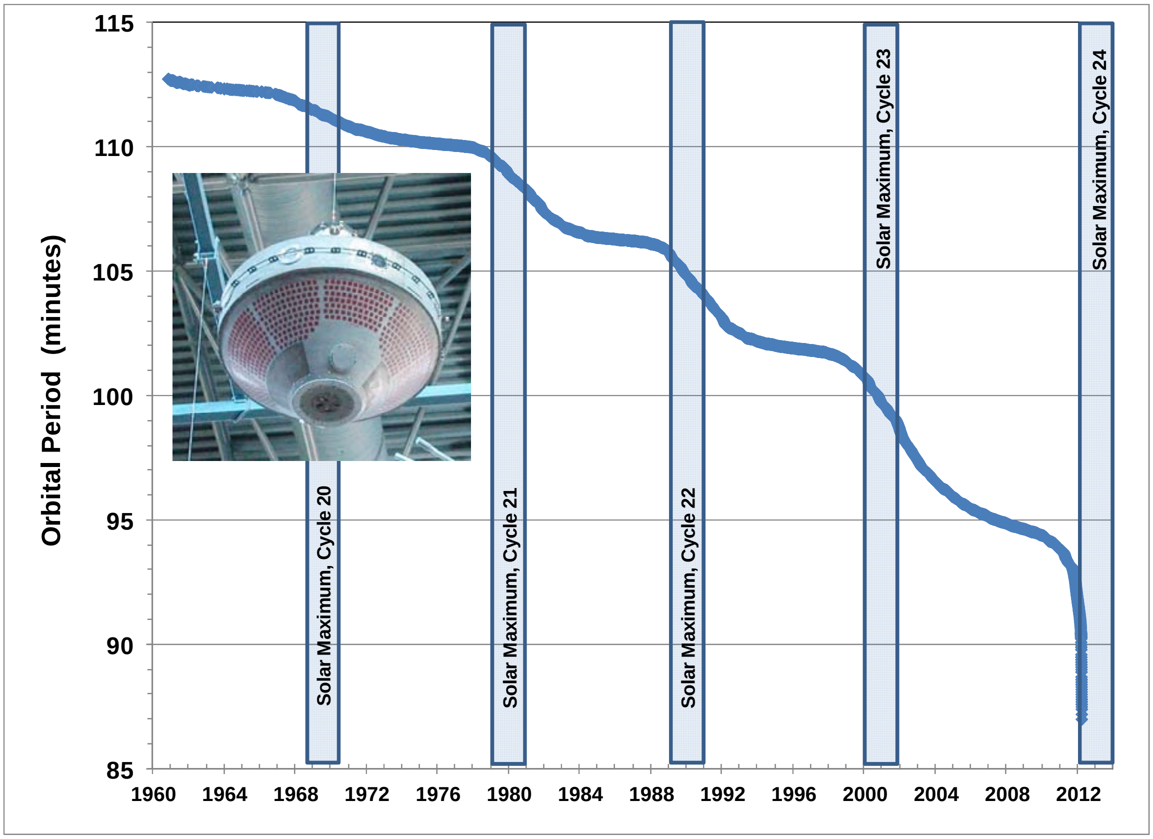

Figure 1. The orbital decay of the Explorer 8 satellite was directly influenced by periodic increases in solar activity. Solar cycles are numbered starting with the solar cycle of 1755-1766 (Solar Cycle 1).

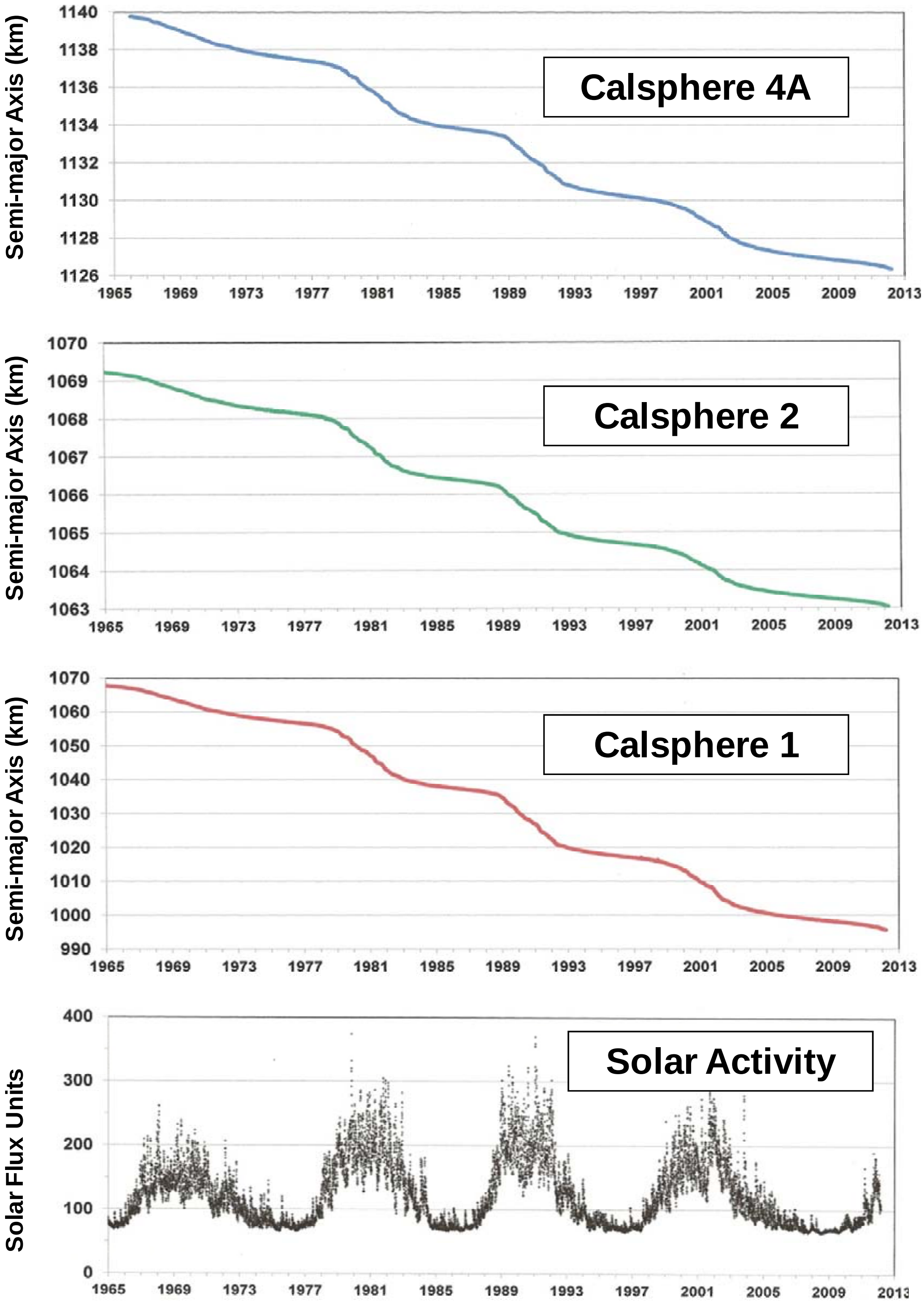

Figure 2. Even at altitudes above 1000 km, the effect of solar activity is evident. The area-to-mass ratios for Calsphere 1, 2, and 4A are 0.1, 0.01, and 0.05 m^2/kg, respectively.

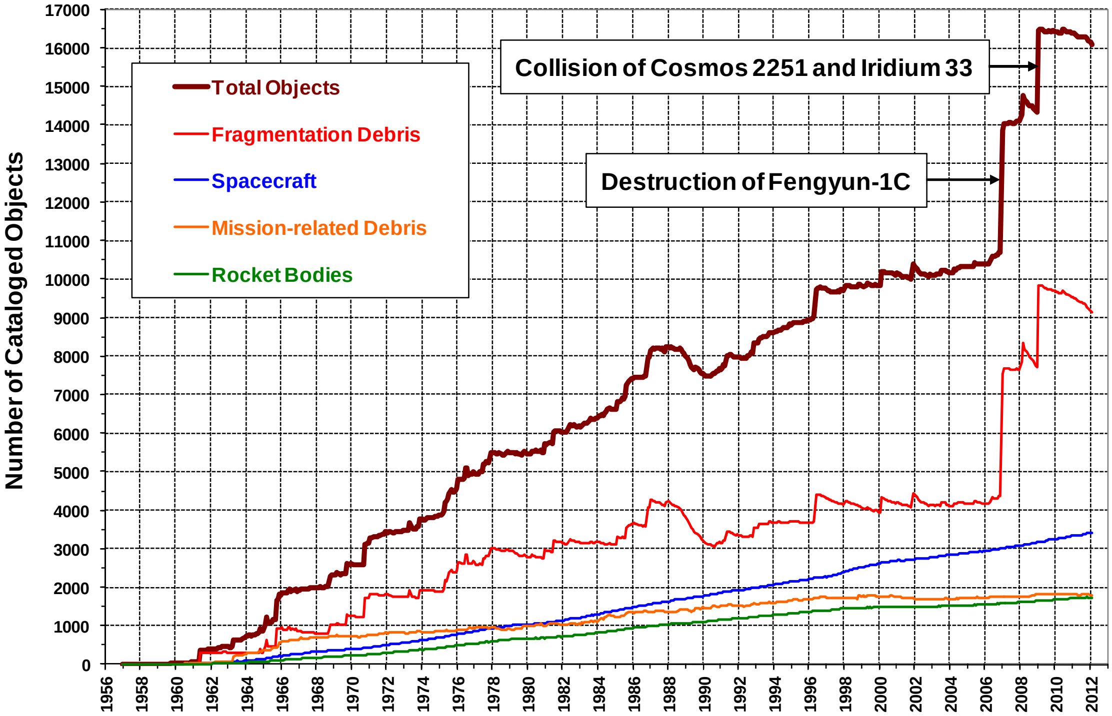

Figure 3. Pronounced decreases in the cataloged satellite population occurred during the solar maximum of 1989-1990 and since June 2010.

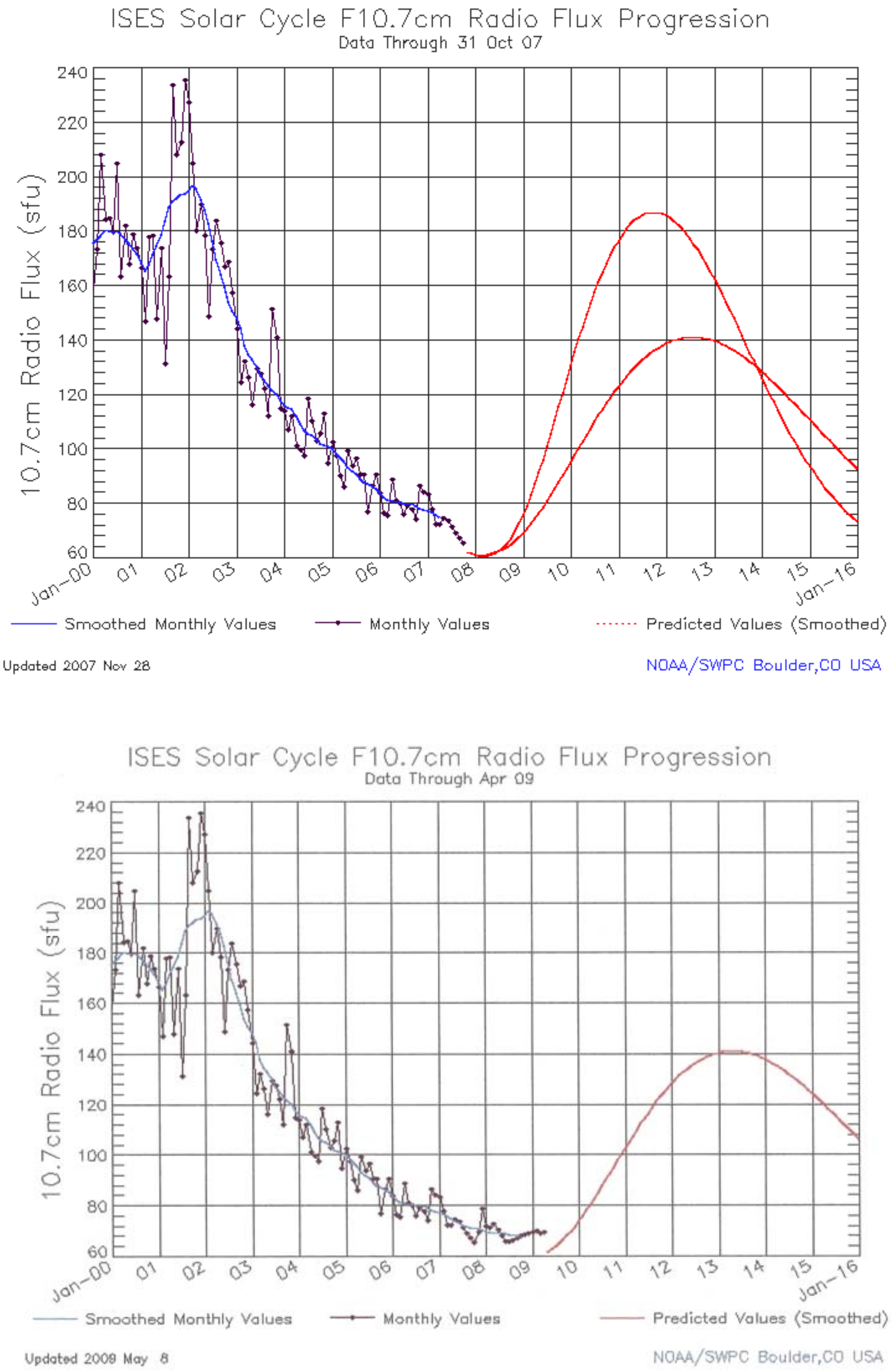

Figure 4. Predictions of the magnitude and timing of the Cycle 24 peak have been the subject of much debate. Two separate forecasts were proposed in 2007 and 2008. The lower graphic, prepared in 2009, depicts the current U.S. NOAA forecast.

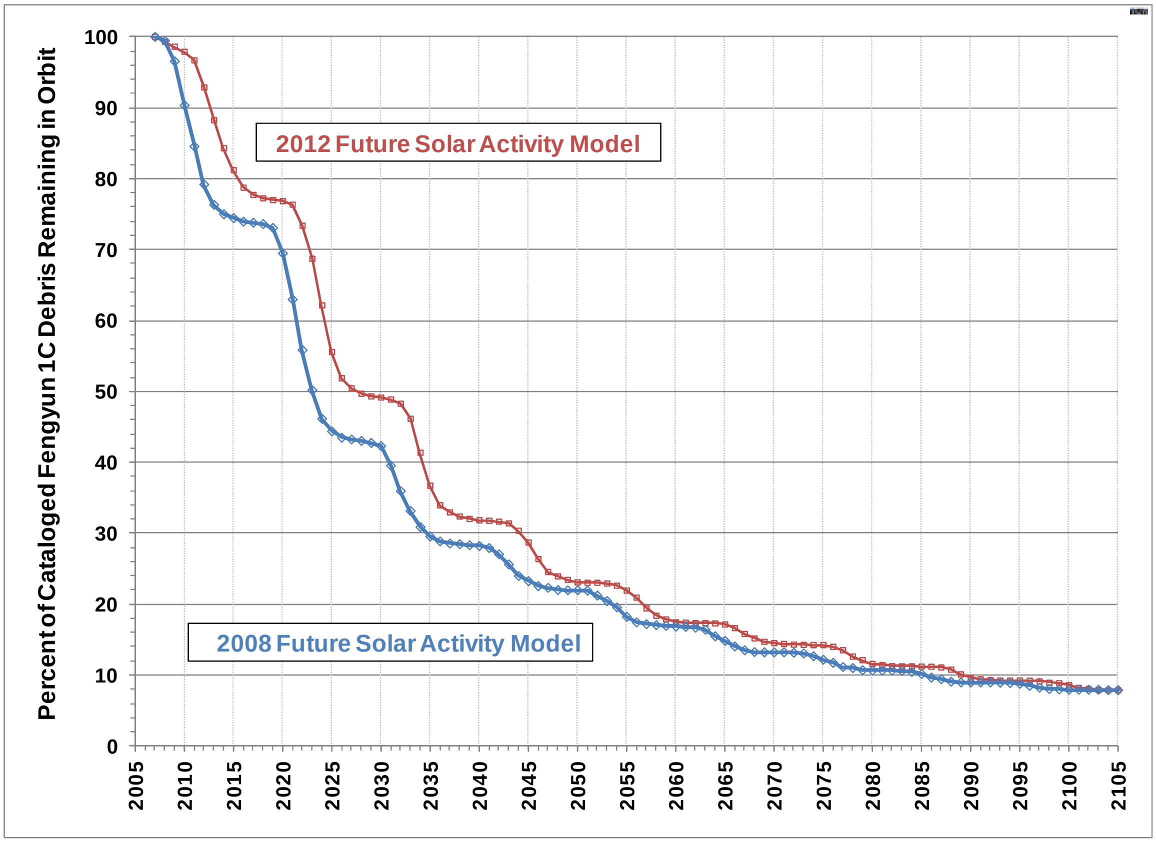

Figure 5. Debris from the Fengyun 1C fragmentation will linger longer in Earth orbit if the forthcoming solar maximum is indeed lower than recent solar maxima. Both models above assume a return to normal solar maxima levels for Cycles 25 and beyond.

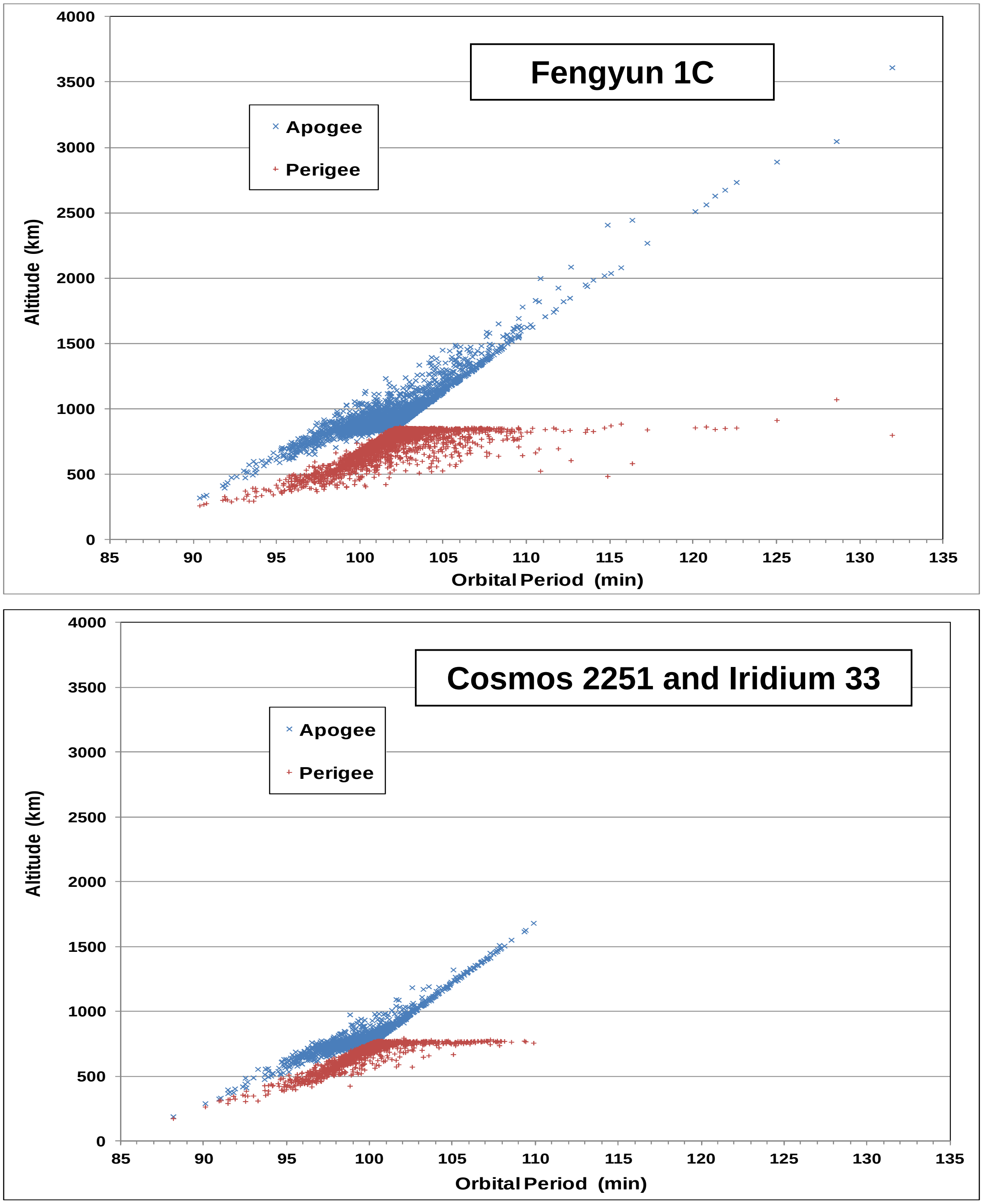

Figure 6. These two Gabbard diagrams indicate the apogees and perigees of each fragment from the three referenced breakups, as of March 2012. The collapse of the left apogee arm is due to atmospheric drag.

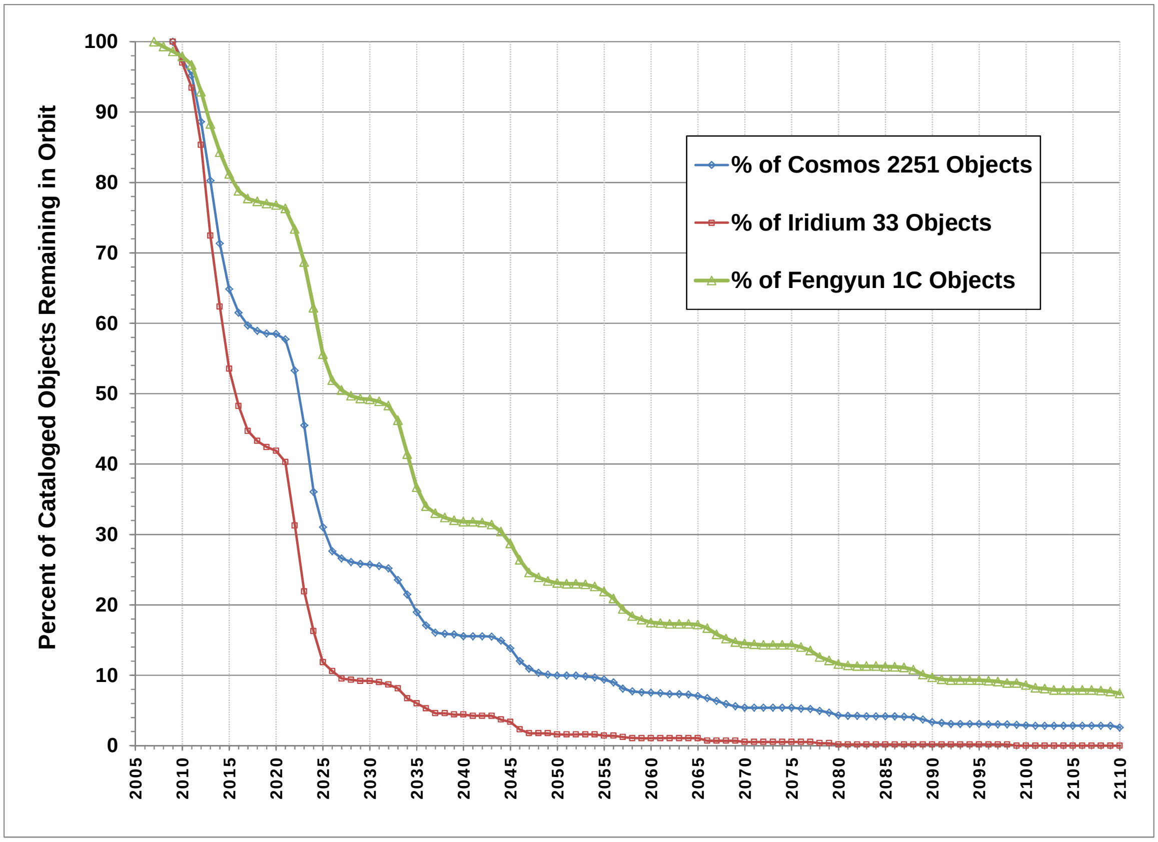

Figure 7. The amount of debris remaining in orbit for the three spacecraft is dependent upon both the altitude of the events and the distribution of area-to-mass ratios of the resultant debris.

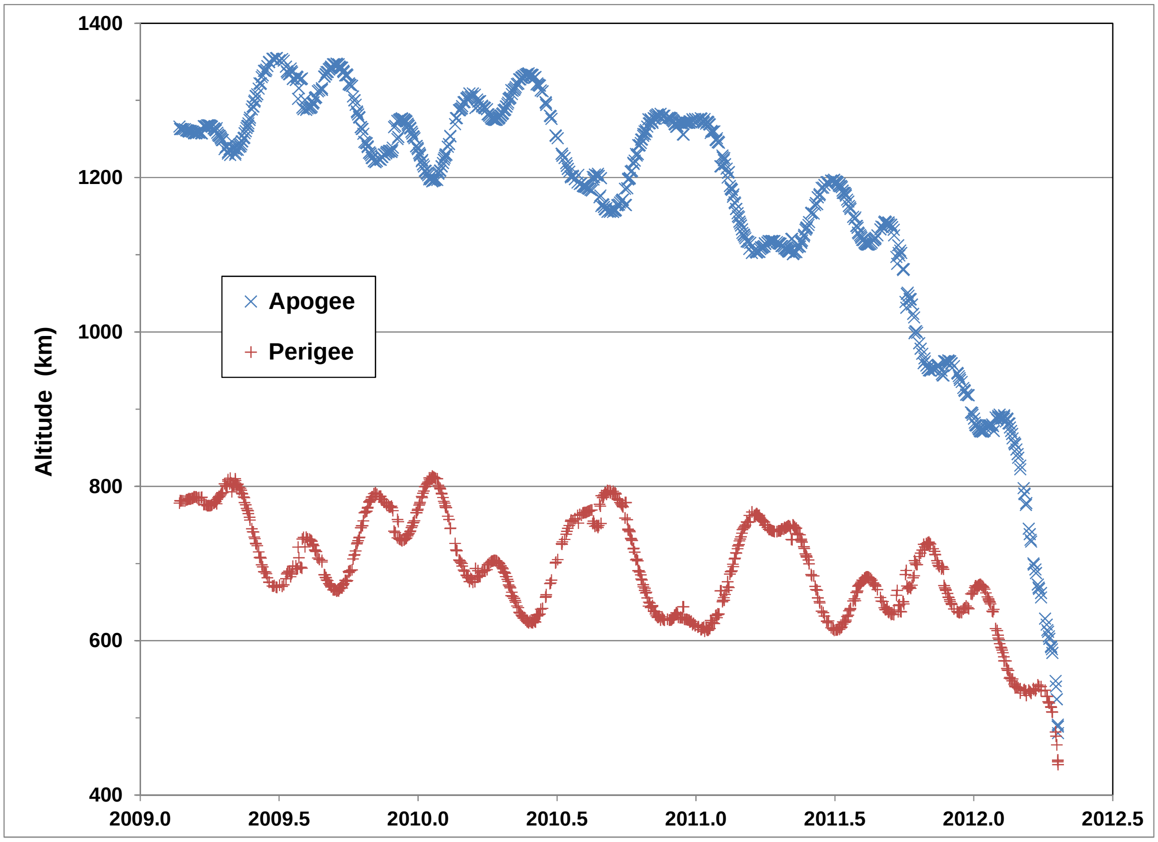

Figure 8. This fragment of Iridium 33 (Satellite Number 33963) exhibited strong influences of solar radiation pressure during its more than three-year orbital lifetime, an indication of a high area-to-mass ratio.

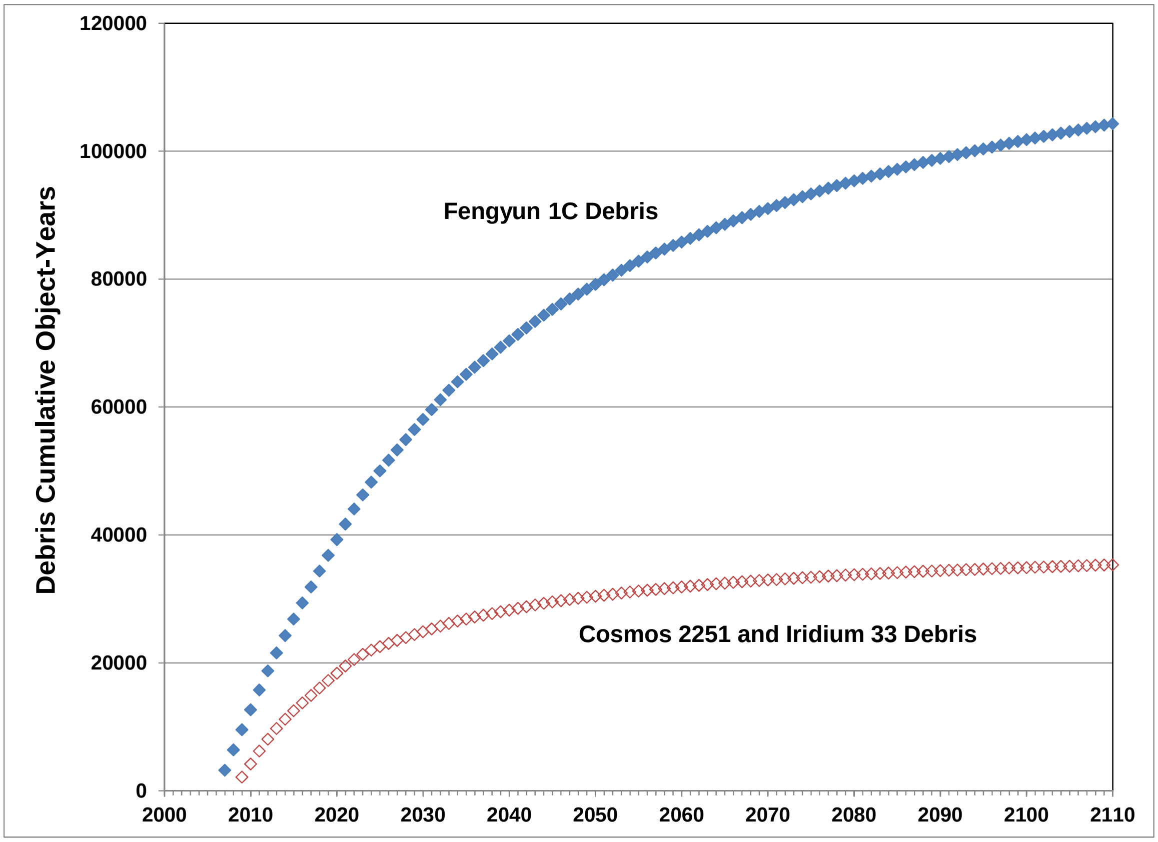

Figure 9. A larger number of debris from Fengyun-1C will stay in Earth orbit longer than the combined debris from Cosmos 2251 and Iridium 33.