AAS 08-126

# INVESTIGATING ORBITAL DEBRIS EVENTS USING NUMERICAL METHODS WITH FULL FORCE MODEL ORBIT PROPAGATION

**Timothy Carrico[*], John Carrico[†], Lisa Policastri[‡], Mike Loucks[§]**

The authors present several techniques that can be employed to investigate and understand orbital debris events. These methods illustrate that high fidelity debris modeling can be rapidly performed by innovatively applying existing high precision astronautical tools. With this approach numerous variants for break-up models and forensic analysis can be performed and studied. The authors show techniques used to examine and reconstruct the Chinese Fengyun 1C ASAT debris event empirically based on TLE data. The paper gives a method to recreate the equivalent 3-dimensional ΔV vector distributions from statistics using geometric and fuzzy logic clustering techniques. The ΔV distributions are then used to create a representative particle debris cloud model which is propagated using a high precision orbit propagator including the affects of atmospheric drag. The resultant particle ephemerides are used to examine debris cloud evolution.

## INTRODUCTION

The work presented in this paper provides techniques to rapidly characterize future debris events to support risk analysis, close approach analysis, collision avoidance maneuvering, forensic analysis and other decision making. The model also supports propagation of other break-up models by using initial state vectors, statistical distribution and other area/mass distributions. The work is based on initial work intended to provide accurate large debris data sets for a new visualization technique to aid in understanding threats to other spacecraft in orbit[1]. That work led to further investigation into debris modeling and prediction.

The need for ephemerides data on all objects in the Earth's orbit is well understood by spacecraft operators. Of the almost 12,000 cataloged objects by the U.S. Space Surveillance Network, about 9000 are considered debris, or space junk with a size greater than 10 cm. These orbit tracks are used by many spacecraft operators to plan collision avoidance maneuvers. The amount of debris tracked is a small percentage of the total debris thought to be in orbit, with some estimates placing over 100,000 pieces of untracked debris sizes 1-10 cm, and tens of millions pieces of debris less than 1 cm[2].

While technological advances continue to improve the ability to detect and track objects in space, object size, limited tracking resources, and the magnitude of space debris will continue to require more

[*] Principal Software Engineer, Analytical Graphics, Inc., 220 Valley Creek Blvd., Exton, PA 19341, tcarrico@agi.com
[†] Senior Astrodynamics Specialist, Applied Defense Solutions, 8171 Maple Lawn Blvd, Suite 210, Fulton, MD 20759, JCarrico@AppliedDefense.com
[‡] Astrodynamics Engineer, Applied Defense Solutions, 8171 Maple Lawn Blvd, Suite 210, Fulton, MD 20759, LPolicastri@AppliedDefense.com
[§] Space Mission Engineer, Space Exploration Engineering, 687 Chinook Way, Friday Harbor, WA 98250, loucks@see.com

capable tools and new methods such that operators, decision makers and commanders will have actionable information on debris effects based on scientific methods for operations and policy.

## TECHNICAL APPROACH

Our approach to debris modeling is based on spacecraft maneuvering algorithms. In this method, we consider a piece of debris as part of the spacecraft until the epoch of the break-up event. Then, we consider the break-up force as an impulsive maneuver applied to the piece of debris at that moment, impart that force, and then propagate with a numerically integrated full force model. This enables us to modify ΔV (maneuver) forces, mass, area and other force models for propagation. The pieces of debris can be propagated in a user modifiable gravity model for a defined period of time or until the piece reenters the earth's atmosphere. The speed of computation provides for this process to be repeated, in a loop, resulting in generating tens of thousands of pieces in a relatively short period of time.

The software used was the trajectory design and maneuvering planning tool *Astrogator*, deployed in spacecraft operations and mission planning[3]. The tool is capable of modeling effects of forces on spacecraft in orbit and predicting their future ephemerides. The set of tools provides a rich set of features to model and target specific orbits. The authors used *Astrogator's* application program interface (API) to control the many debris generation runs made.

To model a single piece of debris, the authors modeled an orbiting satellite (parent) and then created another spacecraft (child) in the modeling environment. The child spacecraft is collocated with the parent spacecraft until the epoch of the debris event, at which time a ΔV is imparted on it and its ephemeris calculated. Specifically, a piece of debris is set up as a Mission Control Sequence (MCS) with three segments:

1. Follow – The piece of debris follows the original spacecraft until the epoch of the break-up
2. Explode – A maneuver segment affects an impulsive force upon the debris object
3. Propagate – Ephemeris data is generated for the piece of debris until one of two stopping conditions is met: duration or altitude

With the above process, each piece of debris can be individually modeled. A prototype application was built to automate the generation of debris pieces by automating the mission control sequence above. The application gave the ability to create debris pieces based on various break-up models. Each model had certain variables exposed as the research progressed to allow the analysts to control the break-up model. The following paragraphs describe the general approach for each model.

## BREAK-UP MODELS

Since each piece of debris is modeled independently, the debris physical characteristics (area/mass) and the ΔV values had to be provided to the model for each piece. The following methods for providing the break-up vectors were investigated.

*Initial state*: In the simplest method, initial state vectors were read in from an external break-up model and the simulation propagated the pieces. These initial state vectors where provided in the form of a comma separated text file. This method was implemented to support an external break-up model that had been created but lacked an ability to accurately propagate and visualize the debris field. This method proved useful in understanding the evolution of break-up models.

*Prototype collision modeling*: This was a simplified collision algorithm only used to prove the viability of implementing break-up models in the simulation environment. This method used first principle physics related to a collision such as the angle of the collision and the coefficient of restitution. This approach was examined briefly with dramatic visualizations, but used only as a technology demonstration that a more accurate model could employ. This work began before the *Fengyun 1C* (*FY-1C*) event, and was later tabled in favor of the empirical model based on actual observations described below. The approach demonstrated the utility of using any break-up model as a proof of concept and allowed other parts of the system to be developed.

*Empirical model based on the statistical distribution of ΔV*: This model generates debris pieces using Gaussian distributions based on observations (Figure 1). This method provides the ability of the user to enter means and sigma for the angle of distribution of ΔV and magnitude. The ability to set the distribution values for debris, from an original orbiting body provided a flexible means to model large quantities of debris in a very controlled manner. The elevation and azimuth (in the local horizontal frame of the original spacecraft) as well as the magnitude was calculated randomly for each piece of debris to fall within the user defined distribution with the mean, sigma and number of pieces adjustable.

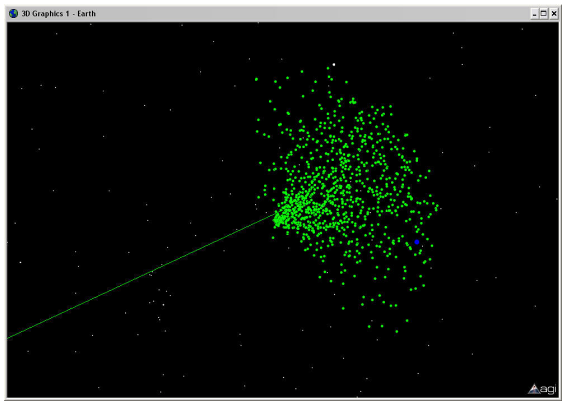

**Figure 1 Debris Model ΔV Gaussian Distribution**

## AREA AND MASS

The above break-up models describe how the ΔV can be calculated to model various debris events. The area and mass of each piece was also controllable by means of normal or uniform random distribution functions. For each piece of debris, a random mass was generated that would be less than the mass of the original satellite. A random density of material was generated between lead and steel (1 to 7850 kg/m$^3$). Given the mass and density, the radius of the equivalent sphere was calculated, and that radius used to calculate the cross sectional area (as a circle) used for atmospheric drag modeling. This value for area, along with the mass and ΔV provide the parameters required to model a single debris piece. There was no attempt to conserve mass at this point in the algorithms. The intent was not to model a realistic debris cloud itself, but rather to show possible and likely resultant orbits that could affect other spacecraft. Future work in this area will include modeling the correlation between mass and ΔV from hypersonic break-up models.

## ORBITAL PROPAGATION

Once the values for ΔV, mass, and area were calculated and the impulsive force applied, the simulation numerically propagated the pieces until the desired duration was met, or until the piece reentered Earth's atmosphere, whichever came first. A piece was considered to reenter when the altitude reached 120 km, at which time the propagation for that piece was terminated. The force models are adjustable, and the following setting provided a good trade-off between computational burden and suitable fidelity to understand the debris evolution:

- JGM2 gravity model, degree and order two
- Jacchia-Roberts atmospheric drag
- Spherical solar radiation pressure
- Sun and Moon 3$^{rd}$ body gravity perturbations

## PROTOTYPE COLLISION MODEL RUNS

The first model run involved two notional satellites (Table 1) that collide. For this model, a single orbit was created, and a second one calculated utilizing the maneuver tool's targeting algorithms which adjusted the Keplerian elements until a close approach was achieved. The epoch of the close approach was then calculated and used for the time of the collision.

**Table 1 Keplerian Elements for Notional Collision Model**

| | **Satellite 1** | **Satellite 2** |
|---|---|---|
| Semi-major Axis | 6678 km | 9255.6230 km |
| Eccentricity | 0 | 0.2788 |
| Inclination | 45 deg | 122.2538 deg |
| Right Ascn of Ascending Node | 0 deg | 113.0334 deg |
| Argument of Periapsis | 0 deg | 55.0889 deg |
| True Anomaly | 0 deg | 281.6972 deg |

With these data, the epoch of the scenario is set and the model then generates 1,000 pieces of debris. The distribution of $\Delta V$ was set to a mean of 0 degrees azimuth, 0 degrees elevation with standard deviation of 30 degrees. The image sequence in Figure 2 below illustrates the debris evolution of 1,000 pieces over a 24 hour period.

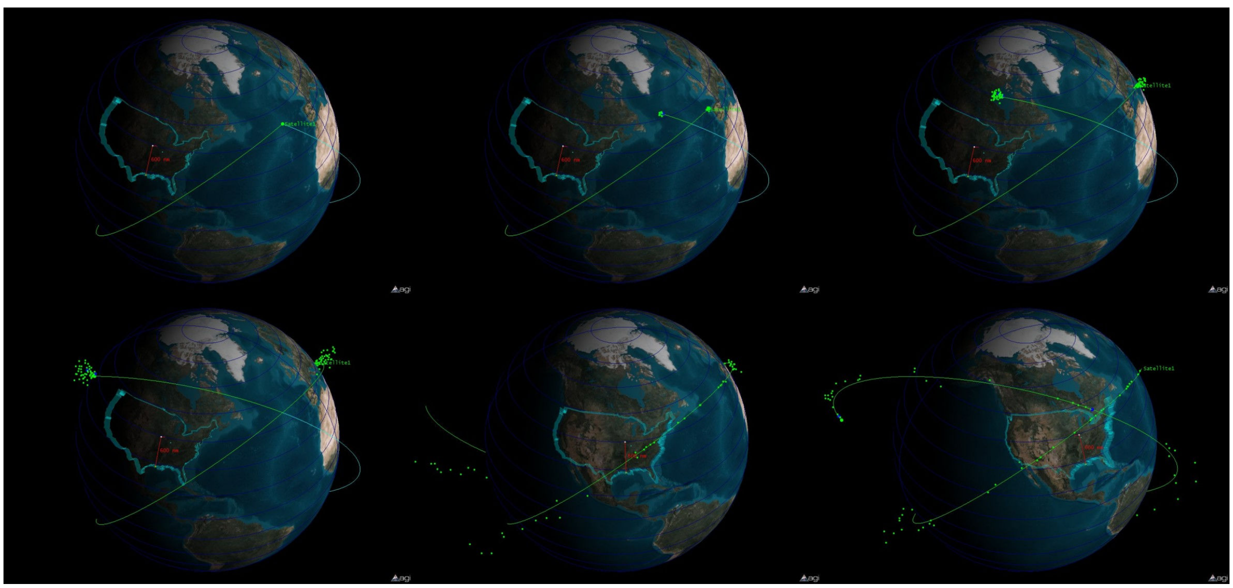

**Figure 2 Debris Evolution From Collision Over 24 Hour Period**

In the model output, the atmospheric reentry modeling is evident as the model stops propagation of the ephemerides at 120 km. These pieces can be seen "sticking" to that 120 km altitude over the globe as in Figure 3. Various runs were made varying the incident angle of the collision orbital ellipses resulting in a variety of collision geometries that increase or decrease the amount of debris that shortly enter the Earth's atmosphere.

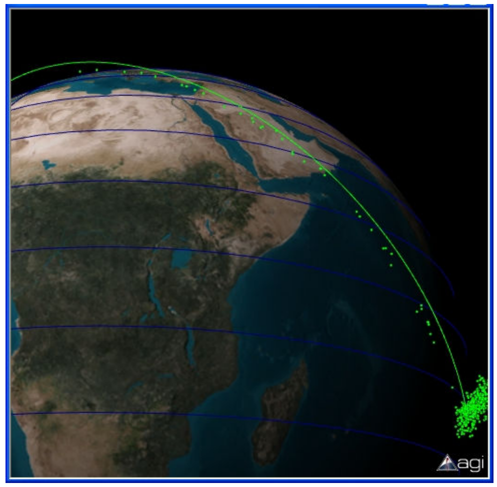

**Figure 3 Modeling Debris Reentry**

Several other on-orbit break-ups and collisions were modeled with the largest run of 100,000 pieces of debris. Further work on this debris modeling was halted with the *FY-1C* event.

**CHINESE ANTI-SATELLITE INTERCEPT OF FENYGUN 1C**

The previous work focused on purely generating debris from orbit break-ups. On 11 Jan 2007, The People's Republic of China launched a ground based missile in an Anti-Satellite (ASAT) test, targeting a Chinese weather satellite *Fengyun 1C* (*FY-1C*). Prior to the destruction, the *FY-1C* was in a 98.6 degree inclination (polar) circular orbit with a mean altitude of about 865 km. The ASAT caused an instantaneous break-up of the missile and *FY-1C*. Tracking efforts by the United States Space Command currently report 2,317 pieces were added to the catalog of space objects, making it the largest debris event recorded. The resultant debris field was theorized to be well beyond this size with some estimates in the 35,000[4], 150,000[5] and 300,000[6] piece range.

This incident provided an opportunity to run the break-up modeling and prediction tool to perform forensic analysis of the event and generate the non-tracked pieces from the empirical data. To obtain the distributions of $\Delta V$, we calculated the statistics of the $\Delta V$ observed from analysis of the debris ephemerides using the Two-Line Elements (TLE) readily available from open sources[7]. The following section details the analytical work performed to arrive at suitable distribution information to run the statistical generation of debris in the model. Statistical characterization of debris is useful for analysis in the absence of full data sets for debris.[8]

To assess how well a $\Delta V$ vector could be calculated from TLE data, a "truth" test was run. A spacecraft in an orbit similar to the *FY-1C* was propagated using a high-fidelity force model (including a 21x21 gravity model), and at a specified epoch, a known impulsive $\Delta V$ was applied. Then a TLE was fit to the ephemeris arc before the maneuver, followed by another after the maneuver. These TLEs were then propagated using the SGP4 propagator to a point where they overlapped at the time of the maneuver, and the radial rate, in-track rate, and cross-track rate were calculated. These three components should be the same as the truth model applied. The truth reconstructed $\Delta V$ compared well to the truth, as shown in Table 2.

The calculation of the reconstructed $\Delta V$ was sensitive to the time of the maneuver. If the $\Delta V$ reconstruction calculation was performed even a few minutes before, or after the time of the maneuver, the components and therefore the direction changed considerably, as shown in Figure 4 and Figure 5.

**Table 2 TLE ΔV Reconstruction Analysis**

| Maneuver Component | Truth | Reconstructed |
|---|---|---|
| Relative In-track Velocity (km/sec) | 0.0149 | 0.01556 |
| Relative Cross-track Velocity (km/sec) | 0.0086 | 0.00850 |
| Relative Radial Velocity (km/sec) | 0.0246 | 0.02485 |
| Magnitude (km/sec) | 0.030 | 0.0305 |
| Azimuth (deg) | 30.0 | 28.63 |
| Elevation (deg) | 55.0 | 54.49 |

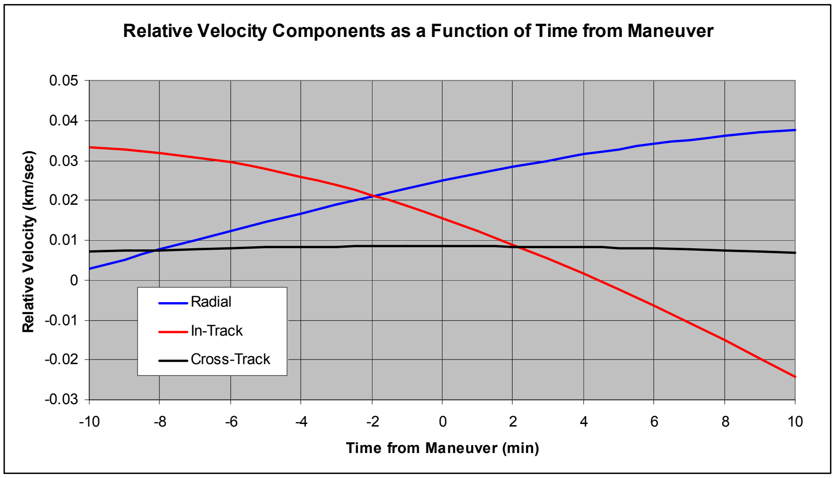


**Figure 4 Relative Velocity Analysis ICR**

This is also seen when displaying the relative velocity in terms of azimuth and elevation angles (in the local system):

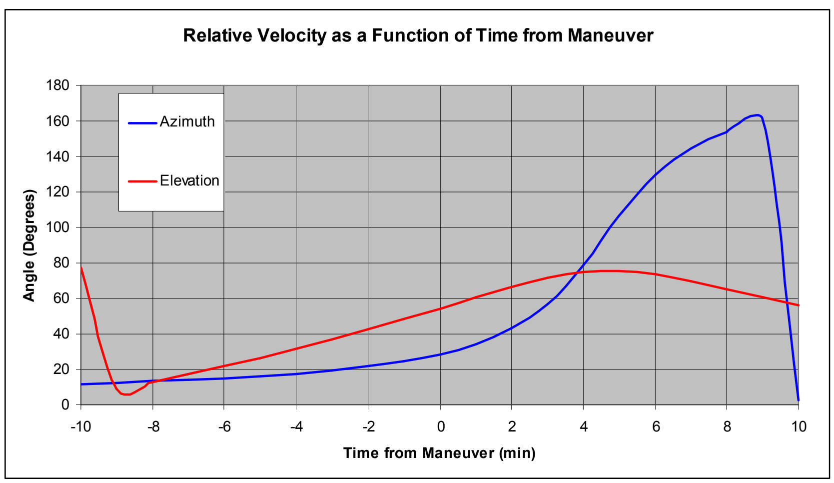


**Figure 5 Relative Velocity Analysis AzEl**

**FY-1C Debris Orbital Data Availability**

To supply the required variables to our debris modeling and predicting methodology, analysis of the *FY-1C* debris event was required. Primarily we required knowledge of the debris event break-up (ΔVs, area and mass) relative to the original *FY-1C* orbit in order to calculate statistical data required in model propagation. The only open source data on the break-up were the publicly available TLEs. Although the algorithms presented here would work using high-precision special perturbations vectors with full numerical integration, the TLEs were available and demonstrate the process sufficiently.

### TLE Data

The progression of publicly available track data from *CELESTRAK* is shown in Table 3 below:

**Table 3 TLE Data Availability**

| Date 2007 | Number of Pieces |
|---|---|
| 18 Jan (am) | 32 |
| 26 Jan (pm) | 141 |
| 27 Jan (am) | 216 |
| 27 Jan (pm) | 426 |
| 28 Jan (am) | 516 |
| 28 Jan (pm) | 517 |
| 31 Jan (pm) | 525 |
| 1 Feb (am) | 552 |
| 2 Feb (pm) | 606 |
| 3 Feb (pm) | 646 |
| 8 Feb | 706 |

TLE data is updated frequently to reflect the best estimate on the position of the object in predicting its ***future*** ephemeris. It is not normally intended for back-propagation in forensic analysis methods and quickly becomes of little utility in such applications as it is updated. To illustrate the degradation in utility of such data for forensic analysis, Figure 6 quantifies some of the difference in the calculation of $\Delta V$ (ICR, AzEl) from of a piece of debris back-propagated to the original *FY-1C* orbit at time of break-up. The graphs show the utility of these updated TLE data sets departing at about the $20^{th}$ update, which is mid/late April 2007, or three months after the *FY-1C* break-up. These data supports a more mathematical determination of this point by examining numerous pieces over time.

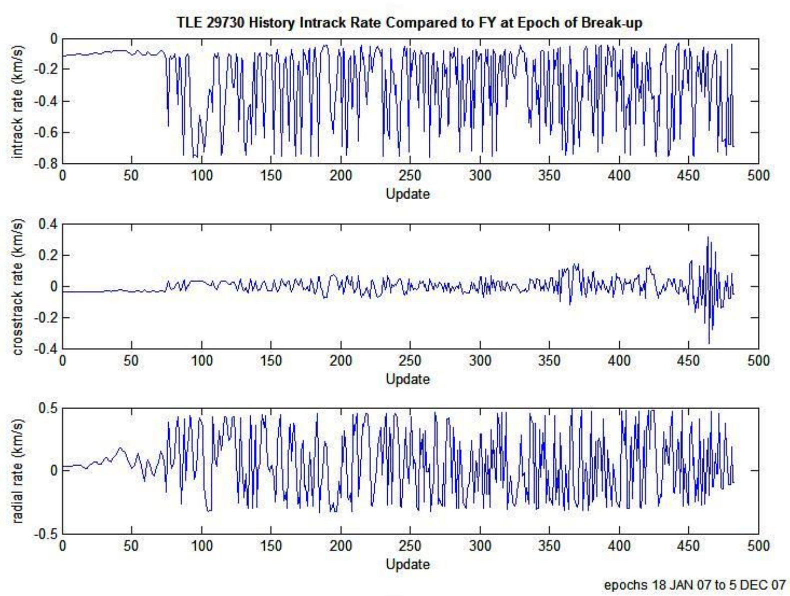


**Figure 6 TLE Forensic Use Degradation as TLE is Updated**

To support our methods, orbital data closest to the time of the event was required. The authors obtained TLE data sets that contained all of the first observations of each piece of debris[9]. Also, since all debris analysis is done relative to the original *FY-1C* orbit, careful selection of the *FY-1C* ephemeris is required. The authors noted that small changes in this epoch greatly influence analysis. Ascertaining the accurate position of the *FY-1C* at the time of the break-up is fundamental to performing statistical analysis on the ΔV distributions. The closest epoch for the *FY-1C* TLE data was found to be 11 Jan 2007 21:44:54:98 UTCG, which is about 45 minutes prior to the break-up event, providing suitable data for our work. For an operational implementation of these methods, it would be beneficial for TLEs or other ephemeris data to be calculated nearest the estimated time of the event. The closer to the epoch of the event will provide more precision in the forensic analysis.

The TLE data was imported into the *Satellite Tool Kit* along with the original *FY-1C* orbit in order to calculate values relative to the *FY-1C* orbit. The initial analysis examined the semi-major axis data from the TLEs as compared to the *FY-1C* orbit. Next, the pieces were backward propagated to the epoch of the break-up. At this epoch, the relative velocity (which is the ΔV from each piece of debris from the original *FY-1C* orbit) was calculated using *Astrogator*. After the ΔV values were calculated, the first set of data (18 Jan 2007, 32 pieces of debris) were plotted in a histogram. The scarcity of data with 32 pieces of debris provided little information of value to run the statistical model as shown in Figure 7.

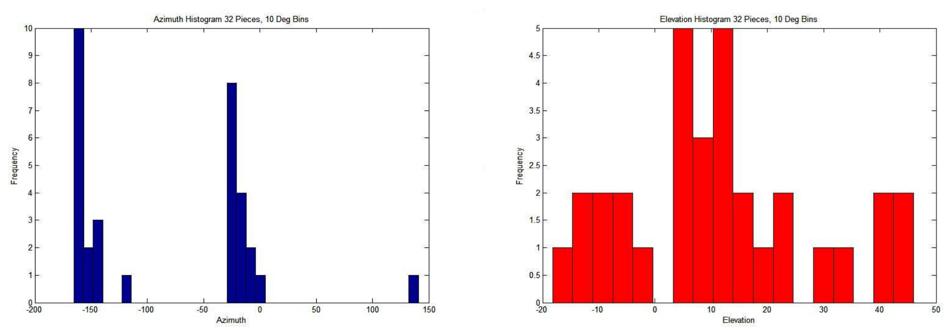


**Figure 7 ΔV Analysis of Initial FY-1C Data, 32 Pieces**

As more data became available, a greater understanding of the event began to emerge to support statistical analysis. Plotting the 706 pieces of debris made available on 8 Feb 2007 provided the following data in azimuth and elevation ΔV distributions. In Figure 8 we begin to see the emergence of Gaussian distribution curves.

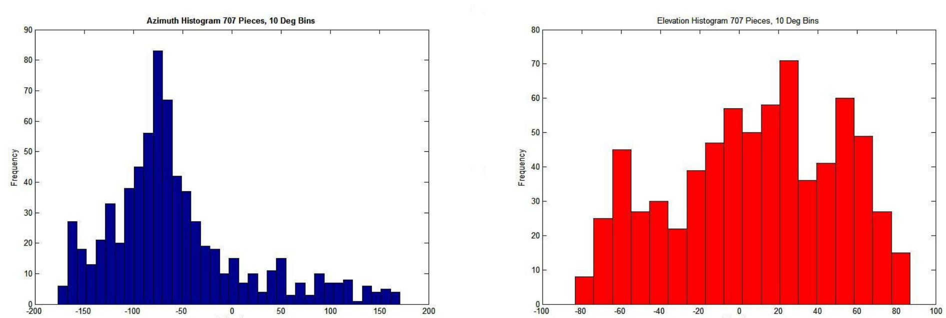


**Figure 8 ΔV Analysis for 707 Pieces of FY-1C Debris**

These data were then brought into MATLAB to obtain the following vector plots where ΔV values are plotted at the epoch of break-up, and the ΔV magnitudes scaled. In-track rate, cross-track rate and radial rate views of the vectors were plotted relative to the *FY-1C* and are provided in Figure 9 and Figure 10.

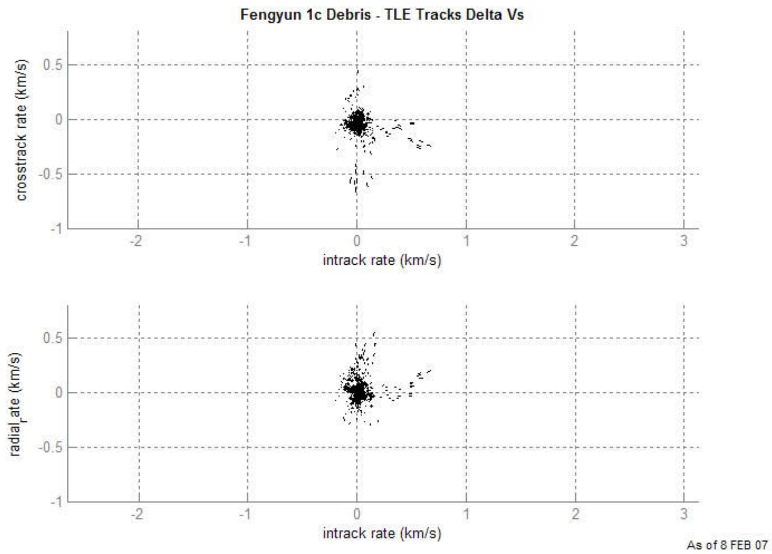


**Figure 9 Analysis of ICR ΔV FY-1C Debris**

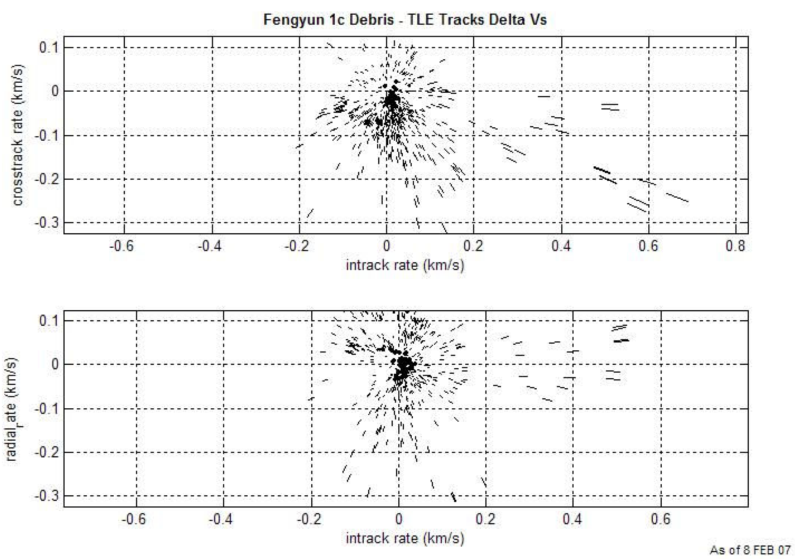


**Figure 10 Analysis of ICR ΔV FY-1C Debris Detail**

These images show some of the physical topography of the break-up event. A 3-D quiver plot (Figure 11, Figure 12) of the ICR was then generated to more closely examine the event.

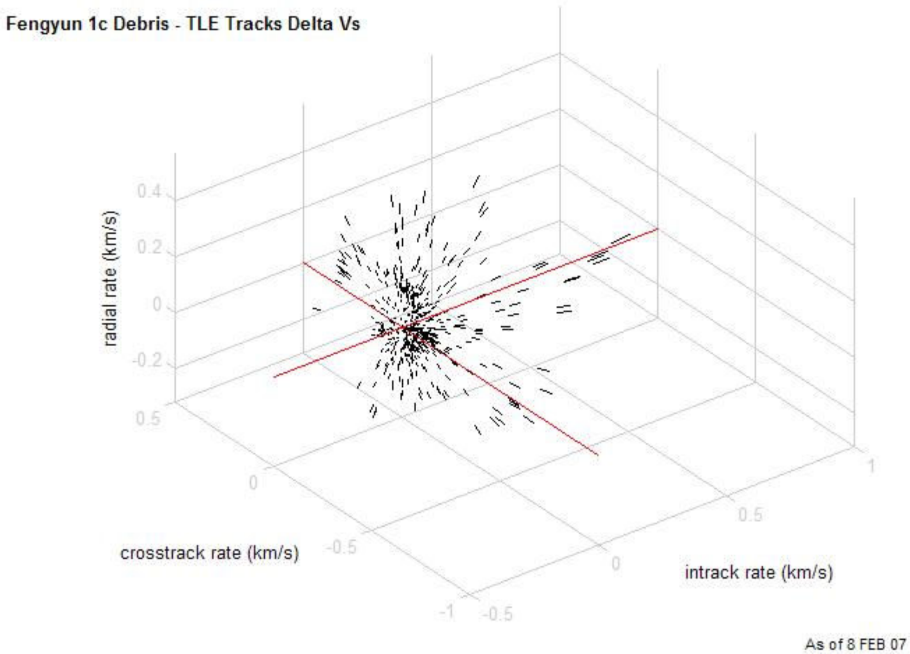


**Figure 11 3-D Analysis of ICR ΔV FY-1C Debris**

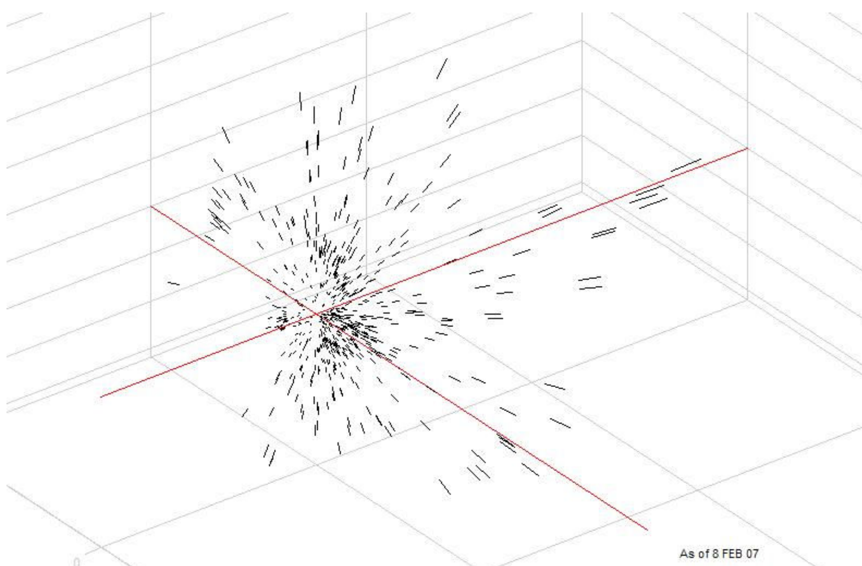


**Figure 12 3-D ICR ΔV FY-1C Debris Detail**

The following figures are 2-D ICR ΔV plots with the addition of magnitude. Figure 13 shows in-track rate to cross-track rate with contour lines indicating magnitude and Figure 14 shows radial-rate to in-track rate with the various magnitudes as smooth contours. The magnitude was found to exhibit a positively skewed distribution (Figure 15).

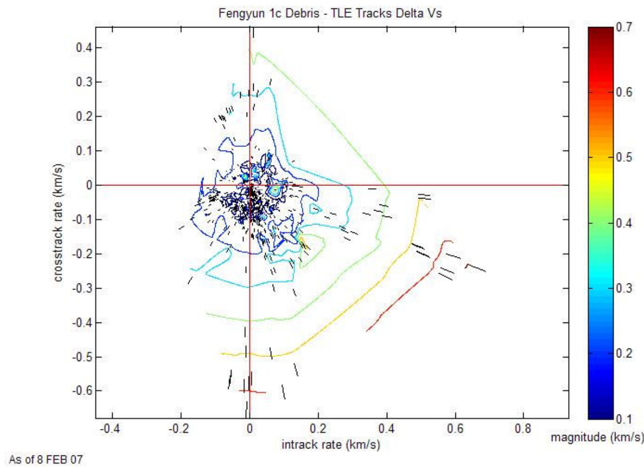


**Figure 13 FY-1C In-track to Cross-track with Magnitude Contours**

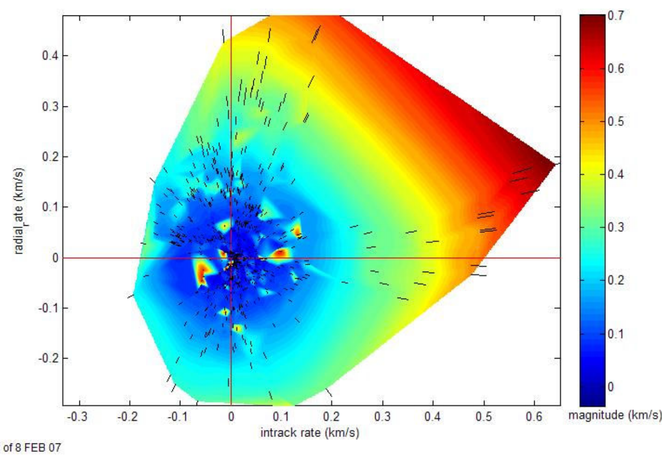


**Figure 14 FY-1C In-track to Radial with Magnitude Contours**

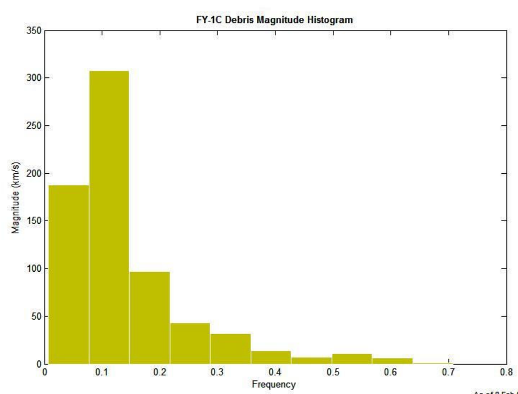


**Figure 15 FY-1C ΔV Magnitude**

## CLUSTER ANALYSIS

Next we plotted the ΔV along azimuth and elevation (Figure 16) and sought to identify natural groupings of data representing unique Gaussian nodes. A data clustering technique known as Fuzzy C-Means (FCM) clustering was employed to partition the data into common ΔV subsets such that discrete statistical analysis on each node could be performed. Clustering analysis works by separating data points into homogeneous classes that have a common characteristic, in this case a common azimuth and elevation vector.

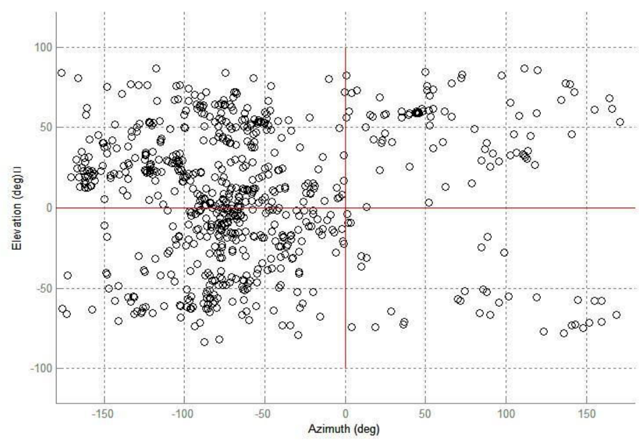


**Figure 16 FY-1C ΔV Azimuth and Elevation**

FCM is a type of cluster analysis employed in pattern recognition[10] that computes the centers of data clusters and the degree to which other data belongs to that cluster by iterating arithmetic means of cluster centers. FCM employs Fuzzy Logic to determine the degree to which (membership function) each datum belongs to that group. The process moves the centers of the clusters, calculates membership of other data to that group and iterates until the algorithm has converged on a sensitivity threshold which represents a minimal change in the cluster center's position. FCM is an advantageous approach for large data sets given its speed of computation; a useful characteristic for this work.

Another investigated approach was a geometric method whereby centers in the AzEl vector plot were selected and debris ΔV vectors were grouped by the closeness of their angle to the mean of the cluster centers. This provided similar results as the FCM technique. Other techniques may be considered including methods to determine the number of cluster centers. However, it is important to remember that only *partial* data is analyzed in order to generate additional data when selecting methods. There are pieces of debris not yet tracked, too small to be tracked, or that have already entered the Earth's atmosphere. The identification of multimodal Gaussian distributions in the TLE data from the *FY-1C* provided the basis for additional piece generation and the goal was to find the mean and standard deviation for each mode for that debris generation. The results of the cluster analysis are shown in Figure 17, and grouped the ΔV vectors into three clusters.

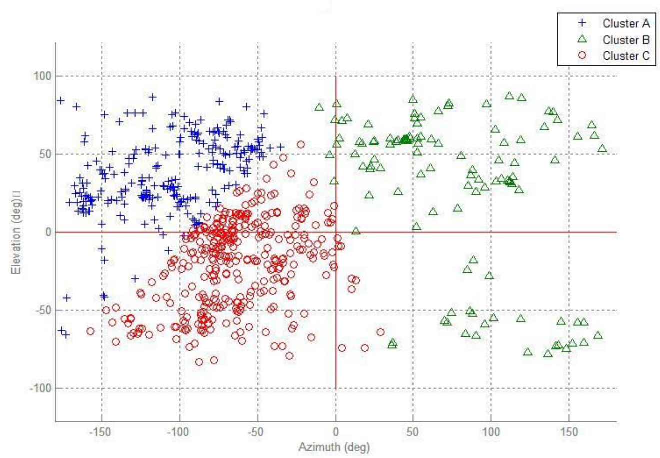


**Figure 17 Fuzzy Logic Cluster Analysis of FY-1C Azimuth and Elevation ΔV**

Each cluster center provided the mean for its distribution and the data were analyzed for mean and standard deviation. These data are shown in Table 4.

**Table 4 Statistical Analysis of FY-1C Azimuth Elevation Clusters**

| Cluster | Mean AZ (deg) | Standard Deviation | Mean El (deg) | Standard Deviation | Mean Magnitude (km/s) | Standard Deviation |
|---|---|---|---|---|---|---|
| A | -106.6 | 35.89 | 36.92 | 24.52 | 0.136652 | 0.084401 |
| B | 76.03 | 47.35 | 27.82 | 50.71 | 0.174549 | 0.095757 |
| C | -63.34 | 32.25 | -20.45 | 27.88 | 0.130565 | 0.130077 |

Each of these clusters was then set up and run in the model generating 1,000 pieces for each cluster with the same statistical distribution as seen in the observed data. The pieces were propagated for 24 hours. Propagation took approximately seven minutes per cluster using the numerically integrated full force model with the 2 x 2 gravity model described above. The three clusters can be seen in Figure 18, the image sequence showing 3,000 pieces generated statistically around the empirical *FY-1C* TLE data. The three colors represent the clusters found in the Fuzzy Logic cluster analysis.

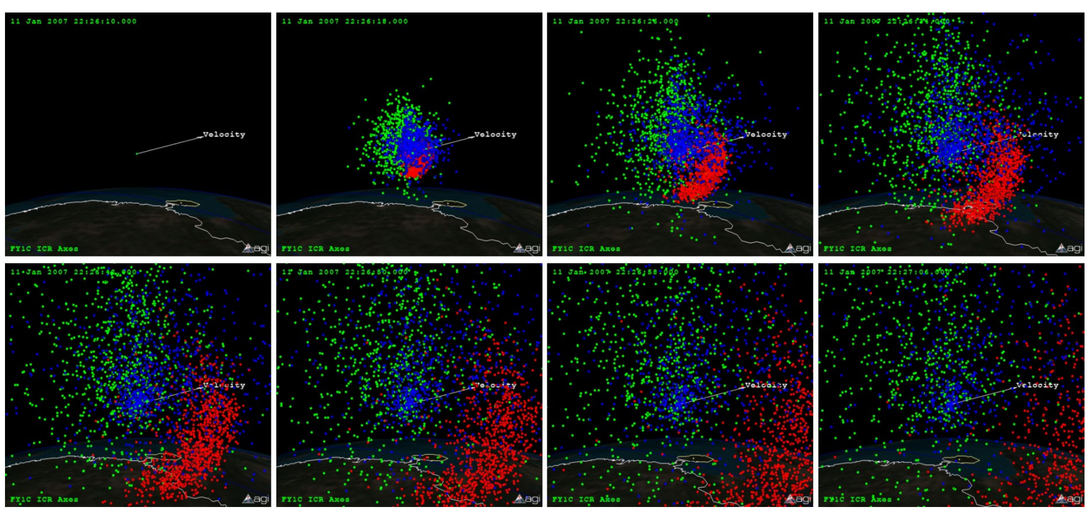

**Figure 18 Propagation of FY-1C ΔV Clusters Derived from Statistical Analysis of Observed Data**

The model provided insight into the debris pinch point, the orbital mechanical phenomena where the debris pieces pass through a narrow choke point and are consequently of greater threat of collision to other spacecraft, as shown in Figure 19.

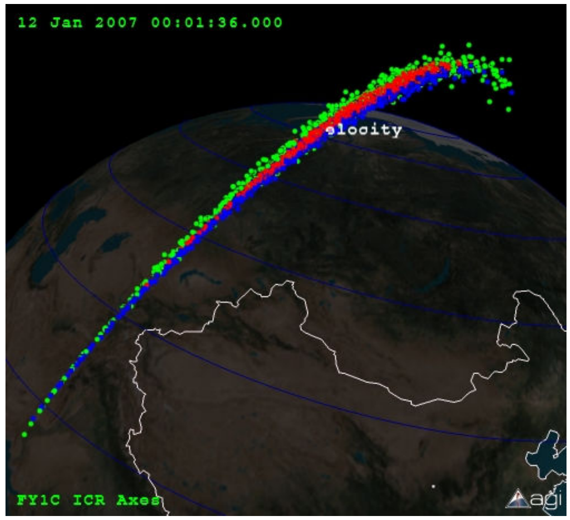


**Figure 19 FY-1C Modeled Debris Approaching Pinch Point**

**Debris Reentry**

The propagation of the 3,000 pieces over a 24 hour period was also used to calculate the percentage of pieces that reentered the earth's atmosphere. This is shown in Figure 20.

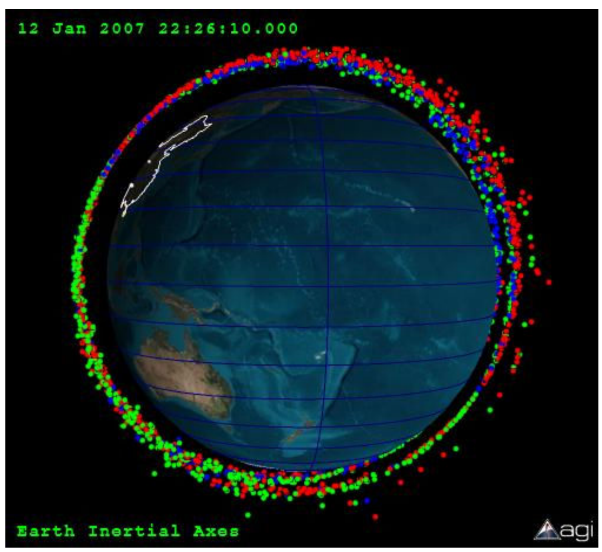


**Figure 20 24 Hour Propagation of 3,000 Pieces of FY-1C Modeled Debris**

Table 5 provides reentry data for each cluster of 1,000 pieces over a 24 hour period and runs of 1,000 pieces over a one-week period.

**Table 5 Reentry Data for FY-1C Modeled Debris**

| **1000 pieces propagated 24 hours** | | |
|---|---|---|
| Cluster | Reentered | Pct |
| A | 10 | 1.0 % |
| B | 17 | 1.7 % |
| C | 2 | 0.2 % |
| **1000 pieces propagated one week** | | |
| Cluster | Reentered | Pct |
| A | 9 | .9 % |
| B | 22 | 2.2 |
| C | 5 | .5 |

**In-Track, Cross-Track and Radial Cluster Analysis**

Additional cluster analysis was performed using the same 707 pieces in the 3-dimensional ICR space. Results of this analysis are shown in Figure 21.

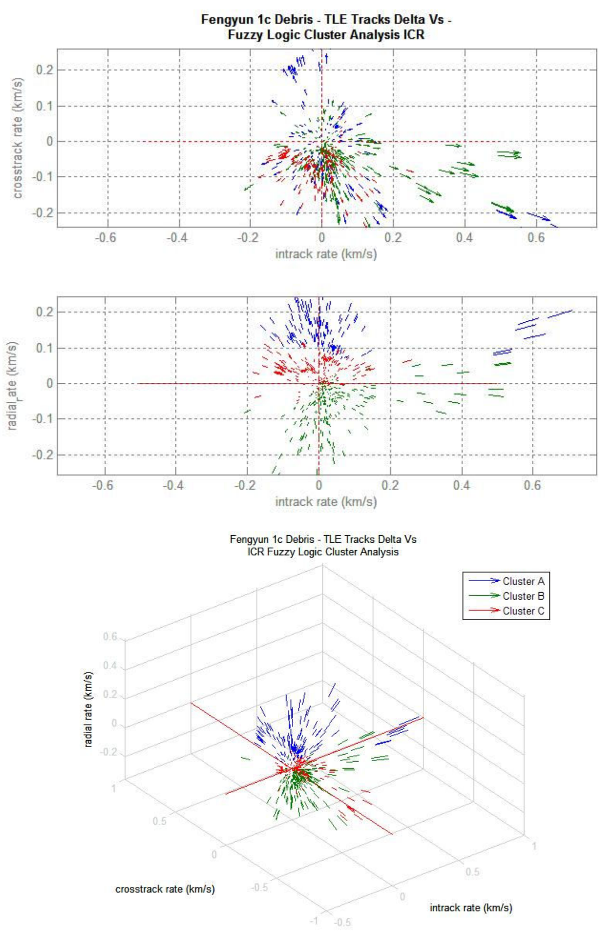


**Figure 21 Fuzzy Logic Cluster of In-Track, Cross-Track, and Radial Rates for FY-1C ΔV**

The choice of three clusters was based on simply looking at the graphs. Formal methods, such as Fuzzy Subtractive Clustering (FSC) [11] along with engineering studies of hypersonic collisions studies may lead to a different choice of the number of clusters, and other iterative techniques could be used to determine the best fit for the number of clusters.

## Gabbard Diagrams

These data were also used to construct Gabbard diagrams illustrating the generated debris' apogee and perigee over orbital period, as shown in Figure 22.

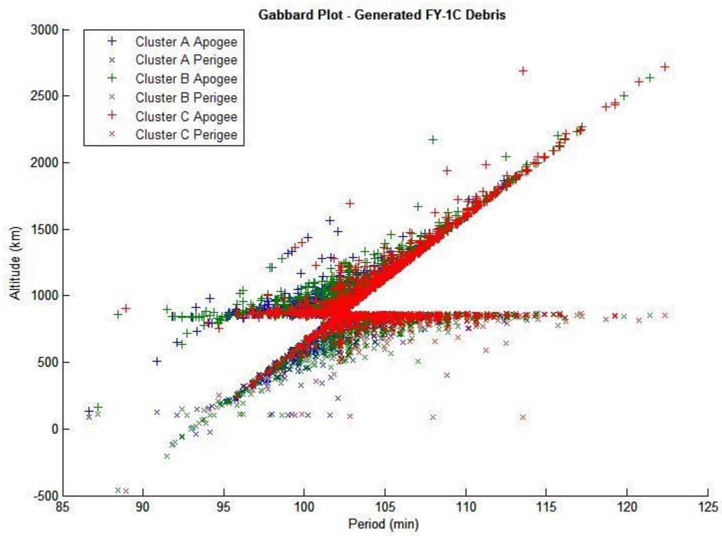


**Figure 22 Generated Debris Apogee and Perigee Over Orbital Period**

## OTHER DEBRIS EVENTS

On 19 February 2006, a *Breeze-M* rocket body was observed to have exploded over Western Australia. Figure 23[12] shows the relationship of the *Breeze-M* debris event to the *FY-1C* debris field. The time of explosion appears to have occurred approximately 37 minutes after the *Breeze-M* passed through the *FY-1C* debris ring.

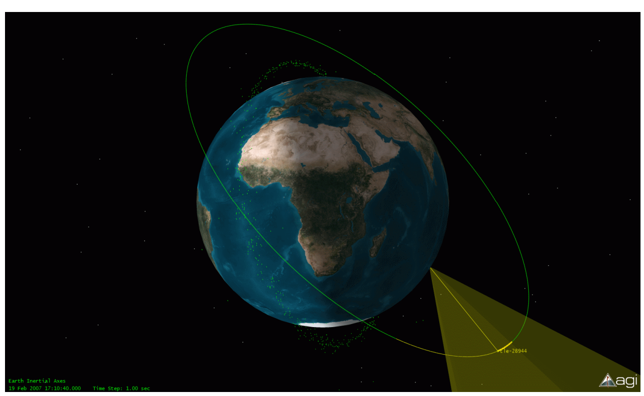

**Figure 23 Breeze-M Rocket Body Debris Observation**

The authors looked at this debris event to examine the physical possibility of a piece of debris from the *FY-1C* causing the *Breeze-M* break-up. The first analysis looked at the possibility of an in-plane impact that could have led to the break-up 37 minutes later. To perform this analysis, *Astrogator* was set up to target a sample piece using a shooting method with singular value decomposition. This shooting method varied the area-to-mass ratio and three components ΔV of a notional piece of debris from the *FY-1C* break-up event until a solution converged on a close approach with the *Breeze-M*. The result was that a small maneuver of less than 0.004 km/sec applied at the time of the *FY-1C* event combined with an area to mass ratio of 0.026 $m^2$/gm results in a collision with the *Breeze-M* as the *Breeze-M* crossed the orbit plane of the sample piece. The epoch was 37 minutes before the observed time of the *Breeze-M* explosion. Note that the physical possibilities of such a piece causing an explosion, and the delay in the explosion after the impact are not the scope of the current work. However, the use of the algorithm to investigate the possibility is demonstrated.

After the initial debris piece was found to intersect with the *Breeze-M* at 19 Feb 2007 16:33:47, equivalent to 37 minutes prior to the *Breeze-M* event time, additional trajectories were run to investigate if there are cases that will intersect closer to the event time.

Using the same *Astrogator* target sequence to vary three ΔV components to achieve a close approach with the *Breeze-M*, a third constraint was added which was the desired time of collision. This was run several times, each incremented a minute closer to the *Breeze-M* explosion. A summary of the target sequence for each case is noted below in Table 6.

**Table 6 Summary of Astrogator Targeting for FY-1C to Breeze-M**

| Time from Breeze Plane Crossing | Debris Name | ImpulsiveMnvr. Cartsian.X (km/sec) | ImpulsiveMnvr. Cartsian.Y (km/sec) | ImpulsiveMnvr. Cartsian.Z (km/sec) | Area-to-Mass Ratio ($m^2$/gm) |
|---|---|---|---|---|---|
| + 1 sec | Piece_p1 | 0.0038417 | -0.0877028 | 0.0081332 | 0.026203 |
| + 2 sec | Piece_p2 | 0.0024640 | -0.1758030 | 0.0154454 | 0.026049 |
| + 3 sec | Piece_p3 | -0.0004878 | -0.2645940 | 0.0161722 | 0.025829 |
| + 4 sec | Piece_p4 | -0.0053294 | -0.3543800 | 0.0166759 | 0.025054 |
| + 5 sec | Piece_p5 | -0.0133950 | -0.4453410 | 0.0168812 | 0.022753 |
| + 6 sec | Piece_p6 | -0.0308340 | -0.5370080 | 0.0273773 | 0.014185 |

The ΔV grew steadily as expected in the cross-track direction. It became very difficult to find solutions after about six minutes from the original plane crossing intersection. We believe that this is due to the fact that the altitude of the *Breeze-M* at about seven minutes after the plane crossing started to become higher than an atmospheric drag-affected orbit. We ran a case of a dense (steel) ball, with no ΔV applied, to see what the least atmospheric decay would be from a piece.

A target sequence was set up for modeling a steel ball with a radius of 1 mm, and an area-to-mass ratio of 0.0955 $m^2$/kg, modeled without any maneuvers, and propagated to 19 Feb 2007 17:10:40 UTCG, the time of the *Breeze-M* event. The semi-major axis, eccentricity, and altitude of the steel ball at the initial time (the *FY-1C* Break-Up) and the final time (*Breeze-M* event) are reported in Table 7.

**Table 7 Steel Ball Debris Propagation FY-1C to Breeze-M**

| | **Semi-Major Axis (km)** | **Eccentricity** | **Altitude (km)** |
|---|---|---|---|
| Time at FY Break-Up | 7230.41 | 0.000516 | 864.127 |
| Time of Breeze-M Event | 7226.95 | 0.003558 | 882.406 |

The decay in the semi-major axis is as expected, however the altitude is somewhat counter intuitive. The two events occurred over different latitudes, and therefore even though the orbit was lowered by atmospheric drag, the altitude at one spot can still be higher than at another.

The altitude of the *Breeze-M* satellite model was plotted in Figure 24. This plot includes altitudes before, during, and after the event. Note that the final steel ball altitude of 882 km falls between 16:41 and

16:42 on the *Breeze-M* altitude plot. After that point in time, the *Breeze-M* is higher in altitude than the decayed steel ball.

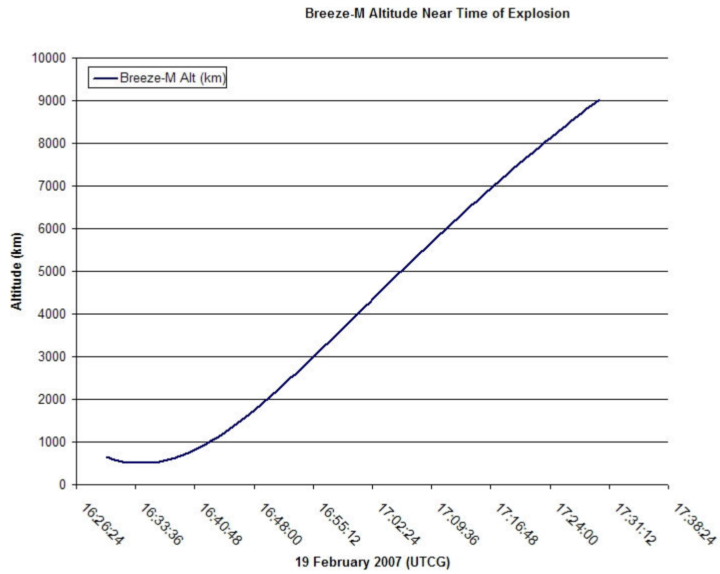


**Figure 24 Breeze-M Altitude Near Epoch of FY-1C Break-up**

It is important to note that these results do not provide any probabilities of collision, only possibility within physics. These techniques provide data that can help others calculate probability, refute, or dismiss any debris consequent event based on real numbers. Such physics-based analysis provides valuable insight and welcome relief from much of the subjectivity visualization techniques alone can offer.

## MODELING ENVIRONMENT OBSERVATIONS

Computational time has been an issue cited as a limitation of similar methods for debris generation. However, the authors found that modest commercial processors provided good results in the generation of large data sets. Table 8 shows data from various debris models[**].

**Table 8 Computational Time for Debris Generation**

| Pieces | Propagation | Computation |
|---|---|---|
| 1000 | 1 day | 7 mins |
| 1000 | 7 days | 22 mins |
| 10000 | 7 days | 210 mins |

The debris modeling capability developed employing the maneuver tool *Astrogator* provided very good results in a highly configurable and controllable accurate physical environment. Models could be adjusted quickly, with discrete understanding of the break-up event forces, areas, and masses. Propagation of large volumes of data were quickly achieved using modest equipment in non-parallel configurations. The authors are confident that much greater speed could easily be achieved with more powerful processors and simple parallel processing techniques since each piece of debris is individually propagated. The ability to generate a statistically significant amount of debris in less than one hour, in an environment where other satellites can be modeled and close approach analysis performed, has significant implications in the operational space community for debris event prediction, damage control and forensic analysis.

[**] Dell Precision PWS490, Intel Xeon CPU, 2.66GHz, 2.00 GB RAM

## CONCLUSIONS

The authors found that the use of the high precision astronautical tool (*Astrogator*) used in a numerically integrated full-force modeling environment provided utility in understanding debris events including analysis of atmospheric reentry. The unique opportunity of examining the evolution of an actual break-up event (*FY-1C*) and responding as data became available, led to the observations of emerging statistically significant information. The refinement of the analysis, in real-time, led to some insight into data sets most useful for forensics analysis – newer is not better for this work. Additional data (meta-data) on ephemeris data and more modern data access technologies (e.g., web services) that allow analysts to construct custom historical data sets would benefit this work going forward. To better support early debris characterization in the future, the allocation of sensor and other tracking resources could be reviewed to focus the time-critical initial efforts on producing ephemeris data samples most conducive to statistical analysis.

The authors employed several technical tools in this work, but none more important than the eye, which helped reveal suspected information in 3-D and numerous $\Delta V$ plots. All of these observations can be further investigated with more formal methods. However, future work will also benefit with additional subject matter experts and tools.

The subsequent *Breeze-M* debris event was only a minor footnote in the wake of *FY-1C*, but the event requires more analysis given the fact that there have been few observed debris events. An additional event, the SL-12 rocket body explosion on 14 Feb 200 also deserves attention and would benefit from some of the advanced techniques demonstrated here employing advanced targeting algorithms. There may be additional debris events that could be more technically examined for possible physical relationships to the *FY-1C* to investigate if one piece could have hit another spacecraft, and when.

Statistically generated debris based on empirical data can provide portions of the debris field that has yet to be characterized due to inherent complexities in orbit determination of dense debris fields. While not a substitute for debris ephemeris, it does provide a controllable means to generate data for missing, (too small to track, thought to have reentered, theoretical break-up models) or otherwise not available data. Additionally, these methods show insight into the break-up dynamics, which, when coupled with additional data, could reveal higher fidelity distributions in near-real time.

These methods could aid in placement of ground and air surveillance sensors to better perform future break-up analysis. Placement of sensors in global regions calculated to be most likely for early debris reentry would provide invaluable time-perishable data on the break-up since they will never make it into the catalog. Reentry monitoring may also be suitable for broad area sensors aided by the incandesce effects caused as the pieces reenter the Earth's atmosphere.

As part of an overall rapid debris analysis capability and in debris research activities, these methods provide an expedient capability to the operator, decision makers, commanders, and policy makers and support both the astrodynamics specialist and the non-technical decision maker.

## ACKNOWLEDGMENT

The authors would like to thank Dr. T.S., Kelso for his invaluable assistance and advice in providing tailored TLE data sets to enable the forensic analysis of the *FY-1C* break-up.

---

[1] D. Massa and T. Carrico, "Technical Description of Color and Opacity Blending," *Advanced Maui Optical and Space Surveillance Technologies Conference*, Maui, 2007

[2] NASA Orbital Debris Program Office, "Orbital Debris Frequently Asked Questions," available from http://orbitaldebris.jsc.nasa.gov/ [25 Jan 2008]

[3] J. Carrico, E. Fletcher, "Software Architecture and Use of Satellite Tool Kit's Astrogator Module for Libration Point Orbit Missions," Libration Point Orbits and Applications, Parador d'Aiguablava, Girona, Spain, June 2002.

[4] L. David, 2 February 2007, *China's Anti-Satellite Test: Worrisome Debris Cloud Circles Earth*, available from http://www.space.com/news/070202_china_spacedebris.html [25 Jan 2008]

[5] 2008, "Fengyun-1C Debris: One Year Later," *Orbital Debris Quarterly News*, vol. 12, no. 1, pp. 3-4

[6] M. Kaufman and D. Linzer, "China Criticized for Anti-Satellite Missile Test - Destruction of an Aging Satellite Illustrates Vulnerability of U.S. Space Assets," *Washington Post*, January 19, 2007. sec. A. p. 1

[7] CelesTrak, available from https://www.celestrak.com/ [25 January 2008]

[8] Smirnov, 2002, *Space Debris, Hazard Evaluation and Mitigation*, Taylor and Francis, London

[9] CelesTrak

[10] Menahem Friedman, Abraham Kandel, 1999, *Introduction to Pattern Recognition. Statistical, Structural, Neural and Fuzzy Logic Approaches,* Series in Machine Perception and Artificial Intelligence, vol. 32, Imperial College Press, London

[11] S. Chiu, 1996, "Method and Software for Extracting Fuzzy Classification Rules by Subtractive Clustering," in *Fuzzy Information Proceeding Society, Biennial Conference of the North American*, pp. 461-465.

[12] CelesTrak