An Assessment of the Impact of the January 2007 Chinese ASAT Test on the LEO Environment

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ABSTRACT

Over the past several decades there has been increasing concern regarding the growth of the orbital debris population in the Low Earth Orbit (LEO) environment. Even under the best of circumstances the debris population may be expected to increase under conditions of ambient use by the space-faring nations of the world. It is easy to see that such a situation will obtain since the operational lifetimes of most on-orbit systems are typically less than a decade, while their orbital lifetimes may be many decades to hundreds of years or more. Historically, very little has been done regarding the removal of defunct orbital systems. Making matters worse, there have been many cases of spontaneous explosion of derelict upper stages on orbit. In such an event, a single large "hazard to navigation" becomes hundreds to thousands of pieces of orbiting shrapnel. As the numbers of debris objects increases, for whatever reason, so does the threat of collision with high-value operational assets. Thus, given the importance of minimizing orbital debris in LEO, it is obvious that any nation conducting anti-satellite (ASAT) tests should do so in a responsible fashion – minimizing the long-term deposition of large numbers of orbital debris objects at operational LEO altitudes. It is the thesis of this paper that the January 2007 ASAT test conducted by the Chinese government was particularly careless in this regard. In support of this statement, Oceanit's LEO environment model, PODEM (patented in 2004), was employed. The Chinese ASAT test was conducted successfully at an altitude of about 850 km producing large numbers of debris objects. Results, based on an approximation to this recent event, utilizing the PODEM model, suggest that many debris pieces may remain in the LEO environment for hundreds of years. By contrast, debris ranging in size from one to several centimeters may be expected to drift down, due to drag, through lower LEO altitudes producing a transient spike in hazard within a few years to a decade. The International Space Station (ISS) is a particular concern. By comparison and in contrast, several hypothetical cases of debris deposition in LEO at lower altitudes are illustrated. The current research concludes that the Chinese ASAT test has unnecessarily exposed valuable LEO systems to an enhanced hazard over a long time scale.

1. INTRODUCTION

The Low Earth Orbit (LEO) environment may be taken to be that volume of space defined by a shell around the earth extending from approximately 200 km to 2000 km altitude. An examination of a current epoch of the satellite catalog will show that a large number of all operational payloads of all space-faring nations operate within this regime. A fundamental threat to these payloads is orbital debris.

Orbital debris may be created by a variety of processes including normal operations. For example, when payloads are launched, debris objects and rocket bodies are usually placed in the environment as well. Even the payloads themselves often become derelicts before they decay from the environment. Historically, on-orbit break-ups of upper-stages [1] have also been a significant source of orbital debris. Such break-ups typically convert one large, easy-to-track "hazard to navigation" into a large number of pieces of shrapnel – some easy to track and some not. Whatever the "source" of orbital debris, the only natural "sink" in LEO is the residual atmosphere at orbital altitudes which provides a resistive mechanism allowing objects to decay back into the atmosphere. As discussed in [2] this natural mechanism diminishes rapidly with altitude and results in on-orbit lifetimes measured in decades to hundreds of years above 750 km. In short, orbital debris is easy to create and hard to get rid of once in LEO.

The subject of this paper is an examination of the impact to the LEO environment of the Fengyun-1C ASAT test. In light of the above discussion, the conclusion may be forecast – the test was irresponsible as regards the altitude of the target. In the discussion in the sections to follow, it will be shown that debris from this ASAT test will linger in the LEO environment for a very long time to come. By comparison, the orbital debris produced by the last U.S. ASAT test, conducted in 1985 and at a much lower altitude, has already completely decayed from the LEO environment.

2. THE FENGYUN-1C ASAT EVENT

On May 10, 1999 the People's Republic of China (PRC) launched the weather satellite Fengyun-1C into a near-circular polar orbit from the Taiyuan Space Center. The identifying designations and orbital characteristics for this payload, as found in [3], are: U.S. Satellite Catalog Number = 25370; International Designator = 1999-025A; Period = 102.3 minutes; Inclination = 98.69 degrees; Apogee = 881 km; Perigee = 854 km, and; Radar Cross Section (RCS) = 1.1738 m^2.

On January 11, 2007, at 5:28 p.m. EST, as initially reported in [4], the PRC successfully conducted their first ASAT test by destroying Fengyun-1C utilizing a kinetic kill vehicle launched from the Xichang Space Center on board a ballistic missile. The impact took place at an altitude of approximately 854 km and four degrees west of the launch facility. Over the next six months the total number of fragments identified with the ASAT test continued to rise. By mid-July approximately 2200 probable fragments from the Chinese ASAT test were being tracked with more than 1900 officially cataloged as reported in [5]. By August 11, 2007 – the baseline date for this work – a total of 2085 Fengyun-1C Debris objects were listed as officially cataloged in [3].

In the next section of this paper some of the characteristics of the study population will be presented and discussed prior to a brief overview of the Phenomenological Orbital Debris Environment Model (PODEM) and its application to two cases of the LEO environment disturbed by contrasting ASAT events – P-78/SOLWIND in 1985 and Fengyun-1C in 2007.

3. OBSERVED CHARACTERISTICS OF THE FENGYUN-1C FRAGMENTS

Of the 2085 Fengyun-1C debris objects officially cataloged by August 11, 2007 only 14 had decayed out of the LEO environment – less than 1% of these objects. All 14 of these objects had average altitudes less than 350 km and were thus subject to considerable atmospheric drag. Of the remaining 2071 objects, the population average orbital characteristics are: Period = 102.3 minutes; Inclination = 98.98 degrees; Apogee = 1001 km; Perigee = 735 km, and; RCS = 0.069 m^2. All discussion and illustrations in this section are based on the characteristics of the 2071 fragments still resident in LEO at the time of the writing of this paper.

Utilizing apogee, perigee, and orbital period data, a Gabbard diagram has been constructed and is presented below as Fig. 1. Casual inspection of Fig. 1 readily shows that debris from the Fengyun-1C ASAT event has been broadcast throughout the LEO environment and beyond – some fragments reaching apogees of nearly 4000 km. However, a more focused inspection of Fig. 1 yields the qualitative impression that the bulk of the ASAT debris is currently resident between altitudes of about 500 km to 1500 km. This is a very important part of the LEO environment occupied by hundreds of active satellites operated by all space-faring nations. All of these satellites have been put at some level of enhanced risk by the Chinese ASAT test.

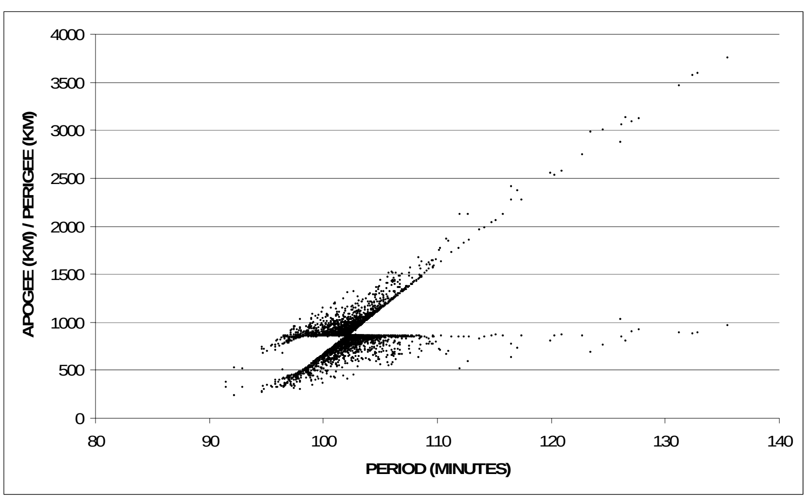

Fig. 1. Gabbard diagram for 2071 Fengyun-1C fragments as of 08-11-2007.

In Fig. 2 a portion of Fig. 1 has been expanded to illustrate the effects of atmospheric drag on the study population. From this illustration the apogee "tail" of the Gabbard diagram clearly indicates the significant effects of drag on 125 elements of the Fengyug-1C debris population having orbital periods less than or equal to 98 minutes and perigees less than or equal to 500 km. In addition, a total of 66 fragments were found to have orbital periods greater than 98 minutes and perigees less than or equal to 500 km. Thus, only 191 fragments – 9.2% of the Fengyun-1C debris population – are likely to manifest significant drag effects on short time scales measured in months to several years.

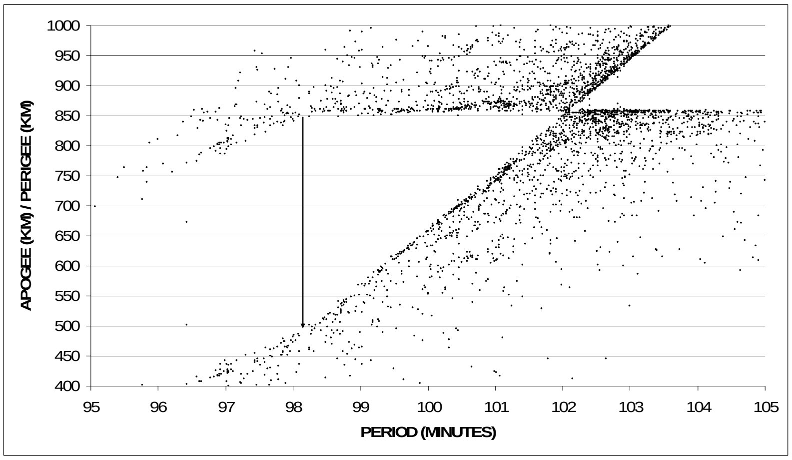

Fig. 2. A slightly expanded Gabbard diagram for the 2071 Fengyun-1C fragments.

In Fig. 3, a graph is presented of Fengyun-1C debris object mean altitudes versus RCS. An immediate conclusion that may be drawn from inspection of this figure is that there are only a few objects having RCS values greater than a fraction of a square meter and they are all located near the original altitude of the parent object. Further, it is interesting to note that all fragments lofted into highly eccentric orbits – high mean altitudes in Fig. 3 – are objects of small RCS.

From the study population data we have the following breakdown by RCS: 7 fragments with RCS > 1 m^2; 31 fragments with RCS values between 0.15 m^2 and 1.0 m^2, and; 2033 fragments with RCS < 0.15 m^2. The NASA Orbital Debris Program Office has estimated [6] that, in total, approximately 35,000 pieces of debris greater than 1 cm in diameter were produced by the Fengyun-1C ASAT test. Therefore, in addition to the cataloged pieces described above, a population of approximately 33,000 fragments is probably present in LEO as well as those just described – unseen, and potentially lethal to operational systems.

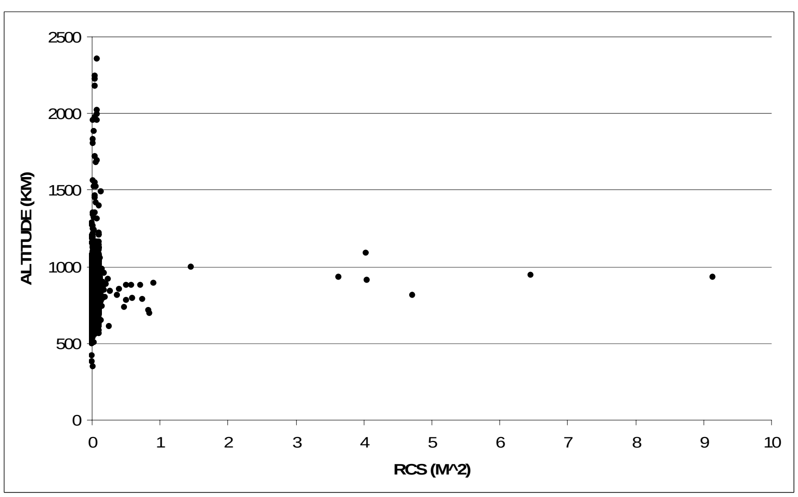

Fig. 3. Graph of altitude vs. RCS indicates the largest pieces of debris remained near the initial altitude.

4. PODEM – AN ORBITAL DEBRIS ENVIRONMENT MODEL

4.1 The Forerunner to PODEM

The possibility that the orbital debris environment might eventually grow in a "catastrophic runaway" was first pointed out by Kessler and Cour-Palais of NASA-JSC in 1978 [7]. Their assessment was based on a fairly simple, but plausible argument. In the years that followed, as the orbital debris problem was taken more seriously, investigations sprang up on several fronts including observational, experimental, and theoretical. Theoretical activity included efforts to model the orbital debris environment.

In 1988, the author of this paper sought to develop an analytic model based on a simple differential equation with an approach to the environment that was thermodynamic in character (i.e., not requiring detailed tracking of all objects in the environment). The results of that model, called the "Particle-In-a-Box" (PIB), were first presented in 1990 [8]. Following extension and refinement of the text, a peer-reviewed paper was published in 1992 [9]. It was this paper that eventually served as the starting point for the development of PODEM.

Before describing PODEM, it is worth pointing out that the basic approach of the PIB model, upon which PODEM is based, has been verified by several independent researchers.

Farinella and Cordelli of the University of Pisa (Italy) published a model in 1991 [10] similar to the PIB model. In their paper, which considered two debris object sizes, instead of a variable equivalent size object employed in the Talent PIB model, they noted …

"A fairly similar model of the orbital-debris production process, based on a single differential equation, has been independently proposed in a recent paper by Talent; in spite of somewhat different assumptions on the source and sink terms appearing in the equations, Talent's results are similar to [ours]."

In addition, a LEO environment evolutionary program called CHAIN was developed by Peter Eichler at the Technical University of Braunschweig, Germany, under the German Federal Ministry of Research and Technology from 1988 – 1991. In Eichler's Ph.D. thesis [11] he notes the similarities of the PIB and CHAIN results as regards those conditions that might lead to catastrophic runaway conditions and mitigation strategies for same.

Therefore, the basic validity of the modeling approach that is the foundation of PODEM has been supported by independent researchers in Germany and Italy.

PODEM was developed from late 1998 through early 2002 under SBIR Phase I (Contract No. NAS8-99018) and Phase II (Contract No. NAS8-00001) funding provided through the NASA-Marshall Space Flight Center. In June of 2004 Oceanit received a U.S. Patent on PODEM (No. 6,757,617).

4.2 PODEM – Modeling Philosophy and Structure

The development of PODEM from the modeling protocol of the original PIB model is founded in the mathematical prescriptions specified as equations (9) and (10) of [9]. Due to space limitations, the reader is referred to that earlier work for a discussion of the equations.

In the PODEM model, the top of LEO is taken to be at 2000 km altitude and the bottom to be 350 km altitude. The lower altitude was chosen based on the assessment that most on-orbit objects at such altitudes or lower will decay from the environment within a year. One year or longer residency in the LEO environment is defined as the "membership condition" in PODEM – the objective is to eliminate transient objects that have little impact on long-term environment evolution. The upper limit to LEO is that altitude below which about 98% of all cataloged objects may be found [12].

In the current version of the PODEM model, ten LEO environmental strata are defined. Since the significance of drag is greater at lower altitudes, close to earth, than at higher altitudes, the PODEM strata are defined such that they are thinner at the bottom than the top of LEO. The specific choice of divisions is fully explained in [12]. The

PODEM altitude strata are: S1, 350-410 km; S2, 410-470 km; S3, 470-535 km; S4, 535-605 km; S5, 605-690 km; S6, 690-780 km; S7, 780-925 km; S8, 925-1180 km; S9, 1180-1550 km, and; S10, 1550-2000 km.
Five discrete object types are defined to represent LEO population members in the current version of PODEM. For the purposes of this discussion each of the object types may be characterized by its value of drag coefficient, C_d(A/M). These values are, specifically: T1, 0.001394; T2, 0.004915; T3, 0.01843; T4, 0.3600, and; T5, 0.1234. The specific choice of object types is fully explained in [12]. However, for the purpose of all further discussions in this paper object types T1 and T2 may be taken to be representative of intact satellites. Object types T3 and T4 will be used to characterize cataloged fragmentation debris, while object type T5 will be invoked to represent the untracked component of the fragmentation population.

The LEO environmental events modeled in PODEM are illustrated Fig. 4. In stratum "S_n" for example, a differential equation exists describing the changes in the population per unit time of each particle type "T_i" due to launches, collisions, explosive fragmentations, and drag. Since the current version of PODEM utilizes five particle types and ten strata, a total of 50 differential equations, including cross-feed terms between strata, are required to model the LEO environment. A default set of coefficients based on an assessment of a variety of phenomenological parameters as well as various published models (e.g., explosion, collision, etc.), is provided in PODEM for all equations. However, the default values are visible to the user and may be changed as considered justified.

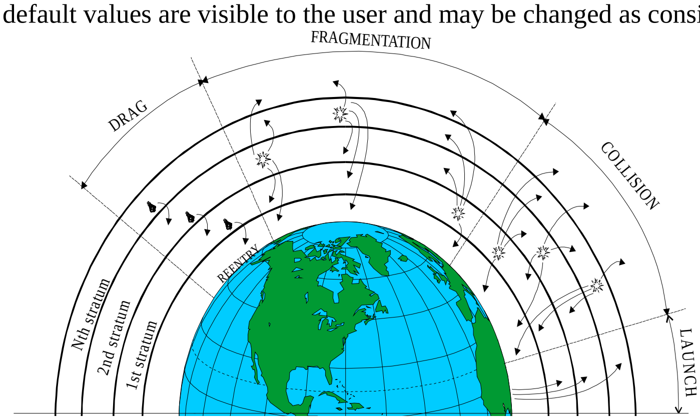

Fig. 4. Illustration of the elements of PODEM.

A PODEM modeling run is initiated via the GUI interface shown in Fig. 5. The starting point is the "Scenario Definition" button which allows the user to establish start and stop dates, launches per year, and other parameters. Because PODEM does not keep a detailed accounting of every object's behavior, scenarios may be established, executed, and examined very quickly. Computational runs that represent evolutionary scenarios of 25 years may be run in a matter of seconds. Long term scenarios even up to 500+ years are equally straightforward. Output may be retained in tabular format or examined graphically.

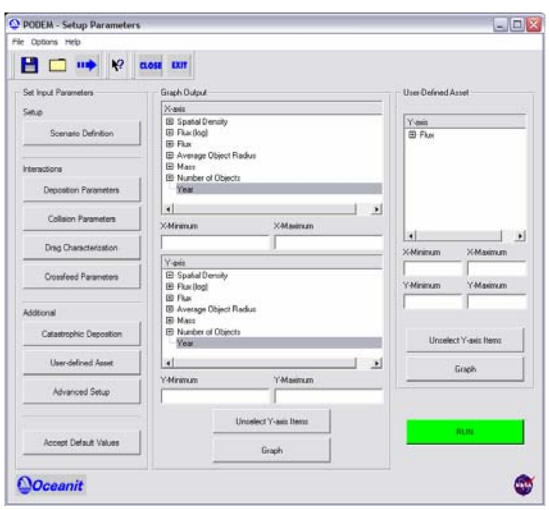

Fig. 5. The PODEM GUI control panel.

Other model capabilities exist through the interactive GUI, such as the option to specify a “Catastrophic Deposition” of objects of any particle type and quantity into any stratum at any time in a model run. This feature, along with the ability to suppress the background population was employed to produce the results presented in sections 5, 6, and 7. All graphical results shown are screen captures of PODEM graphics.

5. PODEM APPLICATION: 1990-2030

The PODEM model, applied to the LEO environment for cataloged objects produces the results shown in Fig. 6. Inspection of the graph shows a cataloged population of approximately 7200 objects at the beginning of 1990 growing to over 16000 by 2030 utilizing nominal model coefficients. As a check, note that the cataloged population at the beginning of 2007 produced by PODEM is approximately 11000. The actual value was closer to 10000 as per [3]. The primary reason for the difference is that, in the current version of PODEM, the solar cycle model was found to produce a run-time error that occasionally caused PODEM to crash during execution. Consequently, for all cases presented in this paper, the solar cycle model has been turned off. This bug will be fixed in later versions of PODEM.

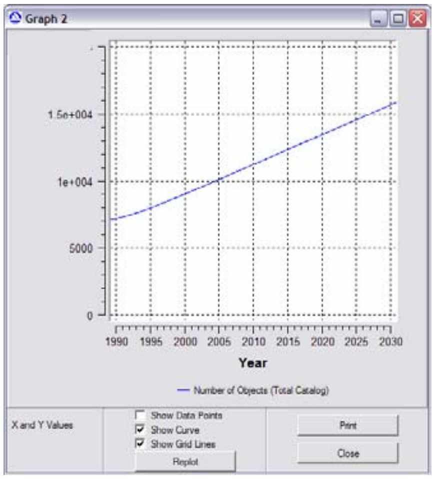

Fig. 6. PODEM model results for cataloged objects in LEO for the interval 1990 to 2030.

In Fig. 7 the results of a PODEM model run are once again displayed with the addition of the “catastrophic deposition” of 2085 T3 objects into stratum S7 at the beginning of 2007. This addition of objects into the LEO environment is, of course, intended to represent the Fengyun-1C ASAT test. In this single event more than 15% of currently cataloged objects in LEO came into existence. As noted in [5], the Fengyun-1C ASAT test has become “by far the worst satellite fragmentation of the space age.”

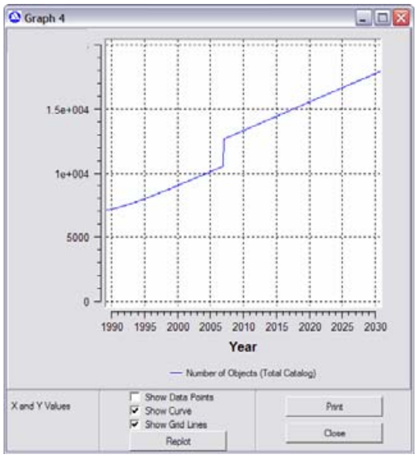

Fig. 7. PODEM model results for cataloged objects in LEO for the interval 1990 to 2030. Included is the 2007 Fengyun-1C ASAT test “catastrophic deposition” of debris into the LEO environment.

6. PODEM APPLIED TO THE SOLWIND ASAT TEST

To illustrate the utility of PODEM as applied to an ASAT test, historical data associated with the P-78/Solwind test – the last U.S. ASAT test – will be employed. On September 13, 1985 an ASM-135A missile was launched from a modified F-15A at 80,000 feet against the P-78/Solwind satellite [13]. As summarized in [14], the ensuing collision took place at 524 km and produced 285 fragments that were ultimately cataloged; only 8 of these fragments remained in orbit as of January 1, 1997 – about 11.3 years later.

To model the P-78/Solwind ASAT test, the option was selected in PODEM to suppress the background population allowing only the examination of the "catastrophic deposition" of 285 T3 debris objects to S3 which is inclusive of the actual 524 km event altitude. PODEM currently requires a starting date of 1990 or later so the event date was specified to be January 1, 1990 – a minor inconvenience.

In Fig. 8 the results of the PODEM run for the P-78/Solwind case are shown for a 15 year interval. The top curve is the sum of all objects remaining in orbit as a function of time. The curve second from the top represents the number of ASAT fragments in S3 as a function of time. The bottom two curves are the numbers of fragments in S2 and S1 as a function of time, respectively.

There are several interesting results to note in Fig. 8. First, the total number of objects predicted by PODEM to still be on orbit after 11.3 years was 7 – clearly close to the actual value of 8 of the P-78/Solwind test. Secondly, the numbers of objects in S3 monotonically decrease with time which is consistent with physical intuition since these objects are decaying out of S3 into S2 and then S1. Third, the number of objects in levels S2 and S1 initially grows, peak at times successively displaced from the original event date, and then decline. Finally, due to the increased efficiency of drag at lower altitudes the peak number of fragments in S2 and S1 are progressively lower due to decreased residency time for any given object in a particular stratum.

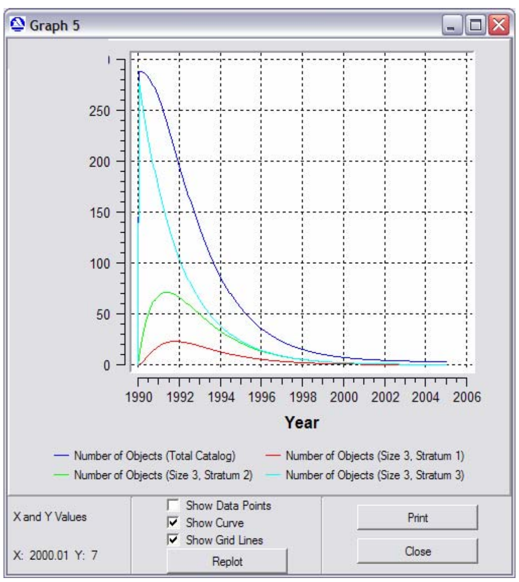

Fig. 8. PODEM as applied to the P-78/Solwind ASAT test – numbers of fragments in successive strata as a function of time are shown.

The P-78/Solwind ASAT test took place 330 km lower in LEO than the Fengyun-1C ASAT test and that has made all the difference. Debris objects from the former test were quickly removed from the environment by atmospheric drag on time scales that did not represent a long term threat to other on-orbit assets.

In the next section, in contrast to the P-78/Solwind ASAT test, the PODEM model will be applied to an assessment of on-orbit debris lifetimes resulting from the Fengyun-1C ASAT test.

7. PODEM APPLIED TO THE FENGYUN-1C ASAT TEST

Utilizing mean altitudes, the distribution of the 2085 Fengyun-1C fragments relative to the PODEM strata is as follows: S1, 0.05%; S2, 0.05%; S3, 0.24%; S4, 1.25%; S5, 5.84%; S6, 13.09%; S7, 58.28%; S8, 18.93%, S9, 1.50%, S10, 0.53%, and; >S10, 0.24%. Since nearly 60% of the Fengyun-1C debris pieces have average altitudes in PODEM stratum S7, this altitude regime will be used for all model runs presented in this section. Further, PODEM particle types T3 and T4 will be used to represent cataloged debris, while PODEM particle type T5 will be used to model the small, untracked population.

7.1 Fengyun-1C Debris Characterized by PODEM T3 Fragments

In the execution of PODEM to produce Fig. 9, just as for the P-78/Solwind case, the background population has been suppressed to illustrate the case of the 2085 Fengyun-1C debris, modeled as PODEM type T3, suddenly being deposited in S7. The total model run time was 500 years. As before, the top curve is the sum of all objects remaining in orbit as a function of time. The curve second from the top represents the number of Fengyun-1C fragments in S7 as a function of time. The next two curves, immediately below, are the numbers of fragments in S6 and S5 as a function of time, respectively. The scale of the graph does not allow the numbers of objects in strata S1 through S4 to be well displayed.

The most important result displayed in Fig. 9 is that after 100 years, if the Fengyun-1C objects may be truly characterized as being similar to the model T3 objects, only 13% will have decayed from LEO. Further, even after 500 years, 14% of these objects may be expected to still be in the LEO environment. Additionally it is noted that as these debris fragments decay to lower altitudes, peaks displaced by about 100 years and 150 years are produced in S6 and S5, respectively. Similar behavior, not shown, is also exhibited for strata S1 through S4.

Regarding the reality of the assumption of T3 objects used here, it should be recalled that the PODEM model reproduced the results of the P-78/Solwind ASAT test using the same choice. Since this choice worked well for this historical ASAT case, it might be expected to work well regarding the future of the Fengyun-1C debris population. However, in the event the general Fengyun-1C population is more correctly characterized by a higher drag coefficient, the case using T4 objects will be examined.

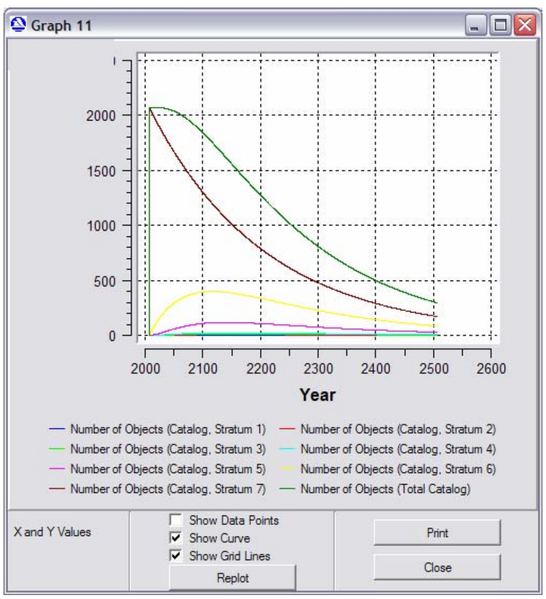

Fig. 9. PODEM run for fragments of type T3, characterized by $C_d(A/M) = 0.018$.

7.2 Fengyun-1C Debris Characterized by PODEM T4 Fragments

In the execution of PODEM to produce Fig. 10, the background population was again suppressed to illustrate the case of the 2085 Fengyun-1C debris, modeled as PODEM type T4 objects, deposited in S7. The total model run time was 100 years. As before, the various curves represent the debris population in various strata versus time as previously defined for Fig. 9.

It may be seen from inspection of Fig. 10 that after 30 years the number of Fengyun-1C objects resident in LEO will have decayed by 50% using PODEM T4 objects as the basis for the model. Further, after 100 years only 5% of the original 2085 objects would remain on orbit. Additionally, as before, it is noted that as these debris fragments decay to lower altitudes, peaks displaced by about 100 years and 150 years are produced in S6 and S5, respectively. Similar behavior, not shown, is exhibited for strata S1 through S4.

Even under the assumptions associated with the use of a PODEM T4 object compared to a T3 object as the model basis, the Fengyun-1C ASAT test may be concluded to be both qualitatively and quantitatively much worse than the P-78/Solwind ASAT test regarding its impact on the LEO environment.

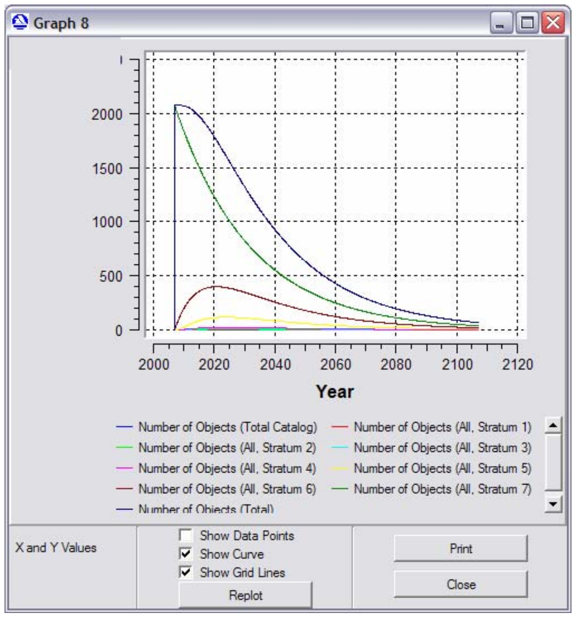

Fig. 10. PODEM run for fragments of type T4, characterized by $C_d(A/M) = 0.036$.

The population of cataloged objects from the Fengyun-1C ASAT test represents a hazard to valuable space assets in LEO. As reported in [5], the number of close approaches has risen significantly and on June 22, 2007 NASA's Terra spacecraft had to execute a collision avoidance maneuver. Unfortunately, those Fengyun-1C fragments that can't be tracked likewise can't be avoided. This population of small, but potentially lethal objects will be examined in the following subsection.

7.3 Fengyun-1C Untracked Debris Characterized by PODEM T5 Fragments

In the execution of PODEM to produce Fig.11, the small debris population from the Fengyun-1C ASAT test was modeled as the sudden deposition of 33,000 objects, characterized as PODEM type T5, in S7. The total model run time was 25 years. As before, the graph displays the debris population in various strata versus time as previously defined for Fig. 9.

As one might expect, the T5 objects – characterized by their large drag coefficient – will not last long in the LEO environment. Inspection of Fig. 11 shows that after only 6 years the number of such objects from the Fengyun-1C ASAT test resident in LEO will decay by 50% and will nearly be gone from the LEO environment within 25 years.

As these objects decay from the LEO environment, transient peaks in S6 and S5 may be expected in late 2009 to early 2010. Because of the increased atmospheric density in successively lower strata, the peak value of the number of small debris objects resident in any stratum at any time is successively smaller.

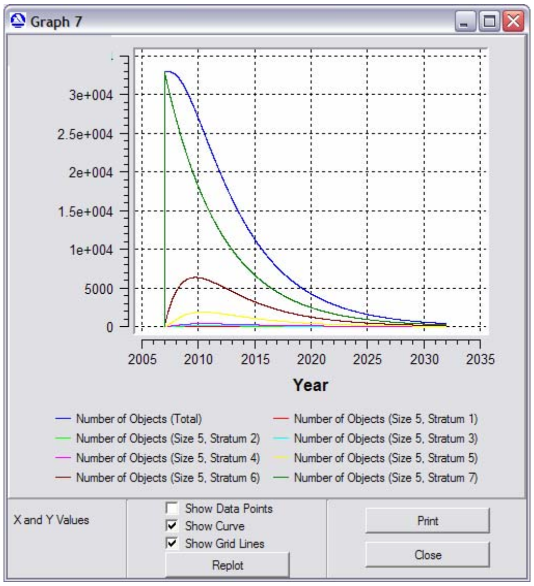

Fig. 11. PODEM run for fragments of type T5, characterized by $C_d(A/M) = 0.123$.

In order to display the transient population of small objects in S1 through S4, the vertical axis of Fig. 11 was rescaled and is presented as Fig. 12. In this figure it is clearly seen that the transient peak in small debris numbers from the Fengyun-1C ASAT test in these strata, in 2010 to 2011, is successively smaller for the reasons cited above. It may also be noted that S4 is the altitude regime in which the International Space Station (ISS) orbits the earth. Clearly, the increase in the number of unseen objects from roughly 2007 to 2025 represents an enhanced risk to the ISS. However, note the peaks in absolute number of objects are moderated by atmospheric drag.

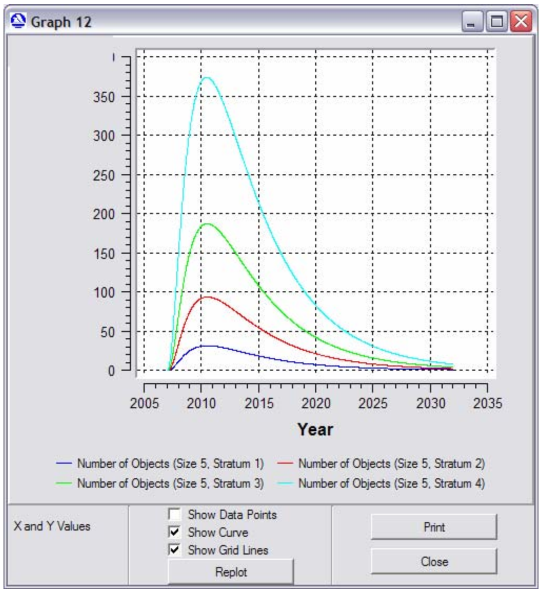

Fig. 12. PODEM model of unseen population objects “drifting down” through PODEM stratum 4, 3, 2, and 1

8. CONCLUSIONS

An examination of the Fengyun-1C ASAT test has been presented based on Oceanit’s PODEM model of the earth orbital debris environment. The PODEM model appears to function well as validated by an examination of the P-78/Solwind ASAT test. Utilizing modeling parameters similar to that case, PODEM predicts a reduction in the number of Fengyun-1C cataloged debris objects resident on orbit of only 13% in the next 100 years; 14% will still remain even after 500 years. Even under a relaxed alternate set of model assumptions, it will take at least 100 years to remove the Fengyun-1C debris.

In addition, debris objects too small to track were created by the tens of thousands as a result of the Fengyun-1C ASAT test. These objects will tend to decay through lower altitude regimes causing a peak rise in relative hazards at ISS altitudes by about 2010 to 2011 from this component of the population.

Even though any model is only an approximation to reality, from this study it may be concluded that the PRC Fengyun-1C ASAT test of January 11, 2007 was exceptionally careless and irresponsible creating an unnecessary and long term orbital debris hazard that must now be dealt with by all space-faring nations for decades if not centuries to come.

9. REFERENCES

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