Fengyun-1C Debris Cloud Evolution Over One Decade

John V. Lambert, PhD
Cornerstone Defense
13454 Sunrise Valley Dr, Ste 220, Herndon, VA 20171
John.Lambert@CSDef.com

ABSTRACT

It has been over a decade since the People's Republic of China conducted an anti-satellite test destroying its Fengyun-1C weather satellite in a sun-synchronous orbit. This test generated over two thousand trackable debris objects and thousands more, smaller and untrackable objects in the most valuable and populated low-earth orbital regime posing an extreme collision hazard to current and future spacecraft for many decades to come. The continuing evolution of this debris cloud is analyzed both *en masse* and through examination of selected individual objects using historical element set data from the Space Track Catalog.

1. INTRODUCTION

Over a decade ago, on 11 January 2007, the People's Republic of China (PRC) conducted an anti-satellite (ASAT) test destroying their aging weather satellite Fengyun-1C [1, 2]. The satellite had been launched on 10 May 1999 and was in a sun-synchronous orbit at an altitude of 850 kilometers and an inclination of 98.8 degrees. The ASAT kinetic-kill vehicle struck Fengyun-1C head-on (from the satellite's anti-velocity direction) at a closing velocity of 8 km/sec. The resulting collision produced a debris cloud of over two-thousand trackable (approximately ten centimeters or larger) objects with an estimated forty thousand smaller (down to one centimeter) untrackable object polluting the most valuable and highly populated low-altitude orbital regime for the foreseeable future. Some analyses have concluded that this debris has increased the object density in the sun-synchronous orbital regime above the criteria for the Kessler Syndrome, i.e., the density at which a cascade of continuing collisions and additional debris generation will ensue.

In the eleven plus years since the event, the United States Space Surveillance Network (SSN) has continued to regularly track the Fengyun-1C debris objects deleting some objects, mostly due to atmospheric re-entry, and adding others as they are detected and verified. As of early 2018, the number of cataloged objects associated with the event was 2,392. As disruptive as the PRC ASAT test was, it provides a unique opportunity to study the evolution of debris clouds. The sheer number of objects with over a decade of frequent tracking provides the basis for data-rich, real-life case studies.

An analysis of the Gabbard diagrams, building on that performed shortly after the event [3], was done to re-examine the characterization and evolution of the collision. Additions and deletions of these debris objects to the catalog as a function of time was also analyzed. The Gabbard diagrams over the years since the event show the continuing decrease in the apogee heights and eccentricities of the objects with lower perigees due to atmospheric drag while objects with perigees at or above the original Fengyun-1C altitude show much less orbital change as would be expected. A more detailed analysis of several individual objects that deviated from the general behavior have been examined as a possible indication of unusually low or high area-to-mass ratios. Objects added to catalog after the event (some as late as last year) were also examined as potential recent collision products, although improved SSN tracking is the most likely explanation. This study is based on analysis of the element sets published in the Space-Track.Org Catalog which provide a reasonable orbital state at the epoch time satisfying the stated SSN requirements and supporting long-term trend determinations.

2. ANALYSIS

As of early June 2018, over four thousand objects have been associated with the Fengyun-1C event. These objects are nominally larger than five to ten centimeters in size. In Fig. 1, the red "Max ID" curve shows the growth in the number of objects that have been associated with the Fengyun-1C event over time as determined from the international designator (99025A through 99025EYQ). New objects are added to the catalog as they are detected and meet the criteria for association and reacquisition. The total number of associated objects appears to be leveling off at about 4,050. The blue "Cataloged" curve in Fig. 1 illustrates the number of associated objects appearing in the Space Track catalog on the indicated date. The difference between the two curves is due primarily to two causes: cataloged objects that were dropped from the active catalog because they reentered, and objects for which updated element sets were not available. To minimize the number of objects missing due to no updated element sets, the catalogs issued for one week around the desired date were downloaded, the Fengyun-1C objects extracted, and any duplicated element sets for each object eliminated. The variation in the curve indicates that several objects may have gone longer than a week without a new element set being issued. This could result from a variety of reasons including poor sensor-object geometries, poor track correlations, etc. Comparing the peaks in the "Cataloged" curve to the "Max Id" curve suggests that, at a maximum, about 1,500 objects may have reentered, but that is a very rough upper limit. A more detailed study is underway to follow individual objects and identify those for which no additional elements sets have been issued and submit that list to the Space Track decayed object search.

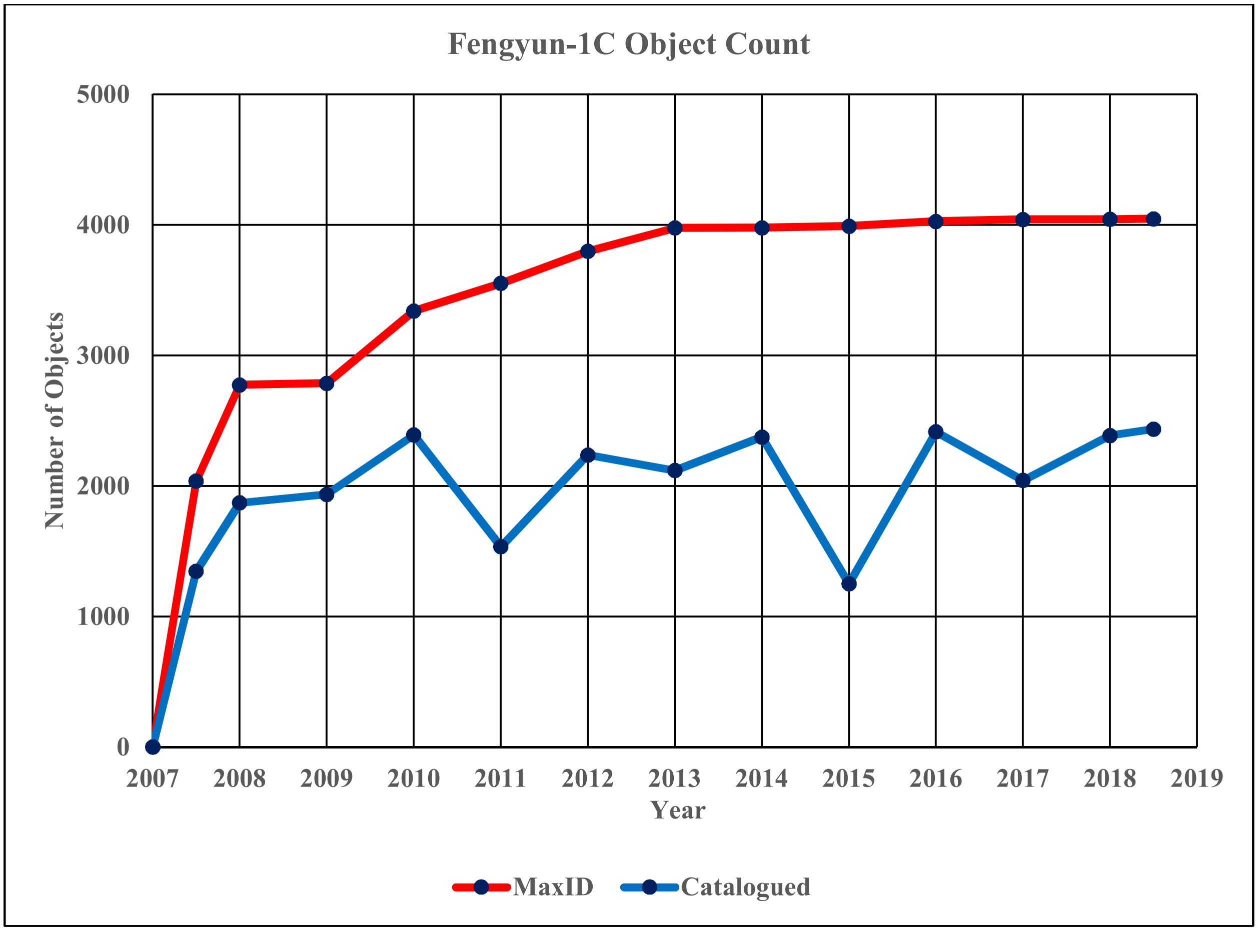

Fig. 1. SpaceTrack.Org Number Of Objects Associated With Fengyun-1C Event (Red) And Number Of Objects With Element Sets Contained In The Online Catalog On Indicated Date.

Reference [4] illustrates the early evolution of the Fengyun-1C debris orbits as a series of scatter plots of the semi-major axis (SMA) versus Right Ascension of the Ascending Node (RAAN) for each object similar to Fig.2. The scatter plots, however, do not illustrate well is the variation in the distribution of the RAANs. Fig. 3 shows the variation in the distributions as a function of normalized population versus RAAN between January 2008 and January 2018. While the distribution does initially become more uniform with time, peaks in the distributions do persist that would have to been considered in computing collision risk assessments against other satellite. Of even more interest is the growth of significant peaks in the distributions for 2016 and 2018. The cause of this growth deserves further investigation due to the potential impact on future hazard calculations. One possible explanation is that lower mass, higher area-to-mass (A/M) ratio debris objects obtained higher velocity perturbations in the initial event and are systematically reentering at a high rate leaving a core of higher mass, lower A/M ratio objects that were less perturbed from Fengyun-1C's sun-synchronous orbit. Reference [5] did find a correlation of orbital period and eccentricity with debris object mass.

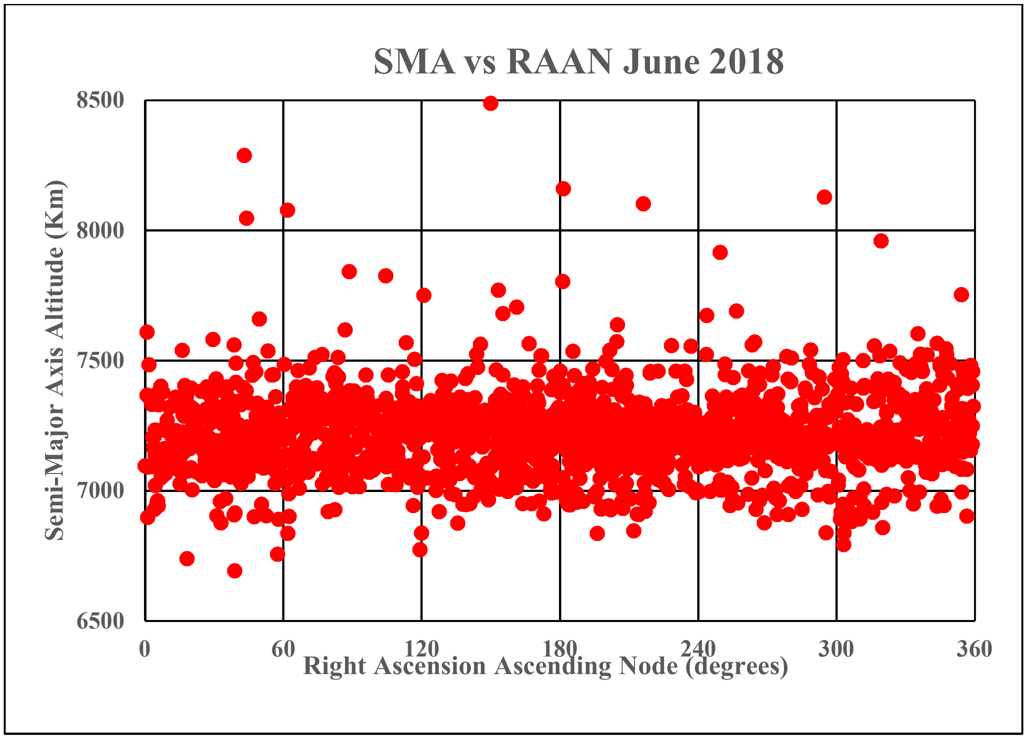

Fig. 2. Fengyun-1C Debris Object SMA Versus RAAN June 2018.

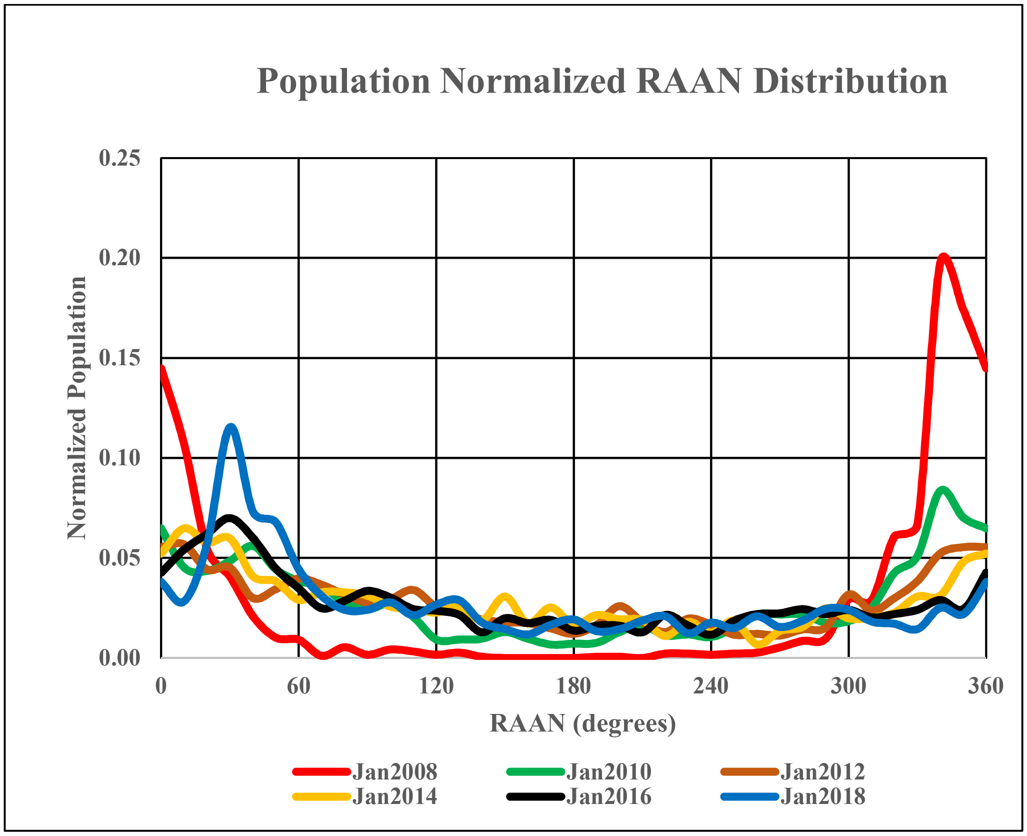

Fig. 3. Fengyun-1C Debris RAAN Distribution Evolution 2008 to 2018.

Gabbard Diagrams [6, 7] are commonly used to characterize the evolution of orbital debris clouds. Each object is represented by two points, its apogee and perigee, plotted as a function of orbital period. An animation of Fengyun-1C Gabbard Diagrams at six to twelve-month intervals was prepared. (A very interesting animation was found on YouTube [8] that shows a day-by-day animation of the Fengyun-1C Gabbard Diagrams during the first year following the event.) Individual objects can be followed as their orbits evolved becoming more circular (lower eccentricity) with shorter periods and lower SMAs causing the left-hand arms of the cloud to "collapse". Individual objects can be observed being "spit out" to lower orbital periods and altitudes as they approach re-entry. Selected Gabbard Diagrams from that animation are shown in Figs. 4a through 4e. The apogee and perigee points for each object from the Space-Track.Org catalog for that date are shown as blue and green points, respectively. The original position of the Fengyun-1C spacecraft is highlighted in yellow.

Three of the Fengyun-1C debris objects (99025NC, AZZ, and BKM) are highlighted in red in Figs. 4a through 4e. (Object 99025BKM first appears in Fig. 4b, January 2008.) Objects NC and AZZ both initially have periods of about 98 minutes (SMA altitudes of 736 and 628 Km., respectively) with large separations between their apogees and perigees indicative of large eccentricities (0.0310 and 0.0430, respectively). As time progress, their periods and eccentricities decrease as they approach re-entry at the lower left of the diagram. Object 99025BKM initially appears with a period of 101 minutes (SMA altitude of 828 Km.) with more closely spaced apogee and perigee (eccentricity of 0.0107). BKM follows the other two objects through most of the time period through 2015, but then quickly catches up between January 2015 and 2018 as the objects enter denser portions of the Earth's atmosphere. This indicates that BKM has a higher A/M ratio than NC and AZZ. A more detailed analysis of the A/M ratios for these three objects is presented below.

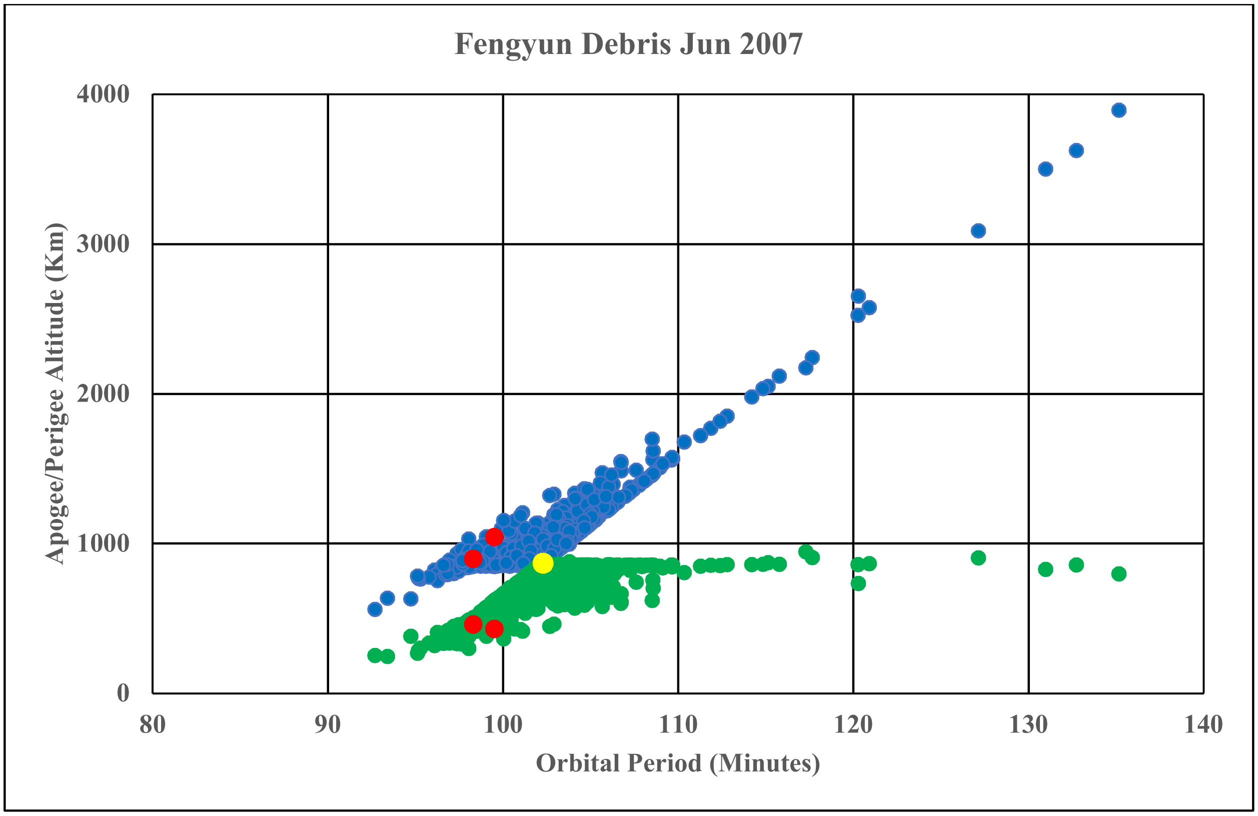

Fig. 4a. Fengyun-1C Gabbard Diagram for Jun 2007.

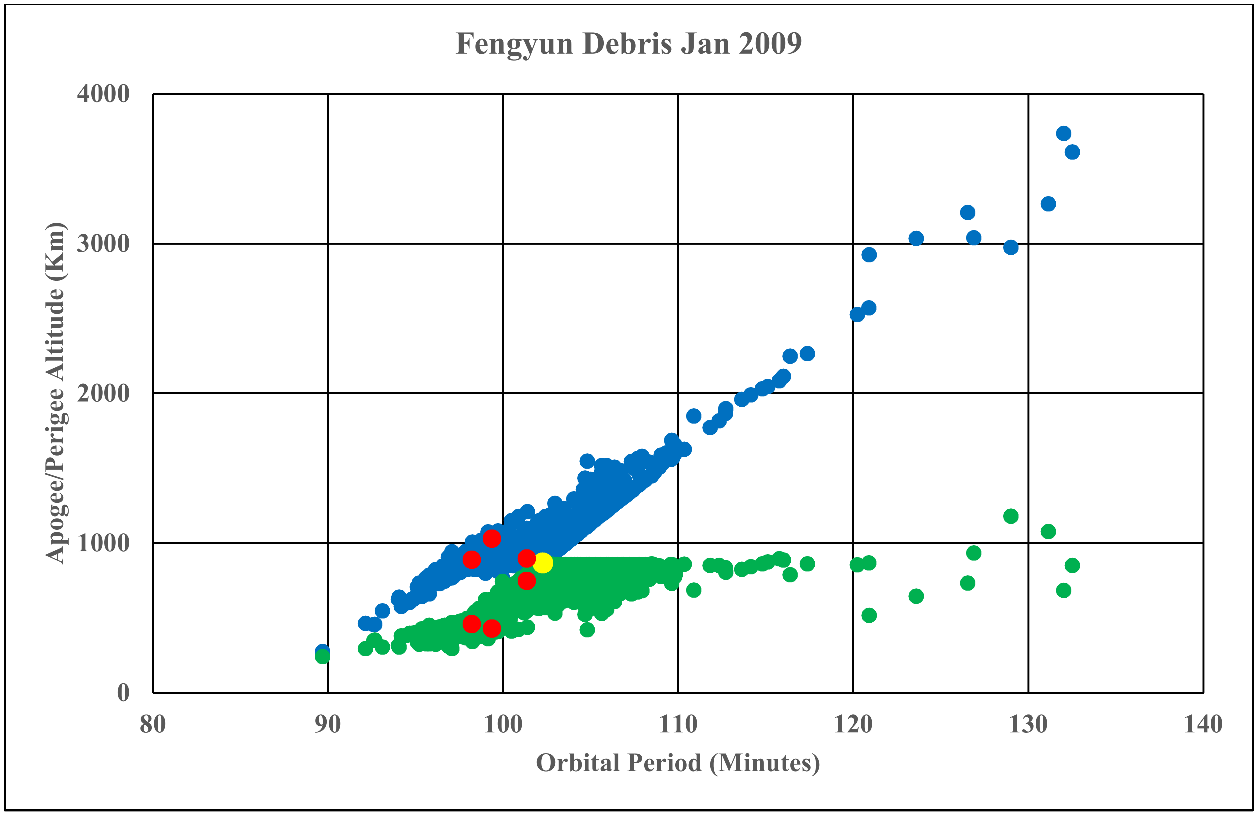

Fig. 4b. Fengyun-1C Gabbard Diagram for Jan 2009.

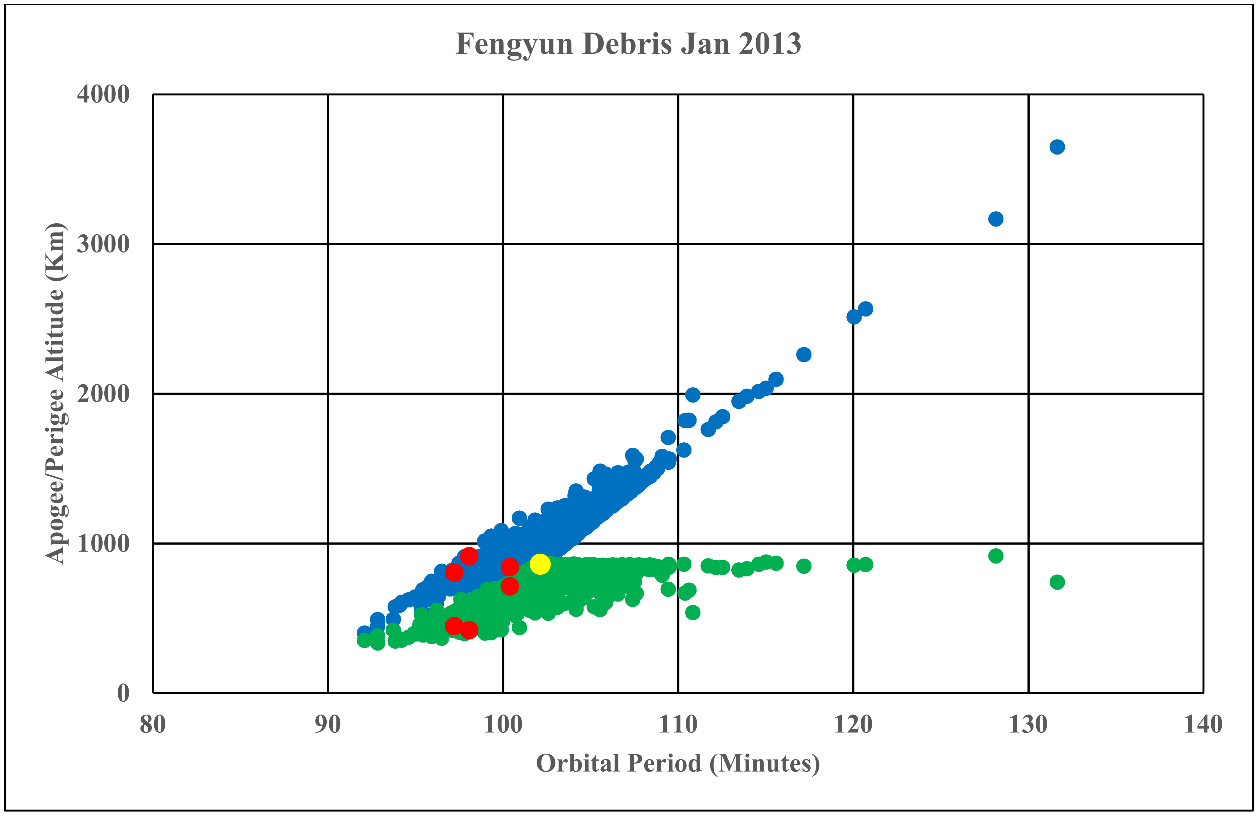

Fig. 4c. Fengyun-1C Gabbard Diagram for Jan 2013.

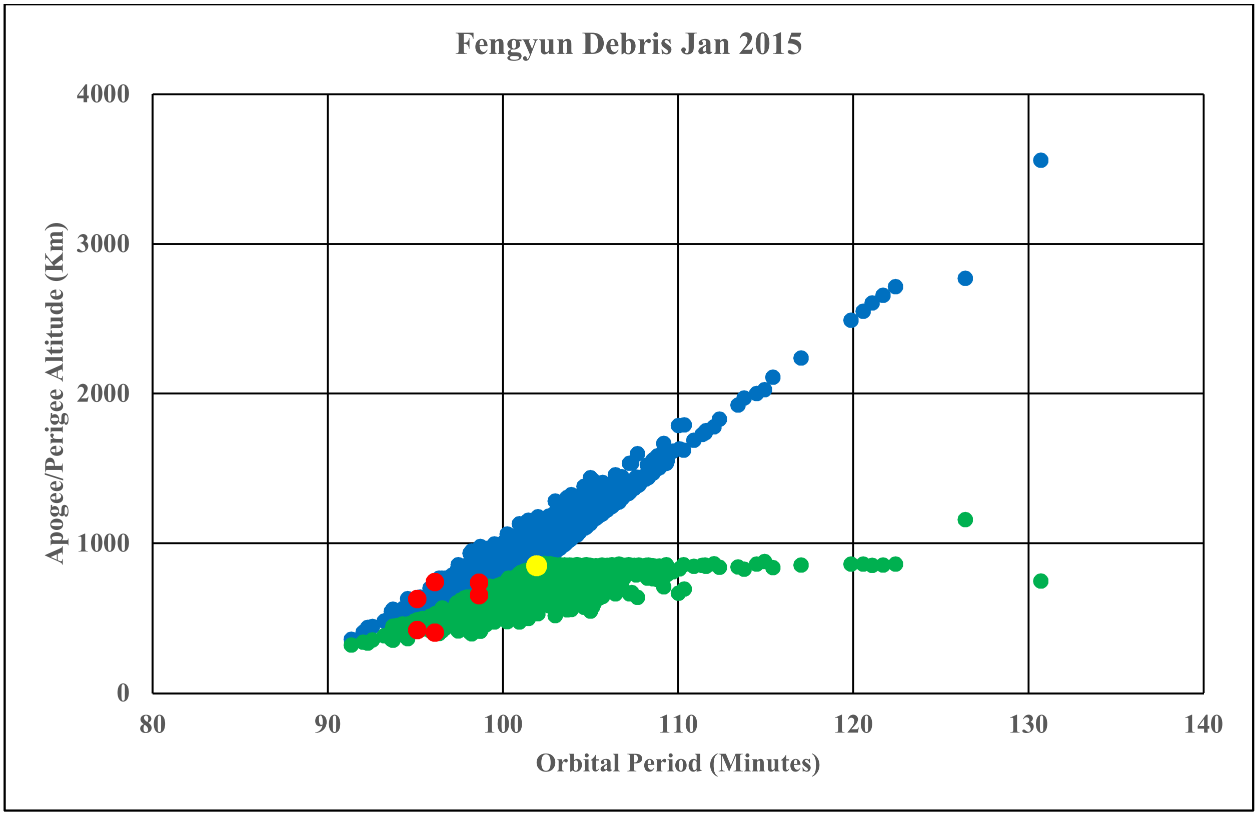

Fig. 4d. Fengyun-1C Gabbard Diagram for Jan 2015.

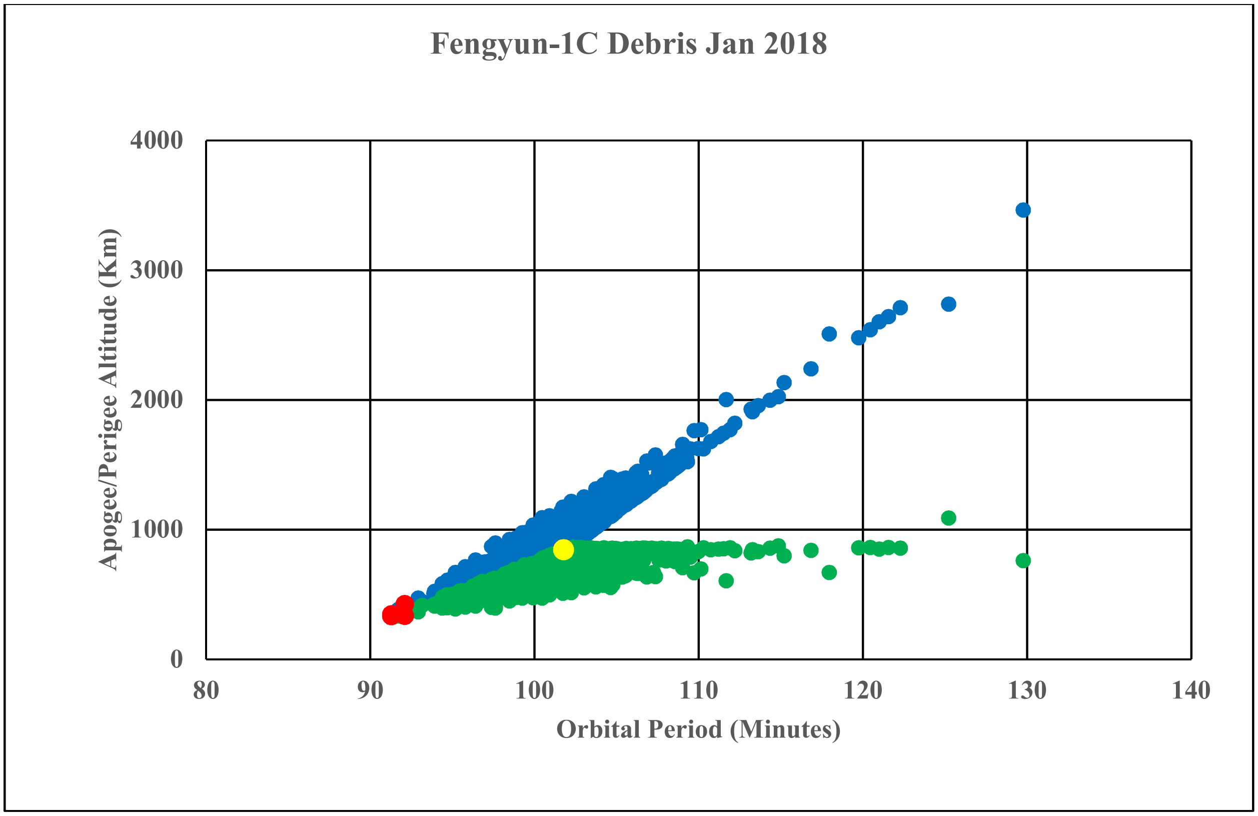

Fig. 4e. Fengyun-1C Gabbard Diagram for Jan 2018.

Considering the density of debris objects in a fairly restricted (but significant) region of Near Earth Orbit (NEO) space, concern has been expressed about the possibility of secondary collisions [3] and even about a potential for a Kessler Syndrome [9, 10] event, a cascading series of collisions that could render an orbital regime unusable for decades. Inspection of the number of objects associated with the Fengyun-1C event as a function of time (Fig. 1) shows a significant increase between January 2009 and January 2010 in both the associated objects and the cataloged objects. The total number of associated objects increased by 554 (from 99025DCE to 99025DXM). The increase could be due to a number of causes including a secondary collision, increased surveillance network attention, or additional detected and tracked objects meeting the criteria for cataloging. The January 2010 Space-Track catalog contained element sets for 344 of these objects. Element sets for the missing 210 objects could result from the objects reentering during the year or not being updated in early January 2010. A Gabbard Diagram for the 344 new catalogued objects is shown in Fig. 5. Comparing this figure to Gabbard diagrams for those for all cataloged object in 2009 (Fig. 4b) suggests that these new objects are less evolved than the general Fengyun-1C population, i.e., the right-hand arms are less "collapsed". This could result from a secondary collision or from these objects being smaller, lower area-to-mass objects recently detected and added to the catalog. The diagram is also centered on the position of the original satellite, 99025A, as are the other diagrams, but this is what would be expected if a secondary collision occurred in the densest region of the debris cloud. While improved tracking of smaller objects is the most likely explanation, more detailed analysis of the time history and orbits of these objects during 2009 would be of interest.

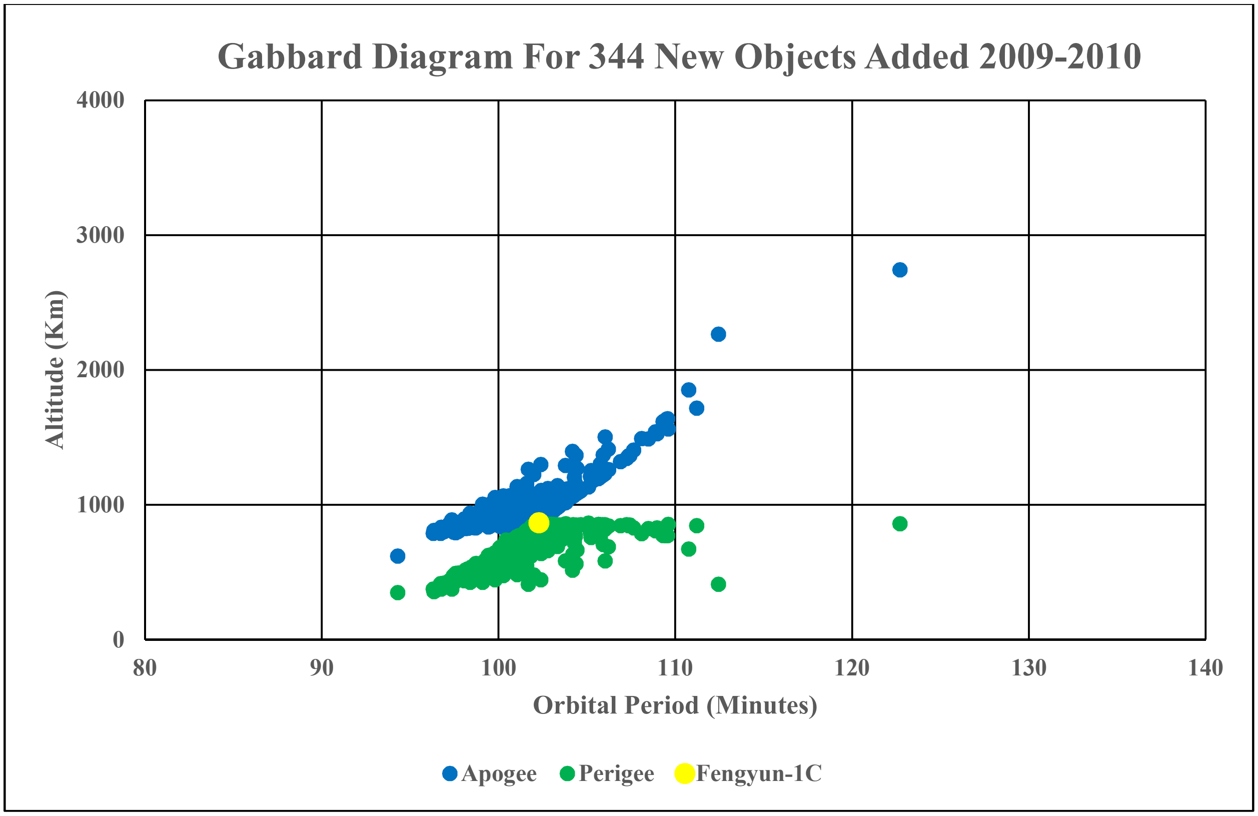

Fig. 5. Gabbard Diagram For 344 New Cataloged Objects Added Between Jan. 2009 And Jan. 2010.

Debris objects from the Fengyun-1C event are reentering the atmosphere, but at a very low rate. In the sequence of Gabbard diagrams (Figs. 4a through 4e), the left arms of the diagram can be seen to be collapsing and individual objects being "spit out" to lower orbital periods and altitudes. In the preceding figures (Figs. 2a-2f), three of these objects (99025NC, AZZ, and BKM) have been highlighted in red allowing their orbital decay to be traced. A Microsoft Excel implementation of the orbital decay prediction algorithms and program contained in Ref. 3 was used in an inverse, iterative mode to estimate the A/M ratio for these three objects using on the last Space-Track element set and one from at least one year earlier. The resulting area-to-mass ratios are listed in Table I. These A/M ratios were then used algorithms to compute the orbital decay altitude profiles and re-entry dates. The computed re-entry dates are within a few days of the Space-Track.Org published re-entry dates (Table I). Using these algorithms again, a detailed time history of the orbital decay effective altitude profile for the three objects during the last twelve to eighteen months was computed and compared to the Space-Track.Org element set data in Fig. 6. The effective altitude is used to approximate for the variation in atmospheric density between perigee and apogee, is defined as:

$$\text{Effective Altitude (Km)} = \text{Perigee Altitude (Km)} + 900 * \text{Eccentricty}^{0.6}$$

and is only valid for eccentricities less than 0.1 [11]. Two of the objects, 99025NC and AZZ, were determined to be low area-to-mass objects (0.026 and 0.052 m^2/Kg respectively) while Object 99025BKM was a high area-to-mass object (0.723 m^2/Kg). These very limited initial results are consistent with the range of A/M ratios found in an earlier, more extensive analysis [5] of over two thousand objects using the more complete element set history over the first sixteen months following the event. Although the present technique is suitable for all debris altitudes, the current application focused directly on the properties of reentering objects while they are in denser portions of the atmosphere where they are more sensitive to A/M ratio differences and avoids the requirement to incorporate the solar index variations over the longer time periods.

Table 1. Object Re-Entry Calculation Results.

International Identification	SpaceTrack.Org Object Number	SpaceTrack.Org Re-Entry Date	Estimated Re-Entry Date	Estimated Area-To-Mass Ratio (m^2/kg)
99025NC	30027	2018-07-11	2018-07-12	0.026
99025AZZ	30935	2017-02-05	2018-02-09	0.052
99025BKM	31207	2018-01-08	2018-01-03	0.723

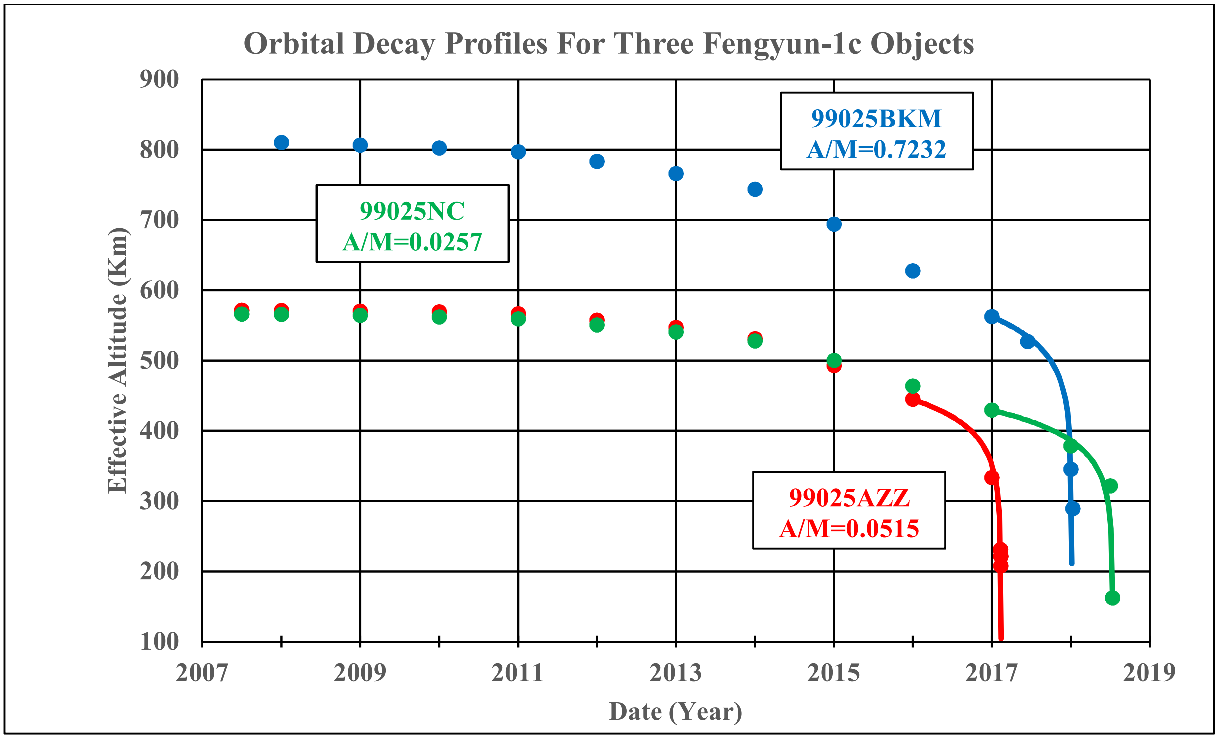

Fig. 6. Orbital Decay Profiles for Three Fengyun-1C Debris Objects.

3. CONCLUSIONS

The Fengyun-1C debris cloud has evolved during the eleven years since the anti-satellite test event that created it. The number of cataloged objects associated with the event appears to be leveling out at just over four thousand; over half of those objects remain in orbit. The RAANs of the orbits have spread around the equator but not evenly. Analysis of the Space-Track.Org element sets suggests that, after becoming more evenly distributed around the equator through 2014, the RAANs are again becoming more concentrated perhaps as the result of the lower-mass, higher A/M ratio that were more perturbed during the event reentering earlier than less perturbed, higher-mass, lower A/M ratio objects near the original Fengyun-1C sun-synchronous orbit. The significant increase in the number of associated objects between 2009 and 2010 was examined for evidence of a possible secondary collision. A Gabbard Diagram of 344 objects added to the catalog during that period suggests that the orbits of those objects may be less evolved than the general Fengyun-1C population. The orbits of many individual debris objects could be tracked in the Gabbard Diagrams for the general Fengyun-1C debris cloud as they decayed to reentry. Three of these were examined in detail and A/M ratios were computed which were consistent with earlier published results. Further studies are planned to determine the changes in the distribution of A/M ratios in the Fengyun-1C debris cloud as objects are removed from the population based on their A/M ratio and altitude.

An additional point of potential interest is that the above analyses were performed using Microsoft Excel. The ability of Excel to quickly and efficiently parse, filter, and process tens of thousands of downloaded Space-Track.Org element sets was very useful. The range of built-in functions such as VLOOKUP and GOALSEEK provide all the needed capabilities and simplifies the production of a variety of graphics. While the computational accuracy of Excel [12] has some quirks and may not be suitable for some detailed orbital calculations, it was more than sufficient for these analyses. Since Excel is a standard tool on most personal computers it would support a variety of student projects on orbital debris or other space related topics.

4. REFERENCES

1. Kelso, T. Analysis of the 2007 Chinese ASAT Test and the Impact of its Debris on the Space Environment. In *2007 AMOS Technical Conference*, Maui, HI. 2007.
2. Weeden, B. 2007 Chinese Anti-Satellite Test Fact Sheet. Secure World Foundation (www.swfoundation.org). 2010.
3. Johnson, N.L; Stansbery, E.; Liou, J-C.; Horstman, M.; Stokely, C.; and Whitlock, D. The Characteristics And Consequences Of The Break-Up Of The Fengyun-1c Spacecraft**.** IAC-07-A6.3.01. 2007.
4. Pardini, C. and Anselmo, L. Evolution of the Debris Cloud Generated By The Fengyun-1C Fragmentation Event. *Proceedings of the 26th ISSFD*. 2007.
5. Liou, J-C, and Johnson, N.L. Characterization of the cataloged Fengyun-1C fragments and their long-term effect on the LEO environment. Advances in Space Research 43. 2009.
6. ftp://ccar.colorado.edu/pub/forbes/ASEN5335/OrbitalDebris/24.%20Orbital%20Debris-2.pdf
7. Satellite Breakup Analysis. http://www.spaceacademy.net.au/watch/debris/collision.htm
8. "littlezaphod", Space Debris (Fengyun 1C). https://youtu.be/hXKvrvSdjgM May 26, 2008.
9. Kessler, D.J., Johnson, N.L., Liou, J-C., and Matney, M. The Kessler Syndrome: Implications to Future Space Operations. 33rd Annual AAS Guidance and Control Conference. Boulder, CO. 2010

10. Kessler, D.J. and Anz-Meador. Critical Number of Spacecraft in Low Earth Orbit Using Satellite Fragmentation Data to Evaluate the Stability of the Orbital Debris Environment. *Proceedings of the Third European Conference on Space Debris*, 19 - 21 March 2001, Darmstadt, Germany.
11. Panwar, Rakseh. Australian Government Bureau of Meteorology. The Australian Space Weather Agency. Satellite Orbital Decay Calculations. http://www.sws.bom.gov.au/Category/Educational/Space%20Weather/Space%20Weather%20Effects/SatelliteOrbitalDecayCalculations.pdf
12. https://en.wikipedia.org/wiki/Numeric_precision_in_Microsoft_Excel