CLOSE APPROACH PREDICTION ANALYSIS OF THE EARTH SCIENCE CONSTELLATION WITH THE FENGYUN-1C DEBRIS

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Routine satellite operations for the Earth Science Constellation (ESC) include collision risk assessment between members of the constellation and other orbiting space objects. Each day, close approach predictions are generated by a U.S. Department of Defense Joint Space Operations Center Orbital Safety Analyst using the high accuracy Space Object Catalog maintained by the Air Force's 1st Space Control Squadron. Prediction results and other ancillary data such as state vector information are sent to NASA/Goddard Space Flight Center's (GSFC's) Collision Risk Assessment analysis team for review. Collision analysis is performed and the GSFC team works with the ESC member missions to develop risk reduction strategies as necessary. This paper presents various close approach statistics for the ESC. The ESC missions have been affected by debris from the recent anti-satellite test which destroyed the Chinese Fengyun-1C satellite. The paper also presents the percentage of close approach events induced by the Fengyun-1C debris, and presents analysis results which predict the future effects on the ESC caused by this event. Specifically, the Fengyun-1C debris is propagated for twenty years using high-performance computing technology and close approach predictions are generated for the ESC. The percent increase in the total number of conjunction events is considered to be an estimate of the collision risk due to the Fengyun-1C break-up.

I. INTRODUCTION

Orbital debris poses a significant threat to spacecraft health and safety. The current estimate for the number of 'tracked' objects that are larger than 10 cm is greater than 12,000, with the number of objects increasing by several hundred per year. Most of these tracked objects are characterized as orbital debris. Satellites are routinely hit by small particles that cause little or no damage. However, if a large particle were to hit an operational satellite, the impact could result in the end of the mission. A large part of the orbital debris population resides in low Earth orbit (LEO), where the density distribution of cataloged objects is concentrated near mean equatorial altitudes of 700 – 1100 km.

Because of the threat posed by orbiting objects, government organizations such as the Department of Defense (DOD), National Reconnaissance Office (NRO), and the National

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Aeronautics & Space Administration (NASA) have established risk assessment and risk mitigation strategies for many of their operational spacecraft. Recent events such as China's anti-satellite (ASAT) test and break-ups such as the Breeze-M rocket explosion have led to an even greater awareness and concern in the satellite community, thus demonstrating the necessity of an operations concept that includes monitoring, computing and mitigating collision risks.

In August 2007, NASA formalized its commitment to mitigating potential on-orbit collision risks by adding requirements to the current NASA Procedural Requirements (NPR) for Limiting Orbital Debris[1] (NPR 8715.6). The updated NPR requires conjunction analysis be performed routinely for all Earth-orbiting spacecraft. Currently, routine collision risk analysis is being performed for the Earth Science Constellation (ESC), which consists of 11 satellites in 705 km mean altitude sun-synchronous orbits.

The ESC Collision Risk Assessment (CA) team at Goddard Space Flight Center (GSFC) performs collision risk assessment analysis based on the data provided by personnel from the Air Force's 1st Space Control Squadron (1SPCS) resident in the Department of Defense's Joint Space Operations Center (JSpOC). The process begins by generating close approach predictions between members of the ESC and other objects in the United States Strategic Command's (USSTRATCOM's) high-accuracy Space Object Catalog. The close approach prediction information in processed and the collision risk is assessed probabilistically. After the collision threat is assessed, the ESC CA team works with the member missions to plan any necessary risk-mitigating actions. This process is discussed in detail in Reference 2.

In January 2007, the Fengyun-1C Chinese weather satellite was destroyed. The Fengyun-1C satellite's similar orbit, approximately 860 km altitude with an inclination of 98.5 degrees, and the thousands of debris objects created during this event posed an immediate threat to the ESC missions. This paper discusses the observed and predicted impact of the Fengyun-1C debris event on the number of conjunction events for the ESC. Section II provides the historical close approach predictions that have been generated through the routine processing for the ESC. Sections III and IV provide background information for the Fengyun-1C debris event. Sections VI and VII present a prediction of the evolution of the Fengyun-1C debris and the increase in close approach predictions between the ESC and the Fengyun-1C debris over the next 20 years.

II. OPERATIONAL CLOSE APPROACH STATISTICS FOR THE ESC

ESC routine CA operations began in January 2005. The Aqua and Aura missions were addressed first, followed by a steady build-up of other constellation missions in subsequent months. By the end of 2005, routine CA operations were being performed for 9 Earth Science satellites. In April 2006, the CloudSat and Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) missions were added to the ESC CA processing.

The ESC CA operations process consists of screening the ESC assets against the high-accuracy catalog using three different mission safety volumes. Table 1 lists the dimensions of these safety volumes. The safety volumes are centered on the primary object and dictate different data product deliveries as well as actions taken by the CA team. The "Monitor Volume (MV)" is the largest safety volume and serves as the initial reporting filter. The "Tasking Volume (TV)" is a smaller volume, and close approach predictions that fall within this volume require further analysis. The "Watch Volume (WV)" is a 1 km 'stand-off' radius. The coordinate frame for monitor and tasking volumes is the radial, in-track, cross-track (RIC) coordinate frame.

Table 1: Safety Volume Definitions

	Radial (km)	**In-Track (km)**	**Cross-Track (km)**
Monitor Volume (ellipsoid)	±2	±25	±25
Tasking Volume (box)	±0.5	±5	±5
Watch Volume (sphere)	1 km stand-off radius		

Figure 1 shows the total number of unique ESC safety volume violations that have been identified for each month across the whole ESC since screening began. The steady increase in the numbers is primarily due to the staggered addition of satellites to the mission set. The figure indicates that the constellation as a whole currently experiences about 800 Monitor Volume violations, 60 Tasking Volume violations, and 22 Watch Volume violations each month. Table 2 lists the monthly safety volume violation averages broken out by individual mission. On average, each ESC member can expect to experience approximately 70 Monitor Volume violations, 5 Tasking Volume violations, and 2 Watch Volume violations per month. The ICESat close approach averages are distinctly less than those of the rest of the ESC members because the ICESat orbital altitude is 100 kilometers lower than the rest of the member missions.

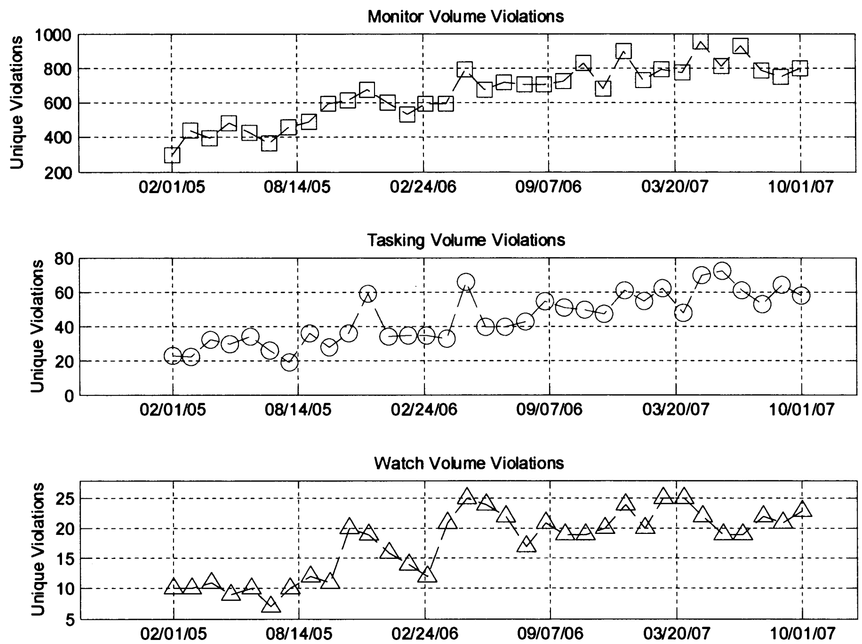

Figure 1: ESC Safety Volume Violations – Monthly Totals

Table 2: Safety Volume Violations – Monthly Averages

ESC Mission	Effective Monthly Average - MV	Effective Monthly Average - TV	Effective Monthly Average – WV
Landsat-5	70.68	5.41	2.21
Landsat-7	68.11	4.57	1.60
Terra	69.67	4.26	2.10
EO-1	72.81	5.26	1.91
SAC-C	70.75	4.84	1.81
Aqua	75.92	4.62	1.65
ICESat	50.34	3.64	1.58
Aura	71.27	4.30	1.53
PARASOL	79.50	5.37	1.94
CloudSat	77.11	5.57	2.52
CALIPSO	72.77	5.95	2.46

In February 2007, there was a 5 percent increase in the total number of Monitor Volume violations. This increase was due to the break-up of the Fengyun-1C satellite that occurred in January (event details discussed in Section III). Although the Fengyun-1C event occurred at an altitude more than 100 km above the altitude of the ESC, the debris was distributed over an altitude range of several hundred kilometers. A few weeks after the break-up, debris pieces of the Fengyun-1C began entering the ESC Monitor Volume. Table 3 gives the date of the first Monitor Volume violation by Fengyun-1C debris for each ESC member.

Table 3: Fengyun-1C Debris vs. ESC, 1st Monitor Volume Violation

ESC Mission	1st CA Event Vs. Fengyun-1C Deb	ESC Mission	1st CA Event Vs. Fengyun-1C Deb
Landsat-5	19-Feb-2007	ICESat	04-Feb-2007
Landsat-7	09-Feb-2007	Aura	23-Feb-2007
Terra	05-Feb-2007	PARASOL	11-Feb-2007
EO-1	17-Feb-2007	CloudSat	12-Feb-2007
SAC-C	11-Feb-2007	CALIPSO	06-Feb-2007
Aqua	22-Feb-2007		

Subsequent months continued to show an increase in the percentage of CA events involving Fengyun-1C debris. Currently, the Fengyun-1C debris makes up 10-15 percent of the total number of objects predicted to violate the ESC asset Monitor Volume.

On Monday June 18, 2007, a close approach between Terra and Fengyun-1C debris object number 31410 was predicted to occur. The time of closest approach was predicted to be Saturday June 23 with a predicted miss distance of 140 meters and a collision probability of 4.8e-6. While that probability number was not especially high, the combination of having a non-zero probability and a very small miss distance caused analysts to flag this event for further analysis and monitoring. Throughout the week as more data were collected on the debris, the miss distance continued to trend downward while the probability rose to the e-2 level and remained consistent. By Friday morning, the miss distance had reached 19 meters with an associated collision probability of 8.8e-2. The decision to maneuver was made and a risk mitigation maneuver was executed Friday evening. The maneuver resulted in an increase in the miss distance to 1.2 km and subsequently drove the probability to zero.

This CA event confirmed that the Fengyun-1C break-up has already begun to have significant operational impacts on the ESC. Since most of the Fengyun-1C debris is still above the ESC orbital regime, additional CA events similar to the Terra event are likely to occur.

The remaining sections of this paper address the Fengyun-1C break-up in detail. Distribution properties of the current and future debris set are presented and an estimate of the increased collision risk to the ESC is discussed.

III. FENGYUN-1C BREAK-UP EVENT SUMMARY

On 11 January 2007, the Chinese weather satellite Fengyun-1C was intentionally destroyed as part of a Chinese anti-satellite (ASAT) test. The Fengyun weather satellite was in a sun-synchronous orbit with a mean altitude of approximately 860 km and an inclination of 98.5 degrees when it was destroyed.

NASA Orbital Debris models estimate that the number of 1-cm pieces generated by this event is approximately 35,000[3]. To date, the number of pieces that have been cataloged by the Space Surveillance Network is approximately 2300. This event constitutes the worst single break-up event in 50 years[3-4]. The result of the ASAT test was to distribute debris in a broad altitude range up to nearly 2000 km with some pieces re-entering soon after the event took place.

Figure 2 shows the height distribution of objects in low Earth orbit organized by 20 km height collection bins. The number of objects in each 20 km height range bin is collected and then the total number per bin is plotted. The Fengyun-1C debris is concentrated near an altitude of 850 km. For a height range between 800 and 900 km, the percentage of objects that are Fengyun-1C debris in each bin ranges from 30 to 60 percent.

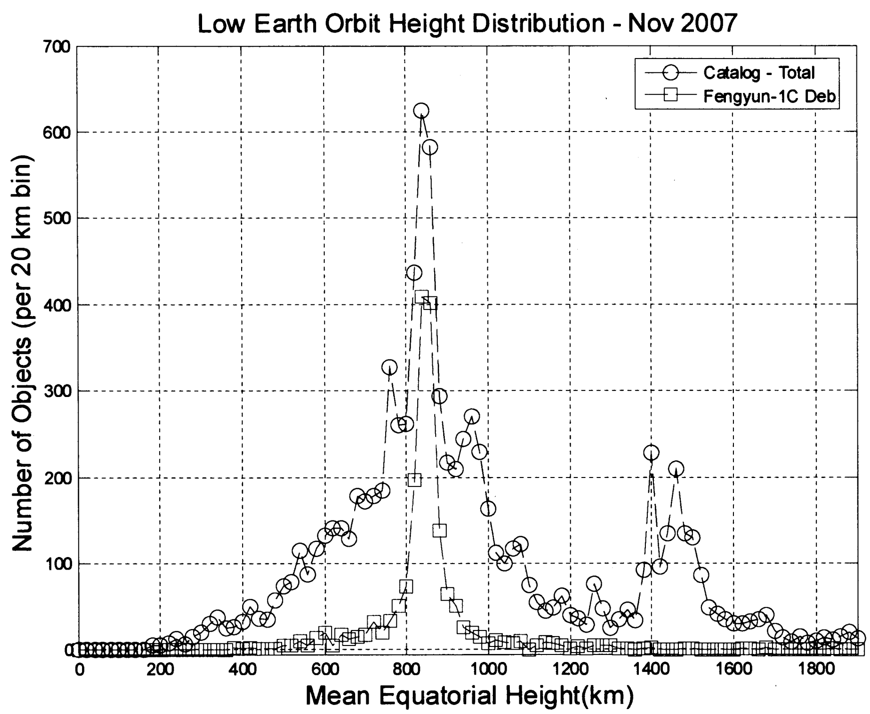

Figure 2: Mean Height Distribution (Nov 10, 2007)

IV. CURRENT CHARACTERISTICS OF THE FENGYUN-1C DEBRIS

Shortly after the ASAT event occurred, the Space Surveillance Network began cataloging pieces of the Fengyun-1C debris. Approximately 30 pieces were cataloged on the 18th of January and by the end of the month more than 500 pieces had been cataloged. To date, more than 2,300 pieces have been cataloged.

Figures 3 and 4 give the distribution of various orbital parameters for the Fengyun-1C debris pieces. These plots and statistics were generated using the Fengyun-1C debris states from 10-Nov, 2007.

Figure 3 shows the mean equatorial height distribution of the Fengyun-1C debris. The mean is 863 km, which is approximately the height where the ASAT event occurred. The minimum height value is 339 km and the maximum height value is 1,871 km. Also shown in Figure 3 is the position of the ESC with respect to the debris height distribution. The ESC altitude is denoted by the red dot. Examination of Figure 3 shows that 92 percent of the Fengyun-1C debris lies above the current ESC operational altitude of 705 km. Table 4 provides the mean equatorial height statistics.

Table 4: Equatorial Height Statistics

Minimum	Maximum	Mean	Standard Deviation
330.7	1,870.9	863.5	142.7

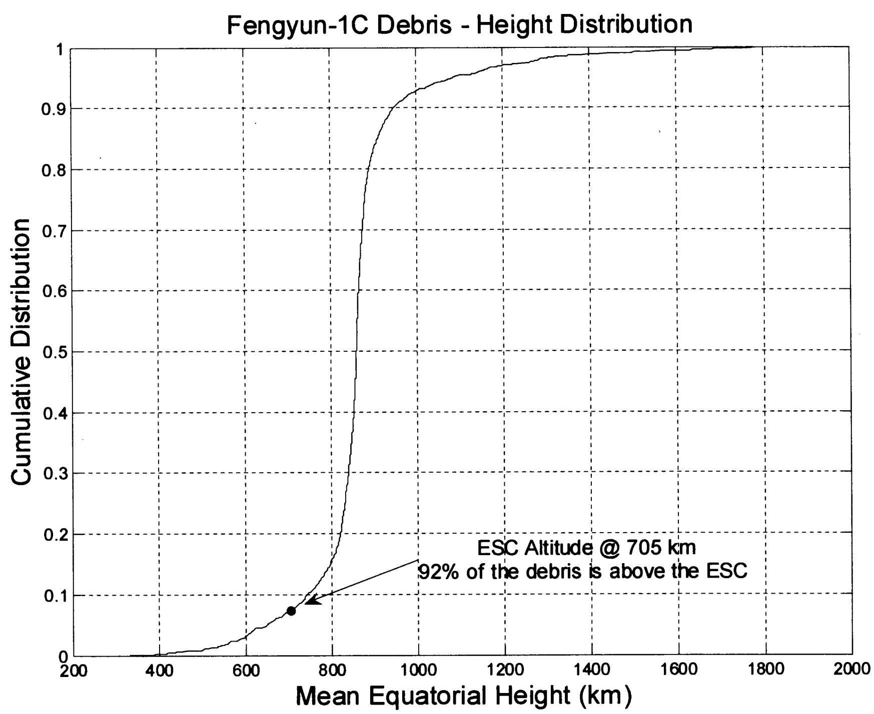

Figure 3: Height Distribution

Figure 4 shows the apogee and perigee height vs. inclination. The dispersion on the inclination ranges from 95 to 99 degrees. Table 5 lists statistics for the apogee and perigee height.

Table 5: Apogee/Perigee Statistics

	Minimum	Maximum	Mean	Standard Deviation
Apogee	541.9	4004.7	994.0	249.4
Perigee	280.4	873.7	736.7	134.9

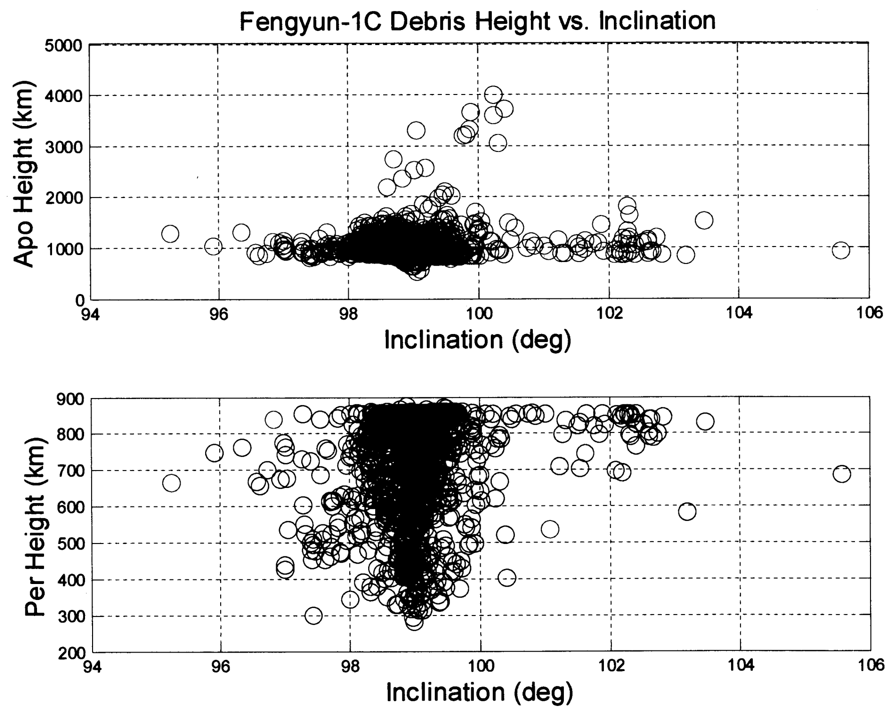

Figure 4: Apogee/Perigee Distribution

V. LONG TERM EPHEMERIS CREATION AND FORCE MODELING

In order to estimate long-term impact of the Fengyun debris on the ESC member missions, GSFC CA analysts decided to perform an analysis of the debris evolution. This section describes the methodology used to generate the 20 years of Fengyun-1C ephemeris data required for the analysis. In order to generate such long-term predictions for several thousand objects, a clustered computing environment was used.

A. Force Modeling

The Fengyun-1C debris population was propagated for 20 years using high fidelity force modeling that includes the Earth's geopotential, luni-solar gravity, and atmospheric drag. Table 6 lists the perturbative forces modeled.

Table 6: Fengyun-1C Force Modeling

Parameter	Modeling
Earth Geopotential Model	4x4 Joint Gravity Model (JGM) -2
Non-Central Bodies	Sun, Moon (JPL DE200 Ephemeris File)
Atmospheric Density Model	Jacchia Roberts
Solar Radiation Pressure Model	Thin plate model
Numerical Integrator	Runge-Kutta 8(9) with 300-s fixed step size

Atmospheric dynamics were modeled using GSFC's Schatten solar flux predictions released in November 2007. Figure 5 shows the F10.7 solar flux prediction profile used in this analysis in Solar Flux Units (SFU). It should be noted here that only the Schatten mean, nominal-timing flux values were used in this analysis.

Included with the Fengyun-1C Debris state information were drag and solar radiation pressure force-model parameters, including the ballistic coefficient, derived via the orbit estimation process. This ballistic coefficient was then used to calculate proportionally correct mass and area values for each object by fixing the area and solving for the mass. The mass and area values were applied and held constant throughout the propagation span.

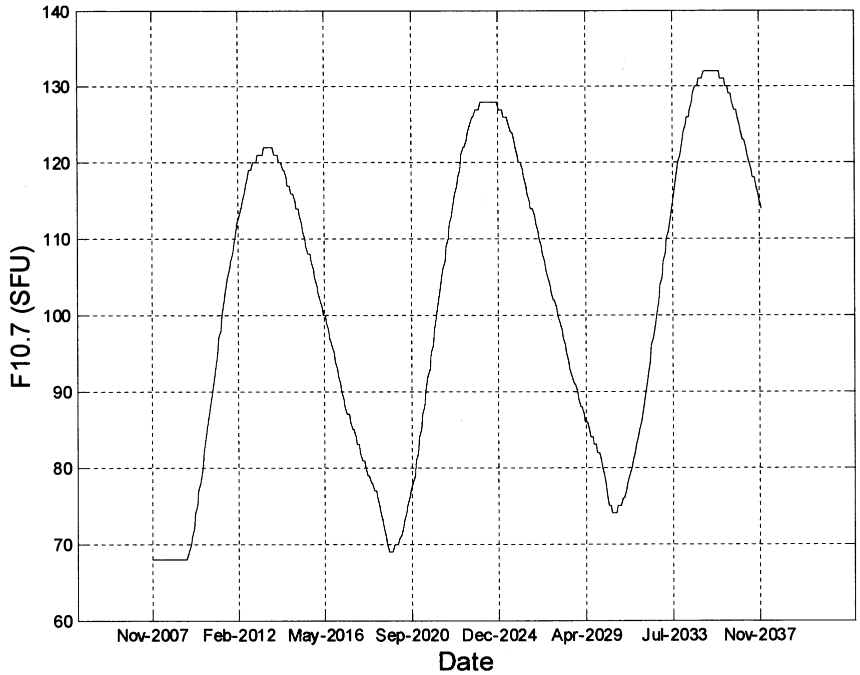

Figure 5: Schatten Solar Flux Predicts - Nov 2007

B. FreeFlyer Cluster Technology

The methodology used to propagate the Fengyun debris objects utilized FreeFlyer® cluster technology. The specific solution consists of low-cost commodity PC hardware coupled with the Microsoft® Windows® Compute Cluster Server (WCCS) 2003 operating system and FreeFlyer® COTS mission analysis software. The WCCS 2003, released in August 2006, is a high performance computing (HPC)-capable operating system based on Windows® Server 2003, and represents the first dedicated, easy-to-use HPC operating system for the Windows® platform. FreeFlyer® is a mission analysis and planning tool that natively runs in the Windows® environment and is used operationally to support CA for the ESC missions. The unique nature of this solution is that it uses a Commercial Off-the-Shelf (COTS) flight dynamics tool in concert with an easy-to-configure, broadly-supported HPC operating system. Figure 6 shows a simple example of a network topology that supports a WCCS 2003 HPC cluster. More complex and involved configurations are possible, and in some cases would aid performance, but this simple example is sufficient and depicts that used in the analysis described here.

In addition to the windows platform benefits afforded by the WCCS 2003, it also provides easy-to-use cluster management and process scheduling tools. The "job scheduler", as it is called in WCCS 2003, is what allows the user to submit "jobs" to the cluster and monitor them. Other than basic monitoring, no other interaction with the scheduler is required during job execution. The job scheduler will execute the individual "tasks" that make up a job, submitting each task to a compute node as a node finishes a prior task and becomes available. For ease of use and automation, WCCS 2003 allows jobs to be submitted in the form of a template. This template is simply an XML file that contains the commands that direct the cluster to execute all the tasks required for a specific segment of the analysis. These segments are described in the following sections.

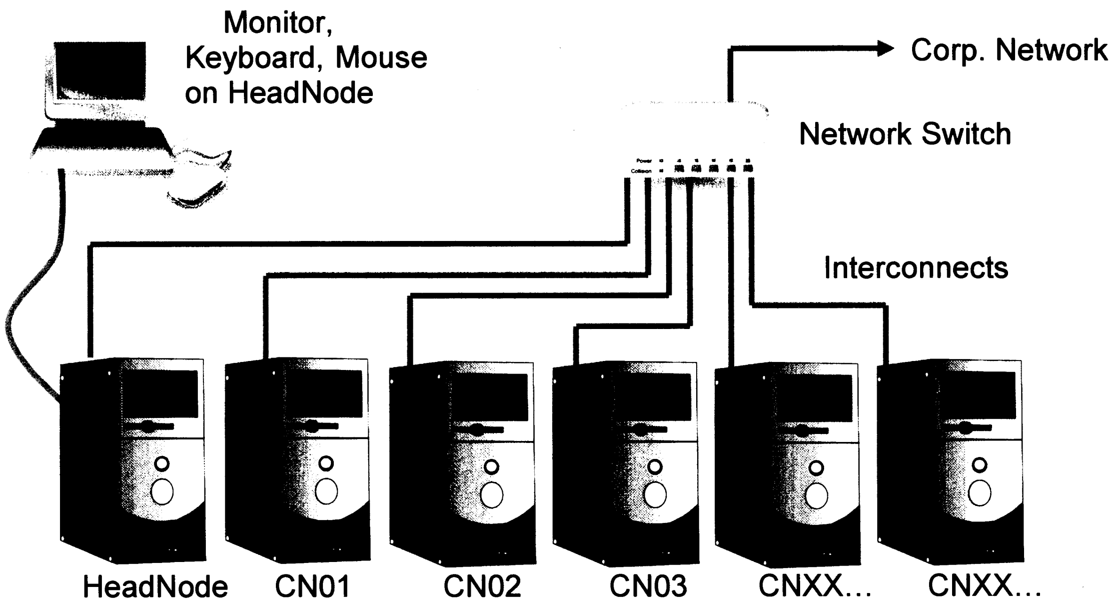

Figure 6: Simple Windows Compute Cluster Network Topology

C. Cluster Work Flow and Fengyun-1C Ephemeris Generation

The work flow used to complete the overall analysis is straightforward and consists of two main steps. The first step involves the creation of ephemeris data for the debris objects of interest and the second step involves the close approach comparison analysis of the debris objects against representative ESC assets. Each step consists of two parts, the creation of a job template containing all the tasks to be run for the next step, and the actual numerical operations associated with the analysis.

The first step in creating the debris ephemeris data was accomplished by running a single instance of FreeFlyer® that accessed a MySQL database and retrieved the high fidelity state data for all the Fengyun-1C debris objects. This FreeFlyer® missionplan uses this data to create an individual task entry in the cluster job template for each debris object that includes the state data. In this way, the job template also becomes a record of the specific run since it contains all the data needed to complete the ephemeris creation. After this point the database is no longer needed to complete the analysis.

The second part of creating the debris ephemeris data was to propagate the initial states out for 20 years. This was accomplished with a very simple FreeFlyer® missionplan that propagated the state forward at 30-day intervals and recorded ephemeris, Energy Dissipation Rate (EDR), and mean altitude data at each interval. The ephemeris data ceased being recorded and the propagation was stopped if the object reached an altitude of 125 km as this is well below any assets of interest and represents atmospheric interface for re-entry purposes. This step, more than any other, is made possible by the HPC cluster solution described above, which allowed the data to be computed with very little effort in a reasonable amount of time.

VI. LONG TERM EVOLUTION OF THE FENGYUN-1C DEBRIS

Once the USSTRATCOM high accuracy catalog data was numerically integrated to generate future state predictions, the analysis of predicted close approaches could be performed. This section describes the analysis of how the Fengyun-1C debris is expected to evolve over the next 20 years. State information from the USSTRATCOM high accuracy catalog was numerically integrated to generate future state predictions. In particular, state data for this process was retrieved in December 2007 totaling 2,227 state vectors.

A. Fengyun-1C Height Evolution

Figure 7 shows the evolution of the mean equatorial height over the period 2008 through 2028 at 30-day intervals for the entire set of Fengyun-1C debris objects. Each year, the statistical mean of all the debris pieces is computed. Very little change in the height is observed from year to year with a mean equatorial height in 2027 of 830 km, just 30 meters less than the 2008 value.

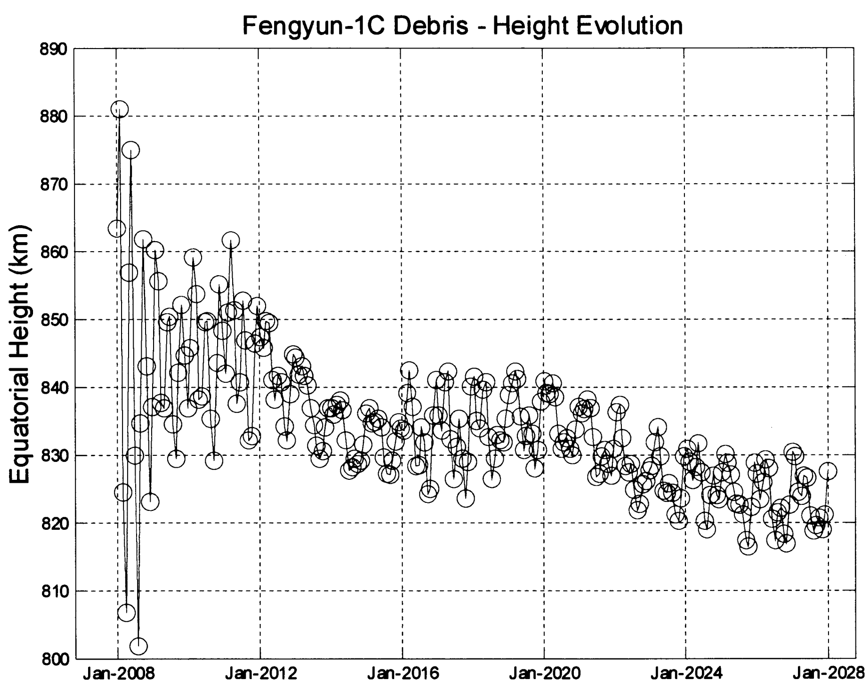

Figure 7: Fengyun-1C Debris Mean Height Evolution

The evolution of the debris percentage that resides above the ESC altitude is nearly identical to the height evolution in Figure 7. Very little change in this percentage is observed over the 20 year prediction period. In particular, in 2027, the percentage of Fengyun-1C debris that is above the ESC altitude is 85 percent; only a 7 percent reduction from the current height distribution. Figure 7 demonstrates that the Fengyun-1C debris will remain in orbit, and thus a collision threat to the ESC, for several decades. The decay predictions in the next section further illustrate this assertion.

B. Fengyun-1C Decay Predictions

Figure 8 shows the yearly decay percentage for the Fengyun-1C debris. When the debris state reaches an altitude of 125 km, it is considered to be re-entered. Ten years after the initial ASAT test event, nearly 80 percent of the debris remains. Twenty years after the event, 70 percent of the debris remains. This numerical integration approach is consistent with predictions made by NASA's LEGEND orbital debris utility[6]. Additional longer term predictions made by NASA's Orbital Debris Office show that 10 percent of the Fengyun orbital debris will still remain after 100 years.

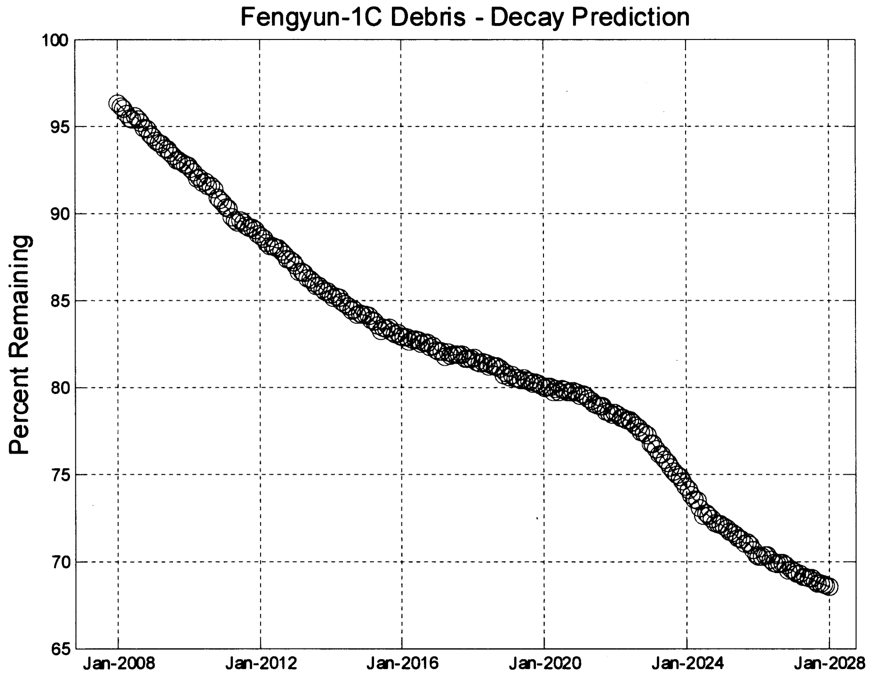

Figure 8: Fengyun-1C Debris Decay Prediction

Although the solar cycle passes through two activity peaks during the next 20 years, the changes in the atmospheric density environment have virtually no effect on the decay rate. However, the changes in the atmospheric density do manifest themselves in the covariance prediction, which ultimately affects the collision probability calculation.

C. Fengyun-1C EDR Distribution

The Energy Dissipation Rate of an orbiting object is a representation of the amount of drag acting on an object. The EDR is the dot product between the drag acceleration and the velocity vectors. The objects in the space object catalog are broken-up into ten different EDR classes based on the amount of drag that they experience. A high EDR value indicates a high susceptibility to atmospheric drag. The predictive covariance (particularly the in-track position and radial velocity) is primarily driven by tracking frequency and drag effects. So if an object is well-tracked, and has a low EDR, changes to its orbit state are expected to be small. Table 6 shows how the EDR bins are defined.

Table 7: EDR Bin Definition

Bin #	EDR Range	Bin #	EDR Range
1	[0 , 6e-4)	6	[3e-3 , 6e-3)
2	[6e-4 , 1e-3)	7	[6e-3 , 9e-3)
3	[1e-3 , 1.5e-3)	8	[9e-3 , 1.5e-2)
4	[1.5e-3 , 2e-3)	9	[1.5e-2 , 5e-2)
5	[2e-3, 3e-3)	10	>= 5e-2

Figure 9 shows the EDR distribution of all Fengyun-1C debris in January 2008. Ninety percent of the debris lies in EDR Bin #1, indicating a low susceptibility to drag. Three percent of the debris is in EDR Bin #2 and 1.5 percent in Bin #3. Bin #4 - Bin #10 contains the remaining 5 percent.

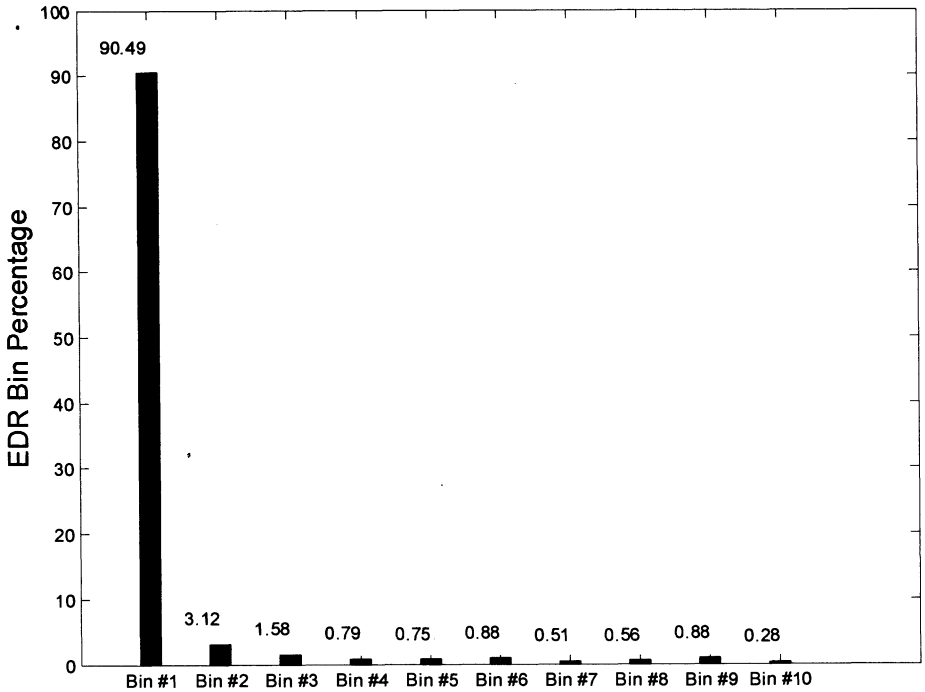

Figure 9: EDR Distribution - Jan 2008

Figure 10 shows changes to the EDR distribution over the next 20 years. The evolution of the distribution follows the solar cycle, where higher solar flux and thus higher drag change the EDR bin percentages. Near the solar maximum, the number of objects in Bin #1 drops to 55 percent.

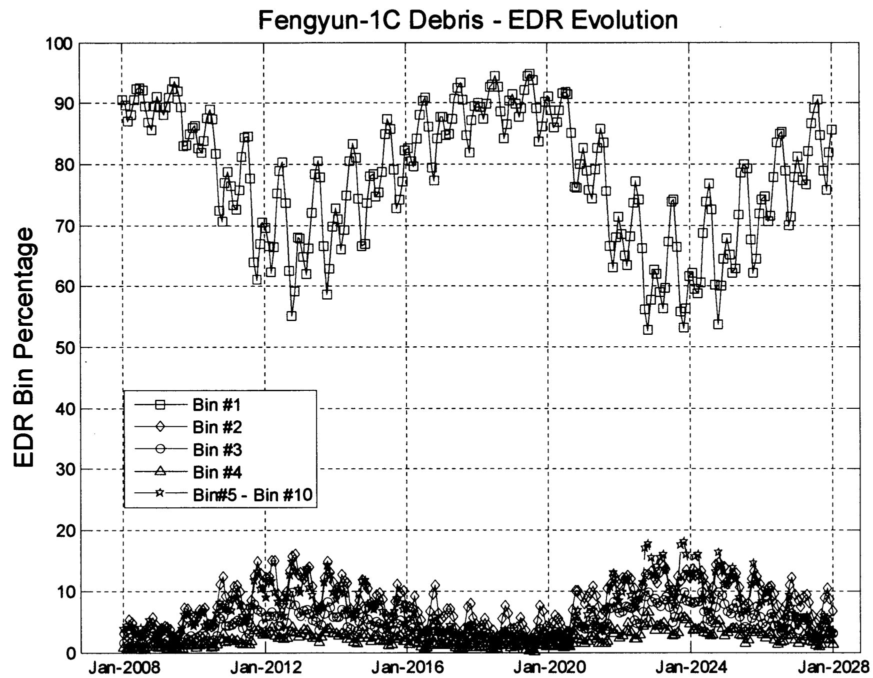

Figure 10: EDR Distribution Evolution

Changes in the EDR distribution will have effects on the close approach predictions. Objects that have higher EDR values will experience larger changes in the state solutions produced by the orbit estimation process. As the EDR bin distribution percentages change from lower EDR bins to higher EDR bins, variability in the CA event predictions are expected to occur. Operationally, this means that a CA event identified 7 days prior to the Time of Closest approach could experience significant changes as the event evolves. Therefore, the operational risk assessment process may require modification during periods of high solar activity.

VII. FUTURE ESC CLOSE APPROACH PREDICTIONS

To estimate the increase in collision risk to the Earth Science Constellation, close approach predictions between the ESC member missions and the propagated Fengyun-1C debris were made. To do this, the ephemeris data computed in the previous step were recorded at 30-day intervals. Those data were used to generate CA predictions by propagating each state 5 days into the future. All predicted CA events during that time having a miss distance of 50 km or less were recorded. A more simplistic force model was used for this propagation than for the 20-year propagation. No drag was modeled, and the step size was reduced. Although the precise prediction of a single CA event several years in the future is unrealistic, the total number of events is a statistical representation of the frequency of future events. The increase in the number of CA predictions is a measure of the change in debris flux for the ESC regime. Moreover, the 30 day sampling frequency is sufficient when coupled with the large miss distance since the Fengyun-1C debris decay rate is small. Thus short periodic changes aren't expected until significant changes in the debris altitude are realized.

Three ESC members, namely Aqua, Aura, and Terra, were used in prediction of CA events. Representative orbital ephemeris data were created without modeling drag effects, thereby maintaining a constant altitude. Moreover, periodic inclination maneuvers were modeled in order to maintain each mission's Mean Local Time requirements.

Two steps were required to generate the close approach predictions. The first step in performing the close approach predictions was again to create a cluster job template. This was done with another FreeFlyer® missionplan that read a list of all debris object identification numbers used in the previous ephemeris generation step. This missionplan took this list of debris objects and a list of the representative ESC assets and created a job template task entry by pairing up every asset and every debris object. Therefore the number of comparisons equals the number of asset spacecraft multiplied by the number of debris objects. The second step in performing the close approach predictions was to complete the actual numerical comparisons of the ephemeris data. This again is accomplished with a FreeFlyer® missionplan that read in the ephemeris file for each object named in the task entry of the job template. At each data interval, this missionplan propagates the state of each object for 5 days and calculates the time of closest approach as well as the miss distance and miss distance components expressed in the radial, in-track, cross-track reference frame.

Figure 11 shows the number of predicted 50 km close approach events starting in 2008 and ending in 2027. Based on the CA prediction scheme that was chosen – 5 day predictions made once a month, 23 CA events are predicted to occur in 2008; compared to 64 in 2027. Clearly the overall trend is that the collision risk will increase in future years as the debris continues to decay. Although there is little change to the altitude distribution of the debris and some of the objects do re-enter, there is still an increase in the number of CA events and thus a clear increase in the collision risk over the next 20 years.

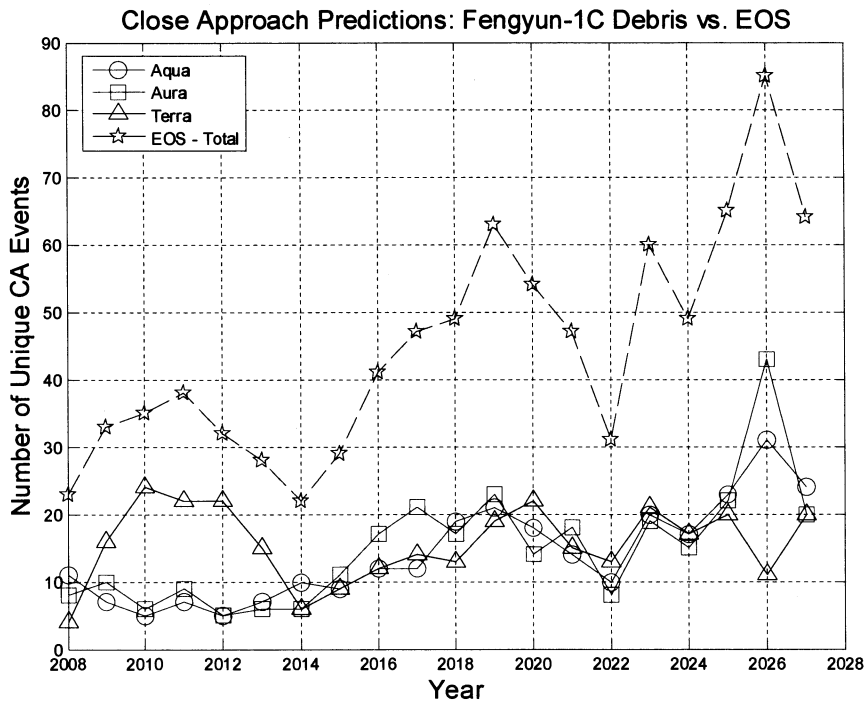

Figure 11: EOS CA Predictions

VIII. SUMMARY AND FUTURE WORK

The results of the Chinese ASAT test were to produce several thousand pieces of debris dispersed in low Earth orbit. Weeks after the event, Fengyun-1C debris pieces began entering the ESC constellation safety volume. Six months after the event, the Terra spacecraft was forced to perform an evasive delta-V maneuver to avoid a collision with a piece of debris.

Analysis of the 20-year propagation of the Fengyun-1C debris shows that the debris remains a threat to the ESC, since very little decay in the orbital altitude is observed. An estimate of the increased collision risk to the ESC was made by generating monthly close approach predictions, showing that the number of CA events will triple by the year 2027.

This type of analysis benefits significantly from a clustered high performance computing environment. Furthermore, the job scheduling and automation associated with the coupling of the Windows Compute Cluster Server 2003 and FreeFlyer proved invaluable.

Future work will include longer term predictions; estimating the lifetime of the entire Fengyun-1C debris population. The effects of atmospheric variations will also be examined.

REFERENCES

1. NASA Office of Safety and Mission Assurance, "NASA Procedural Requirements for Limiting Orbital Debris", NPD 8715.6, August 8, 2007.

2. Newman, L.K. and Duncan, M., "Establishment and Implementation of a Close Approach Evaluation and Avoidance Process for the Earth Observing Missions" AIAA-2006-6291.

3. NASA's Orbital Debris Quarterly, "Chinese Anti-Satellite Test Creates Most Severe Orbital Debris Cloud in History " Volume 11, Issue 2 April 2007.

4. Johnson, M., Stansbery, E., Liou, J., Horstman, M., Stokley, C., Whitlock, D., "The Characteristics and Consequences of the Break-Up of the Fengyun-1C Spacecraft" IAC-07-A6.3.01

5. Pardini, C., and Anselmo, L., "Evolution of the Debris Cloud Generated by the Fengyun-1C Fragmentation Event" NASA Space Flight Dynamics Symposium 2007