AAS 08-127

ANALYSIS OF THE RESPONSE OF A SPACE SURVEILLANCE NETWORK TO ORBITAL DEBRIS EVENTS[†]

David Finkleman[‡]
Daniel L. Oltrogge[§]
Anthony Faulds[**]
Joseph Gerber[††]

This paper will describe development of an efficient work flow and tools for examining the response of a space surveillance network to orbital debris events. The approach is based on commercial off the shelf (COTS) capabilities and interfaces developed with commercially available programming and analysis packages.[‡‡]

INTRODUCTION

Minimizing space debris and mitigating the consequences of near Earth orbital debris have been serious issues for several years.[1, 2, 3] International thrusts to develop standards and practices[4] were invigorated by the Chinese anti-satellite test early in 2007. However, all analysis and planning capabilities that the authors are aware of emphasize projections of the growth of the debris environment and the aggregated risk to missions exposed to that environment.[5] There is much noteworthy research in the mechanics of explosions and collisions among satellites. There are no comprehensive models of the evolution of specific debris generating events.

There are also no analyses of the response of space surveillance sensors to potential debris generating events. Many models of space surveillance system performance are based only on the fields of regard of sensor systems. It is not sufficient that an orbiting object of interest fall within the field of regard of a sensor system. The object must be captured within the instantaneous field of view sufficiently well, and all sensor constraints must be met before the object can be considered to have been detected. Tracking and orbit determination are subject to even more constraints.

Finally, there is absolute dearth of observational data that is well enough characterized to assess the relative performance of the several orbit determination techniques employed in the civil and commercial space community. There are too few sensors[6], and the products of many of them are generally unavailable for reasons of national security.

We have developed a comprehensive approach to estimating the likelihood and evolution of debris generating events, the response of sensor systems that might be able to observe these events, and the ability to distribute observations in order to develop tracks. Using detailed models of sensor performance, we are also able to synthesize observations with covariances as though they were produced by a real sensor system.

[†] The space surveillance network examined in this paper is fictitious and in no way reflects the characteristics of the United States Air Force Space Surveillance Network, commonly known as The SSN.

[‡] Senior Scientist, Center for Space Standards and Innovation, Analytical Graphics, Inc., 7150 Campus Dr , Colorado Springs, CO 80920
[§] Senior Analyst, 1Earth Research, LLC, Box 51412, Colorado Springs, CO 80949
[**] Senior Programmer, Trinnovations, Inc., 42108 Roick Dr., Ste. A, Temecula, CA 92590
[††] Branch Manager, Applied Defense Solutions, LLC, 5636 Altitude Dr., Colorado Springs, CO 80918

[‡‡] All authors are also affiliated with SkySentry, LLC, Colorado Springs, CO, which jointly sponsored this work.

We conjecture that this unique aggregation of tools and techniques is the paradigm for planning and analysis capabilities that are essential for debris management and mitigation as well as planning responses to potential events and assessing the safety of orbital operations.

Since this problem set is very important, our goal was to develop tools and techniques that would be easily accessible and widely available. Even our interface software was not purpose built for a specific circumstance, and it is based on widely used software. This approach also mitigates issues of validation and verification, since all of the analytical elements have been confirmed by a broad user community.

Our technique is based on Satellite Toolkit, a product of Analytical Graphics, Inc., QualNet, a value added evolution of DARPA's Global Mobile Simulation (GLOMOSIM) developed by Scalable Network Technologies, Benchmark, a Government Off the Shelf (GOTS) simulation written in MATLAB, and Microsoft's Visual Studio. The framework is extensible and expandable.

This report will discuss development issues, present the work flow we implemented, and present preliminary applications of the technique.

Development Issues

There were several technical, mathematical, and physical issues.

- Collaborating discrete and time evolving simulation environments.
- Overcoming non-coincident object models
- Assuring consistent and predictable causality
- Representing physical phenomena faithfully and to a consistent level of aggregation.

Collaborating discrete and time evolving simulation environments.

Most astrodynamics analyses employs "continuous" simulation techniques. Governing differential equations are integrated either numerically or analytically, and time evolves monotonically and continuously. Most simulations of processes and communications are discrete event simulations. Progress depends on executing a series of events, some sequential, some in parallel, and some requiring others to be completed before they can be executed. Within discrete simulation mechanism there are a number of logic expressions that are evaluated at discrete points in time. In discrete event simulation, the operation of a system is represented as a chronological sequence of events. Each event occurs at an instant in time and marks a change of state in the system. One cannot interpolate among event outcomes to find intermediate system states. Depending on rates of change, one generally can interpolate among states determined by continuous integration. Sometimes this is necessary, for example, to determine a state at a specific point in time that does not coincide with a numerical integration step. Analytical approximations may be thought of as sophisticated interpolation techniques guided by the defining differential equations.

Electromagnetic phenomena depend crucially upon rates of change. Whether radar or communications, many processes depend on sensing Doppler shifts and precise temporal modulation or transmit/receive times. One should not approximate motion with acceleration discretely. The derivatives of important state variables will not exist at the discontinuities that each event causes. Perceived frequencies will be far out of band, and the rate of change of Doppler may make it impossible to close phase locked loops.

The phenomena we chose to examine embody both continuous and discrete event simulation techniques. The manner in which these techniques interact depends on the nature of the problem of interest. We considered two co-simulation approaches: representing continuous events discretely as waypoints in the discrete event model and computing physical states at the time associated with events in the discrete event queue. The first is appropriate either when physical phenomena vary slowly compared with the time in which discrete events might take place or when the physical aspects of the problem are addressed exclusively in the continuously evolving simulation. The latter approach is employed in Satellite Toolkit. Ephemerides are generated at discrete intervals, and when an event of interest occurs between these discrete times equations of motion are integrated over the short interval. This is more computationally efficient than propagating continuously from inception for each specific event time.

Overcoming non-coincident object models

This issue pivots on the lack of common technical terminology. Service Oriented Architecture and XML Schemas are among the most widely used buzz words in data analysis and computation. So far there has been much activity but little progress developing a data model acceptable across the astrodynamics enterprise[7], although international standards are maturing[8]. It is difficult to determine object correspondences among simulation environments built for diverse purposes.

Even worse, object parent-child relationships are inconsistent among such simulations. STK uses a platform/sensor/device hierarchy in which kinematics and dynamics are inherited from a platform, pointing, field of regard, and field of view are inherited from a sensor, and electromagnetic and procedural phenomena reside in a device. The principal object in QualNet is a host that inherits mobility from a node file, physical characteristics from external antenna files, and communication characteristics from radios. Benchmark has yet another paradigm in which independent objects such as payload shrouds are children of the object from which they are spawned. The set of properties at a single hierarchical level in STK are distributed throughout the hierarchies of the simulation environments we wish to collaborate with.

Assuring consistent and predictable causality

Heisenberg had it right. Touch something and you change it. There are physical and mathematical consequences associated with collaborating diverse simulations. Radar and communications clearly do not affect the motion of satellites, but satellite kinematics and dynamics do affect electromagnetic interactions. Routes through networks, detection, and tracking processes can be affected significantly by satellite motion. This can delay responses and constrain the spectrum of feasible maneuvers, depending upon when a conjunction is anticipated. Timing and execution of critical uploads to satellites can also be affected greatly.

There are several alternatives and, as above, the choice depends on the nature of the problem of interest. One alternative is a continuous exchange of state information among the simulations. This is computationally intensive and generally infeasible. Protocol Data Units (PDU's) that inform the simulation ensemble of object states in federated virtual simulations are impractical for collaborating constructive co-simulation among diverse, purpose built environments. The other alternative is to conduct all independent physical simulation elements in the environment most appropriate and pass the resulting states to the higher layer process and electromagnetic models. The entire scenario can be executed in advance or at least until that time at which a higher layer outcome causes physical changes, such as issuing a maneuver command.

DESCRIPTION OF THE MODELS EMPLOYED

Satellite Toolkit (STK) STK is a flexible, precise constructive simulation environment that evolves object states continuously with time. The capabilities most relevant to this investigation are the ability to estimate current and future states of satellites with a variety of validated mathematical and analytical techniques, efficient tools for determining accesses among space, airborne, and terrestrial objects under constraint, representations of the physical layer aspects of sensor operation and communication phenomena, and exquisite visualization.

QualNet QualNet is a value added commercial off the shelf outgrowth of the DARPA funded Global Mobile Simulation (GloMoSim) project for efficient analysis of large, heterogeneous communication networks. There are several such commercial products, each of which has capabilities that favor its application in a given problem set. OPNET is the most widely used among them with a rich library of

Open Systems Interconnect (OSI) protocol stacks and commercial device characteristics. As noted emphatically previously, the choice of simulation environment and implementation depends heavily on the nature of the problem of interest. We chose QualNet because its native instance represents wireless communications and because it exists in a native parallel operating environment. This will be important as we progress to examining space debris scenarios in which hundreds of sensors interact with thousands of objects. All network simulation tools are discrete event environments since they represent processes and procedures rather than physical entities.

Radar and Other Sensor Representations: The interface we developed can also interact with a variety of representations of real radar and electro-optical sensors. In this paper we employ only the level of representation native to STK and its commercial adjuncts. However, more detailed representations are necessary to construct sensor observations as they would be provided to orbit determination techniques. A comprehensive research standard must be independent of any specific orbit determination or propagation technique. Since the trajectories used in analyses such as that we are describing are generated with a specific technique, we must restore or reconstruct statistical independence. Characterizing measurement uncertainty is an important step. The models we are considering represent well this measurement noise and provide realistic covariance information.

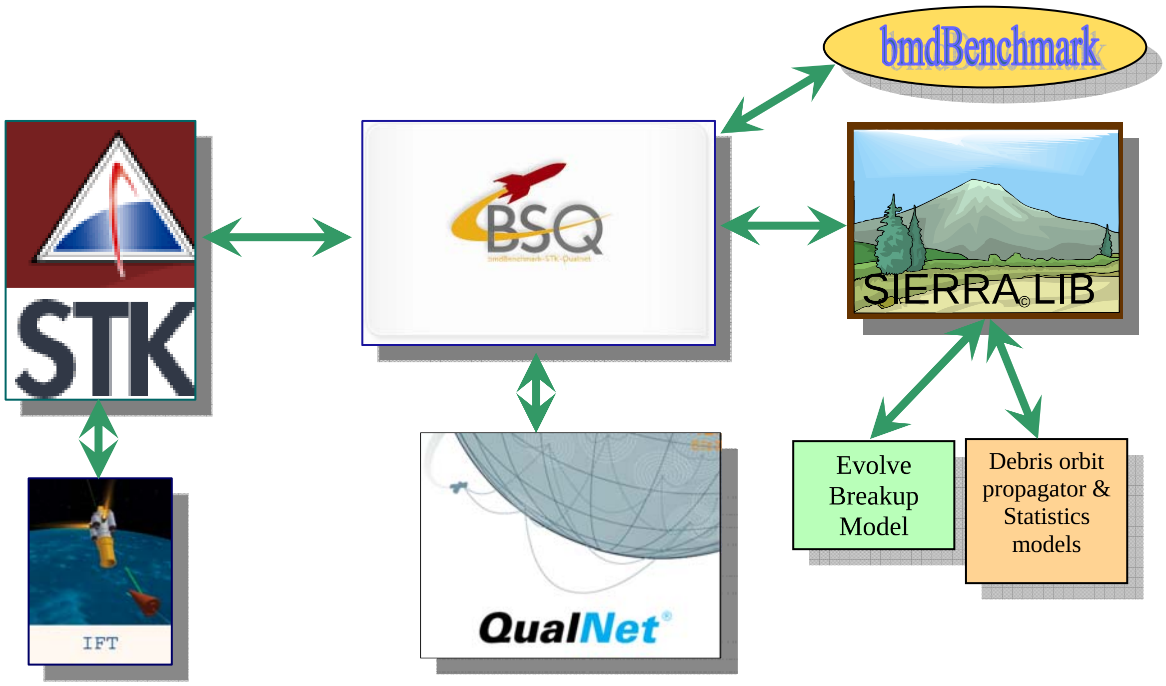


Figure 1 SN Debris Impact Analysis Process

DESCRIPTION OF THE SPACE DEBRIS GENERATION APPROACH

Breakup Models: There are many models of explosive and collision-induced breakup. While we have made every effort to faithfully implement the latest models, we recognize that large uncertainties will always exist in such modeling efforts.

For this work, 1Earth Research implemented four breakup models. The first approach is based upon the breakup algorithm developed by Dr. Chobotov[9] incorporating an early formulation of breakup statistics which use fragment mass as the independent variable as based on a 1985 NASA breakup formulation[10]. The second approach is based upon the much more recent Evolve 4.0 Breakup Model[11, 12, 5] which has ‘characteristic length’ as the independent variable. As a third option, modifications to the original Evolve 4.0-based implementation suggested by ESA were also implemented. The fourth model generates pseudo-fragments which span the range of ballistic coefficients and velocity increments that a given breakup event may have, with the velocity increment equally distributed across a equal angles grid. The user can select which model of the three is desired at runtime. Ref. 12 has a detailed discussion of the heritage of these models, illustrating the influence of various model developers and data sets in the breakup modeling process.

Since the objective of this paper is not to go into great depth on debris breakup models, we will show some breakup model output in standard formats for comparison with figures in peer documents. Our implementations of the Evolve breakup models were used to create Figure 2 through Figure 5. Comparisons of these figures with similar plots found in Ref. 5, 11 and 12 show excellent agreement.

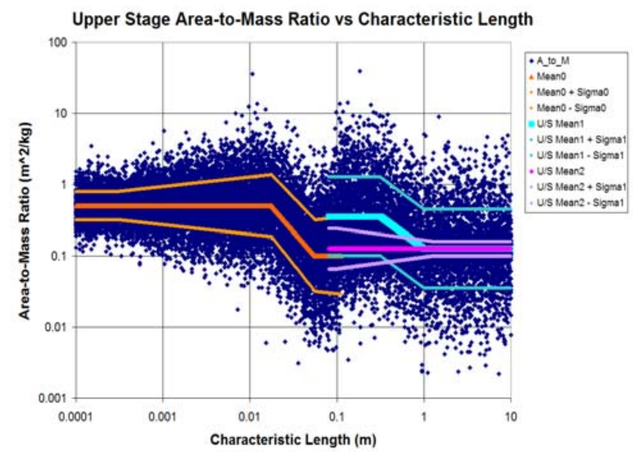


Figure 2 Sampled Area:Mass Statistics for Upper Stages Corresponding to NASA’s Original Evolve 4.0 Paper

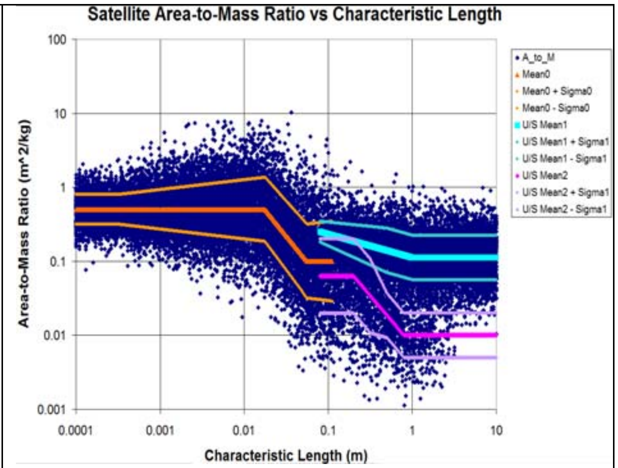


Figure 3 Sampled Area:Mass Statistics for Satellites Corresponding to NASA’s Original Evolve 4.0 Paper

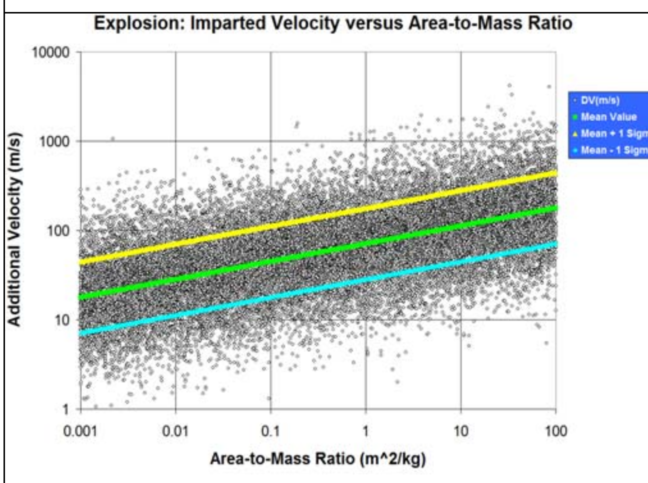
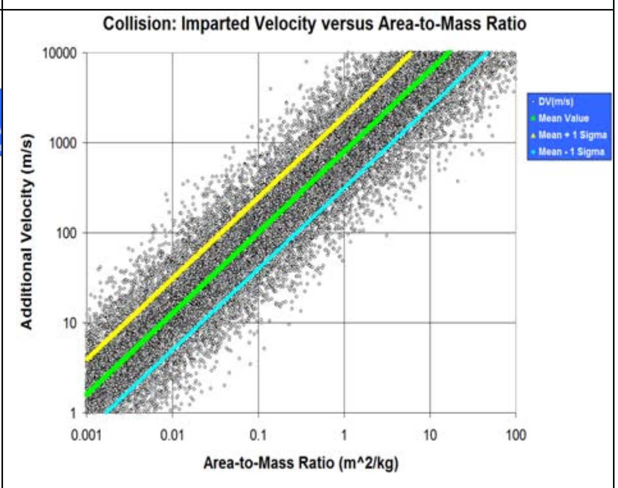


Figure 4 Sampled Imparted Velocity Statistics for Explosions Corresponding to NASA’s Original Evolve



4.0 Paper	Figure 5 Sampled Imparted Velocity Statistics for Explosions Corresponding to NASA's Original Evolve 4.0 Paper

The European Space Agency's MASTER[2005] model technical developers believe that NASA's Evolve model has shortcomings in the representation of the particles' area-to-mass ratio for objects smaller than 1 mm, and ESA[12] has proposed remedies to the Evolve formulation. The proposed Evolve/Master model is implemented as shown in Figure 6 through Figure 9.

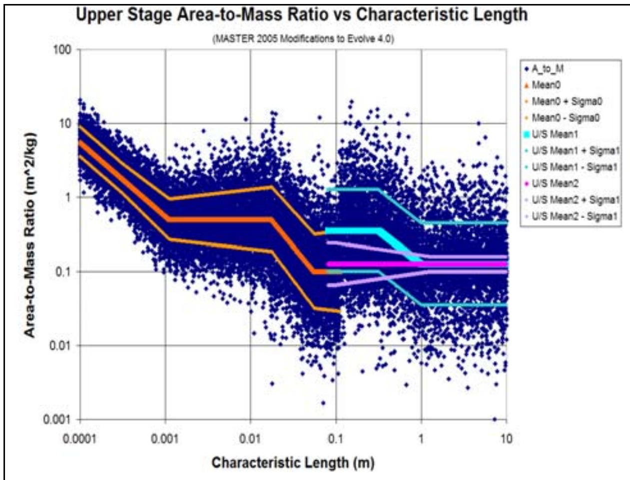


Figure 6 Sampled Area:Mass Statistics for Upper Stages Corresponding to ESA's MASTER2005 Proposed Modifications to the Evolve 4.0 Model

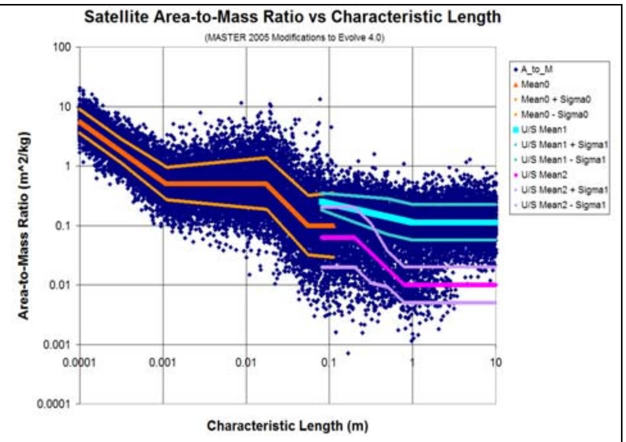


Figure 7 Sampled Area:Mass Statistics for Satellites Corresponding to ESA's MASTER2005 Proposed Modifications to the Evolve 4.0 Model

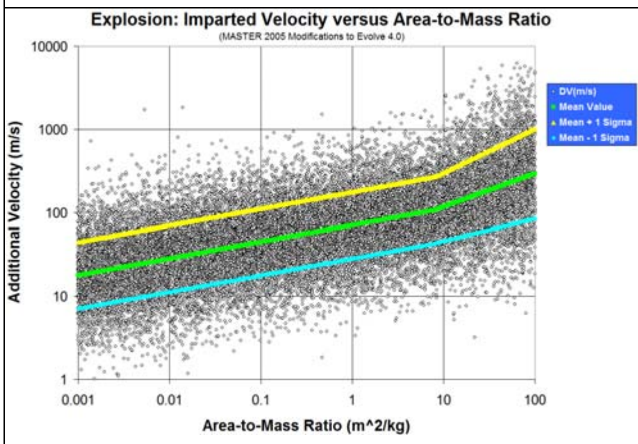


Figure 8 Sampled Imparted Velocity Statistics for Explosions Corresponding to ESA's MASTER2005 Proposed Modifications to the Evolve 4.0 Model

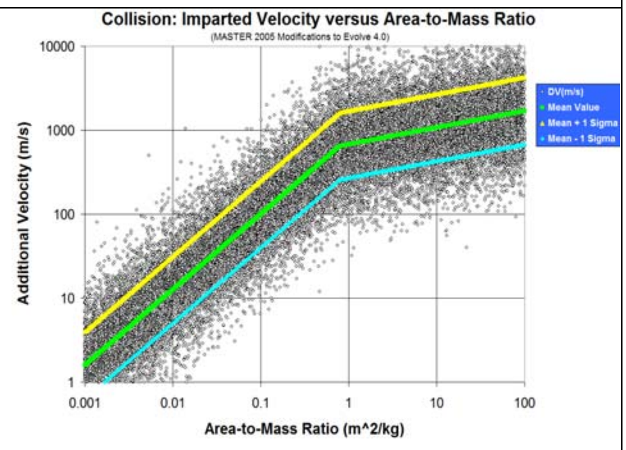


Figure 9 Sampled Imparted Velocity Statistics for Explosions Corresponding to ESA's MASTER2005 Proposed Modifications to the Evolve 4.0 Model

Number of Debris Fragments Estimated by the Evolve Breakup Model: In the Evolve 4.0 model, the number of fragments (N) larger than a fragment's characteristic length L_c (in meters) can be estimated from:

$$N(L_C)_{\text{explosion}} = 6L_C^{-1.6} \tag{1}$$

and

$$N(L_C)_{\text{collision}} = 0.1(M)^{0.75} L_C^{-1.71} \tag{2}$$

where M is proportional to mass as defined in Ref. 11. As an example, Eqn. (2) was evaluated for numerous cases to generate Figure 10, assuming that the mass of the 'target' object was 95% of the total combined mass of the target/projectile system.

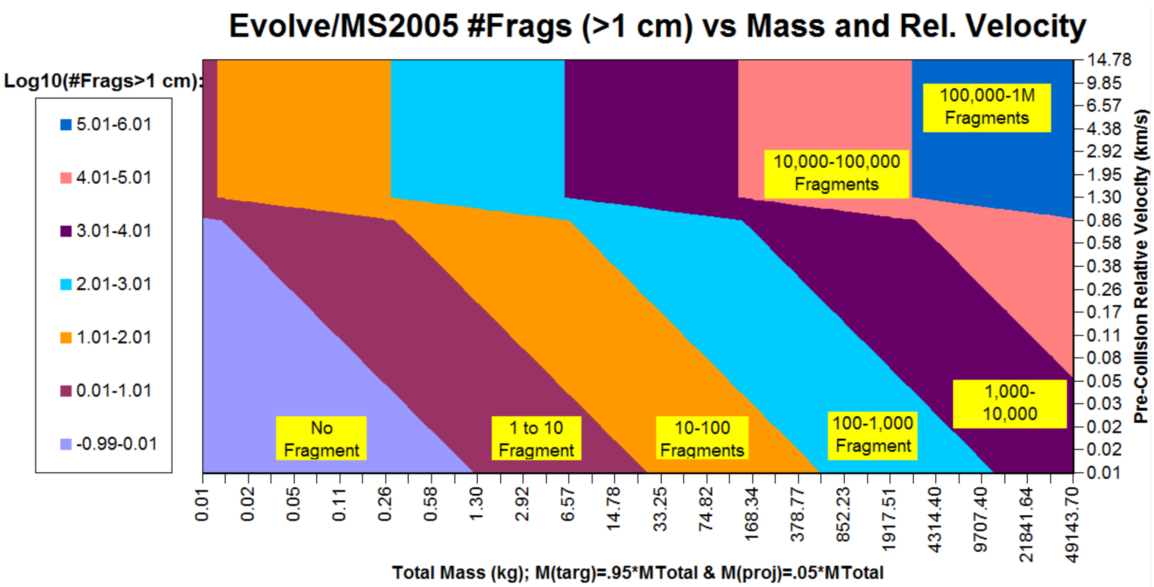


Figure 10 Number of Fragments Corresponding to ESA's MASTER2005 Proposed Modifications to the Evolve 4.0 Model, for a 19:1 Assumed Mass Distribution

Equations 1 and 2 may be easily inverted to obtain:

$$L_C(N)_{\text{explosion}} = \left[\frac{6S}{N}\right]^{0.625} \tag{3}$$

and

$$L_C(N)_{\text{collision}} = \left[\frac{(Mass_{total})^{\frac{3}{4}}}{10N}\right]^{\frac{1}{1.71}} \tag{4}$$

Equations 3 and 4 permit the user to select N values incrementally and evaluate the characteristic length, L_C

Application of Conservation Laws to Breakup Models: The Evolve 4.0 breakup model, much like its predecessors, does not inherently obey necessary conservation laws. The significant conservation laws for collision-induced breakup are provided below in equations 5-11:

Conservation of mass:

Conservation of mass for an explosion or collision event is simply:

$$\sum_{i=1}^{N} m_i = m_1 + m_2 \tag{5}$$

As simple as this equation is, however, it is this conservation law which presents the most difficulty for the user of current breakup models. Much uncertainty exists in the presumed mass distribution for the largest fragments; for example, the largest fragment may be as large as 30% to 50% of the original object[13]. As shown in Figure 11, the Evolve-predicted/attained mass for a sample collision test case exceeds the actually available mass in all 15 trials. This single test case can be expanded across a range of total masses (we make an assumption that the projectile is roughly 5% of the total mass and the target is the remaining 95% of the total mass for demonstration purposes) and ΔV values to produce the generalized plots shown in Figure 12 and Figure 13.

We now see a distinct break line at the magenta section; the Evolve model under-predicts the total mass to the left of the magenta section, and it over-predicts total mass to the right of the magenta section. We can readily identify the 'breakline' to be located at the boundary between 'catastrophic' and 'non-catastrophic' collisions, as shown in Figure 14. Thus the generalization appears to be that the Evolve model yields fragments with too much mass for 'catastrophic' collisions and fragments with too little mass for 'non-catastrophic' collisions.

Three solutions to this dilemma present themselves: (1) all predicted fragment masses can be scaled such that their mass sum totals the pre-collision or pre-explosion mass; (2) an N-offset term can be defined such that by starting at N=N_Offset, the sum of the remaining fragment masses equals the pre-event total mass; or (3) a combined method may be used. Since the second solution (the N-Offset method) will not accommodate too little mass as observed in the non-catastrophic case, the combination method (3) has been adopted.

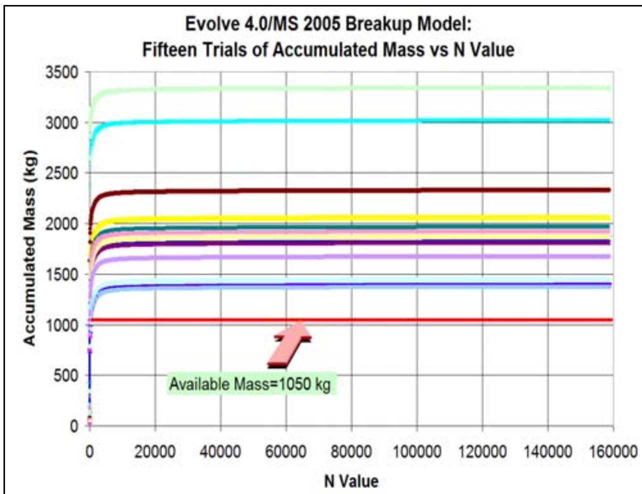


Figure 11 Accumulated Mass for one collision test case (ΔV=11.9 km/s, Mass(total) = 1050 kg), over 15 Pseudo-

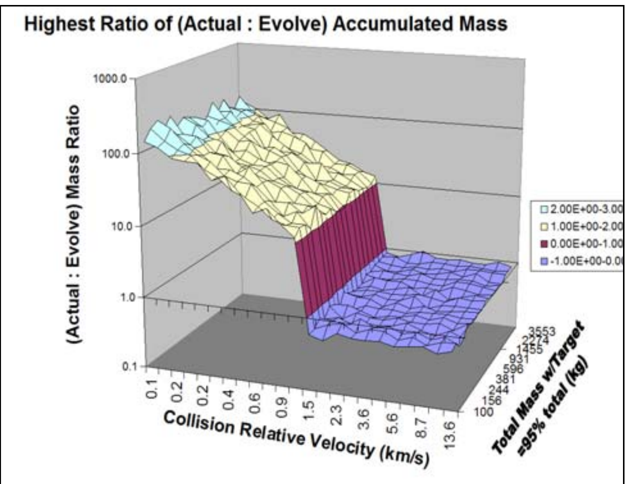


Figure 12 Maximum Ratio of Actual Mass (pre-collision) to post-collision Accumulated Mass predicted by Evolve/MS 2005 over 10 Pseudo-random

random Trials.	Trials.

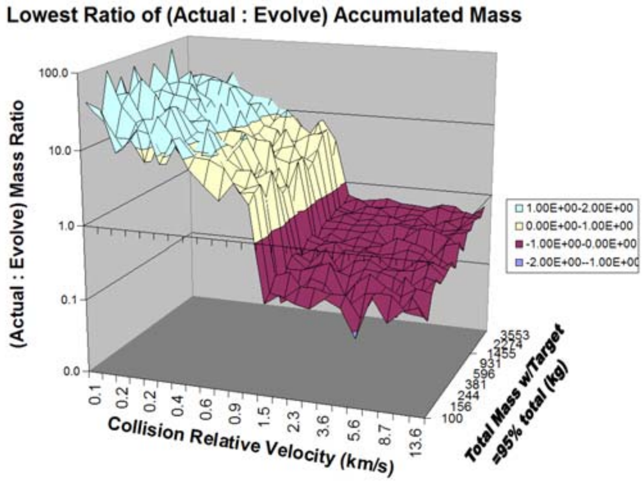
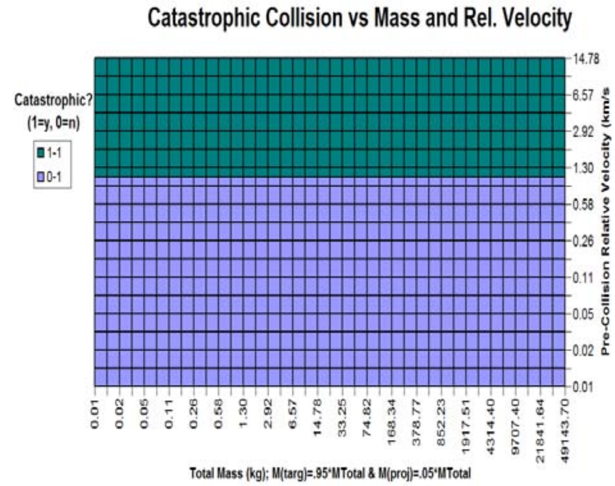

	

Figure 13 Minimum Ratio of Actual Mass (pre-collision) to post-collision Accumulated Mass predicted by Evolve/MS 2005 over 10 Pseudo-random Trials.	Figure 14 "Breakline" between catastrophic and non-catastrophic collisions.

Conservation of Angular Momentum:

Angular momentum is conserved for the orbital system via:

$$\bar{r} \times \bar{v}_{cm} = \left[\frac{\left(m_1 \left(\bar{r} \times \bar{v}_1 \right) + m_2 \left(\bar{r} \times \bar{v}_2 \right) \right)}{\left(m_1 + m_2 \right)} \right] \tag{6}$$

Conservation of Linear Momentum:

For the collocated target and interceptor objects at the instant of collision, Eqn. 6 can be simplified to yield the linear momentum governing equation:

$$\bar{v}_{cm} = \left[\frac{\left(m_1 \bar{v}_1 + m_2 \bar{v}_2 \right)}{\left(m_1 + m_2 \right)} \right] \tag{7}$$

As implemented in the 1Earth breakup code, linear momentum is iteratively ensured by adopting an equal-angle subdivided Icosahedron grid for fragment DV directions. The Icosahedron (shown in Figure 15). Subdivision of each face in a regimented way permits an ideal, index-selectable grid which minimizes vector storage and reduces analysis time. Indeed, this distribution has been adopted for such disparate studies as terrain, weather, gravity modeling and visualization.

Due to the rigorous implementation of the Icosahedron, it is relatively easy to 'randomly' select Icosahedron faces which point away (at least partially) from the previously accumulated linear momentum vector. This directly facilitates conservation of linear momentum.

Regular Icosahedron

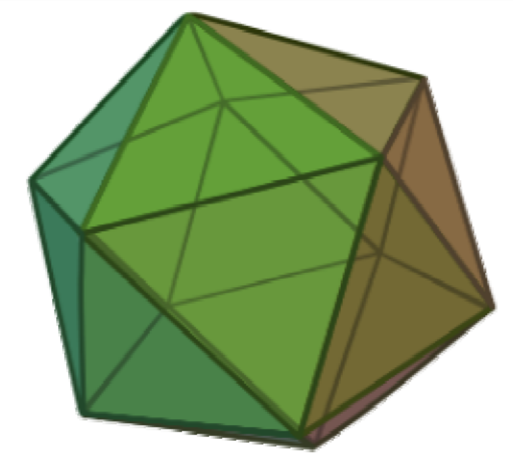


Figure 15 The 20-faced Icosahedron.

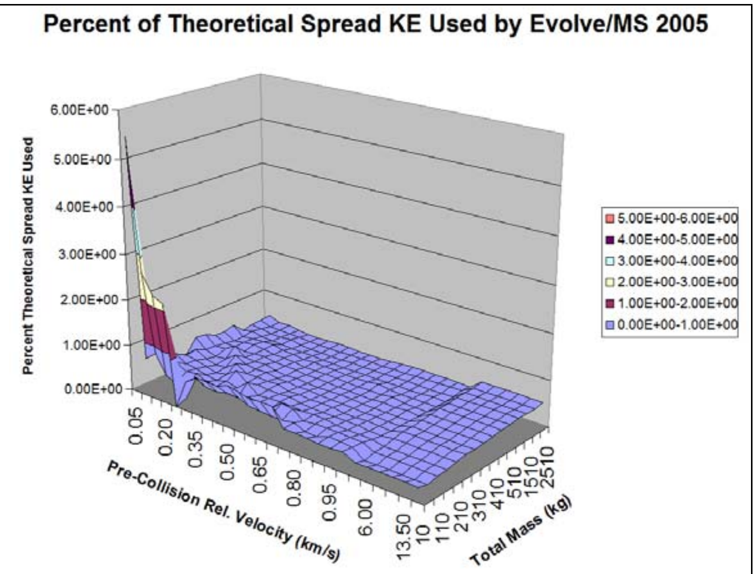


Figure 16 Evaluation of Percent of Spread Kinetic Energy Utilized by the Evolve/MS 2005 Model.

Conservation of Kinetic Energy:

For orbit collisions, kinetic energy is conserved via the following equation, where Q_{loss} is the loss of energy (e.g., due to heat, light, and fragment rotational velocities). This can be expressed as:

$$KineticEnergy = \frac{1}{2}m_1 v_1^{\;2} + \frac{1}{2}m_2 v_2^{\;2} = \frac{1}{2}\sum_{i=1}^{N} m_i \left|\bar{v}_{cm} + \Delta\bar{v}_i\right|^2 + Q_{loss} \qquad (8)$$

The above equation can be simplified to:

$$KE_{total} = \frac{1}{2}m_1 v_1^{\;2} + \frac{1}{2}m_2 v_2^{\;2} = \frac{1}{2}m_{total} v_{cm}^{\;2} + \sum_{i=1}^{N} m_i\left(\bar{v}_{cm}\cdot\Delta\bar{v}_i\right) + \frac{1}{2}\sum_{i=1}^{N} m_i \Delta v_i^{\;2} + Q_{loss} \qquad (9)$$

By defining η [ranging from 0 to 1] to be the portion of Kinetic Energy that is theoretically available to fragment spread velocities that is actually obtained, and by grouping terms, Eqn. 9 can be rewritten as:

$$KE_{orig} - KE_{cm-translation} - Q_{loss} = \eta\left(KE_{orig} - KE_{cm\_translation}\right) = \sum_{i=1}^{N} m_i\left(\bar{v}_{cm}\cdot\Delta\bar{v}_i\right) + \frac{1}{2}\sum_{i=1}^{N} m_i \Delta v_i^{\;2} \qquad (10)$$

Unfortunately, we don't know what η would be. But in order to conserve kinetic energy, we know that η can be no larger than one; therefore, models must adhere to the following constraint:

$$\left[\sum_{i=1}^{N} m_i\left(\bar{v}_{cm}\cdot\Delta\bar{v}_i\right) + \frac{1}{2}\sum_{i=1}^{N} m_i \Delta v_i^{\;2}\right] < \left(KE_{pre-collision} - KE_{cm\_translation}\right) \qquad (11)$$

However, examination of this constraint against numerous invocations of the Evolve breakup model indicate that η is quite low, as shown in Figure 16. The graph illustrates that, based upon the Evolve 4.0

breakup model, typically only about 5% of the collision energy is not lost due to heat, light, tumbling and other energy dissipations.

Sample Breakup Model Outputs:

The implemented breakup model can be applied to a wide range of conditions. For example, Figure 17 shows the number of fragments greater than 10 cm as a function of collision ΔVs and total mass. To illustrate the functionality of the implemented breakup models, a sample collision is examined, shown in Figure 18.

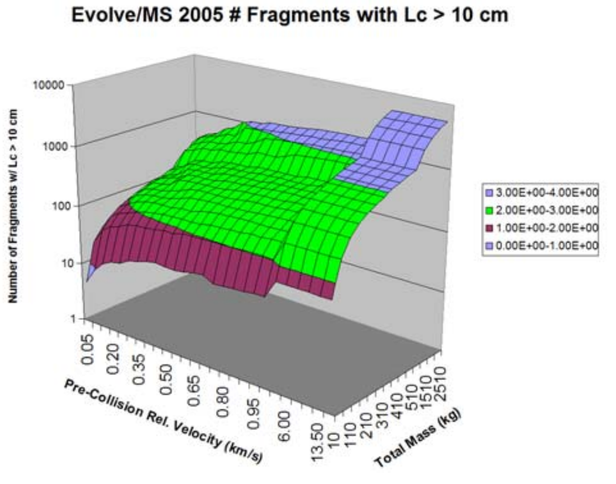


Figure 17 Number of fragments with Characteristic Length L_C > 10 cm.

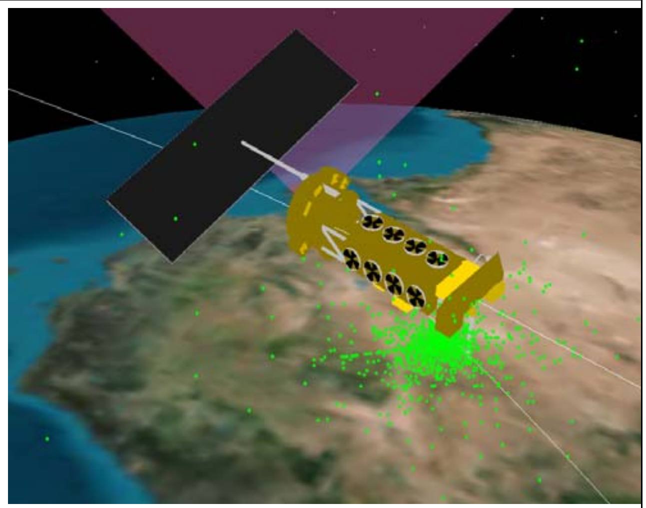


Figure 18 Sample post-collision breakup.

THE WORK FLOW:

We developed the interface among these simulations to estimate the environment created by explosions and collisions and to guide contingency response planning.

The co-simulation that encompasses the hierarchy of constraints and phenomena beyond simple geometry and kinematics while enhancing the physical description of debris events. We employ a rapid orbit conjunction detector coupled with a detailed debris orbit propagation scheme to propagate debris orbits and operate interactively with Satellite Toolkit for initial conjunction estimation and post-impact visualization. Objects perceived by the radars lead to messages at appropriate asynchronous intervals and with the content that represents actual communication network formats. We then pass these messages through a well recognized communication network simulation, QualNet. Network topology can be instantiated a priori or conveniently constructed through the interface we have developed. The simulation encompasses all elements of the Open System Interconnect hierarchy if necessary with router, buffer, error correction, and other network unique components. The final step is to deliver an asynchronous information stream adulterated by real world sensor and communication phenomena to track association and track development algorithms. Our simulation environment spans the mission chain from event, through perception, to processing, communications, and actionable tracks.

One can begin either with a network architecture in the communication simulation or a physical scenario in STK. Generally some of each is best. We will describe the work flow as though we began with a physical situation instantiated in a simulation such as STK.

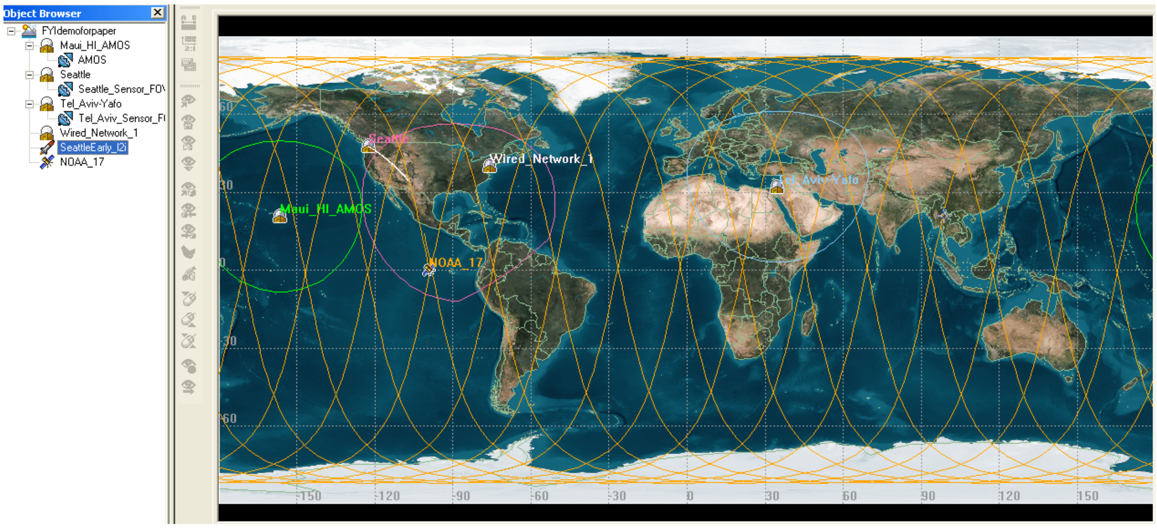


Figure 19   Sample Scenario

In the scenario shown in Figure 19, we chose a sun synchronous satellite to illustrate a situation similar to the Fengyun 1C event. The satellite, herein called NOAA 17 is retrograde with an inclination of 98 deg and elliptical with an apogee of 800 km and a perigee of 300 km. We have placed at AMOS, Seattle, and Tel Aviv, fictitious sensors with 300 km range and 45 degree fields of regard with fixed azimuth and elevation, as might be the case for untasked surveillance. The observation sites are linked through a wired hub in Exton, PA, AGI headquarters.

The following charts show how the interface we have developed is used to generate realistic debris distributions.

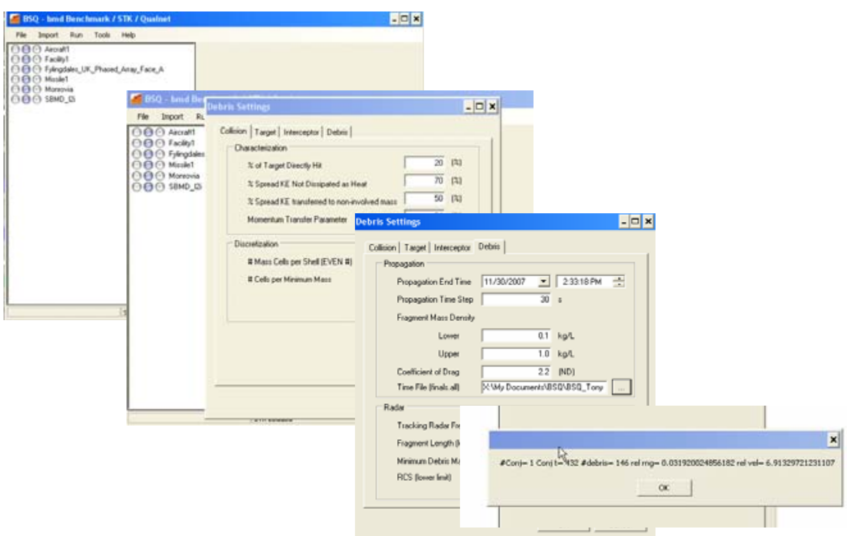


Figure 20   Debris Generation Work Flow

The first step is to bring the STK scenario into the interface. The scenario must already have one or more conjunctions, arranged iteratively or through STK utilities with coarse conjunction thresholds. Subsequent utilities in our interface search for close approaches and refine the conjunction, which is then the point of departure for the NASA debris model. Next invoke “Create Debris” from the Tools item on the BSQ Menu Bar as shown in Figure 20. The parameter set defaults to an event we have chosen in which the mass of the interceptor is small relative to that of the target. This leads to a debris cloud dominated by the state of the target vehicle at conjunction. The debris generation model incorporates both mechanical and explosive elements. The distribution is governed by the percent of target hit parameter. Zero implies pure explosive disassembly. There are also accommodation coefficients for dissipative and inelastic processes. The figure ends with a message informing the analyst that a conjunction was processed and debris created. This result is communicated to the STK scenario as shown in Figure 21.

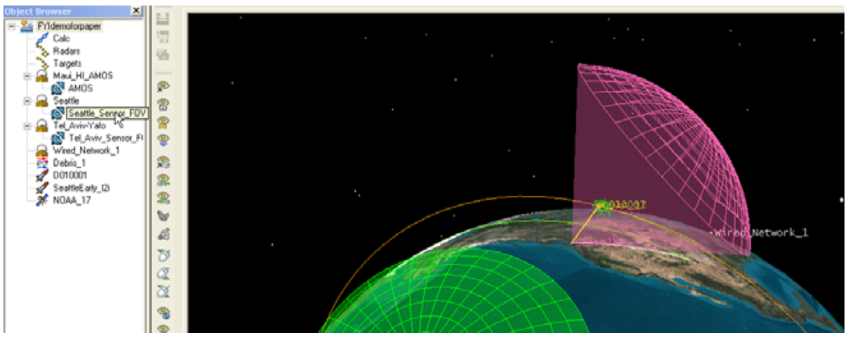


Figure 21 Debris imported to the STK scenario

The interceptor was launched from Seattle. The predicted debris cloud has several hundred objects, whose ephemerides are stored in a user designated location. Using STK utilities, we also produce Two Line Element Sets (TLE) for all of the debris. However, it is computationally inefficient to import all of the debris into STK as independent STK objects. For visualization only, we use the STK Multiple Target Object to depict the evolving debris cloud. A single debris element has been imported for demonstration purposes only. Note that it reenters very quickly.

The next step is to determine sensor accesses as shown in Figure 22. For this demonstration, we show only how one would determine sensor geometric access, but with range, scan, and other constraints at that level of representation.

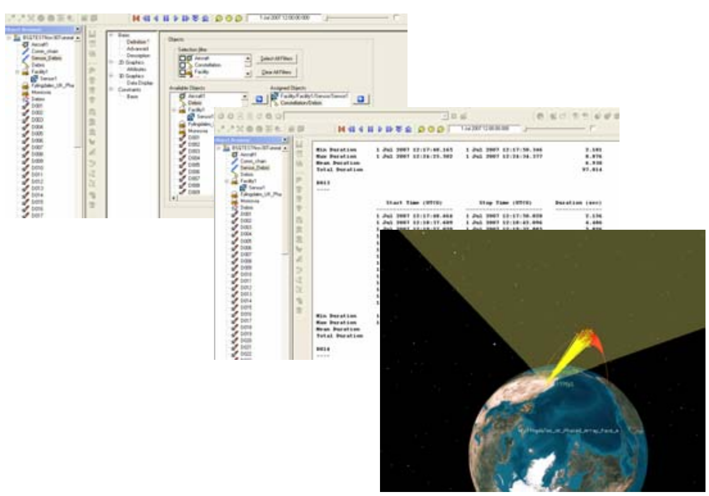


Figure 22   Sensor Accesses

In this example, we show the full detail of access determination as though debris elements had been imported into STK. In practice, the accesses are determined without that complication. The STK Deck Access utility may be used. for line of sight or only sensor to object access. We had to extend that methodology to determine radar access through a sensor object positioned on a fixed or moving platform. Figure 4 shows the progression from creating constellations of debris and collections of sensors the accesses among which are determined with STK Chain objects. The figure includes representative exportable reports of individual object access times and durations.

The next step is to develop the communications analysis.

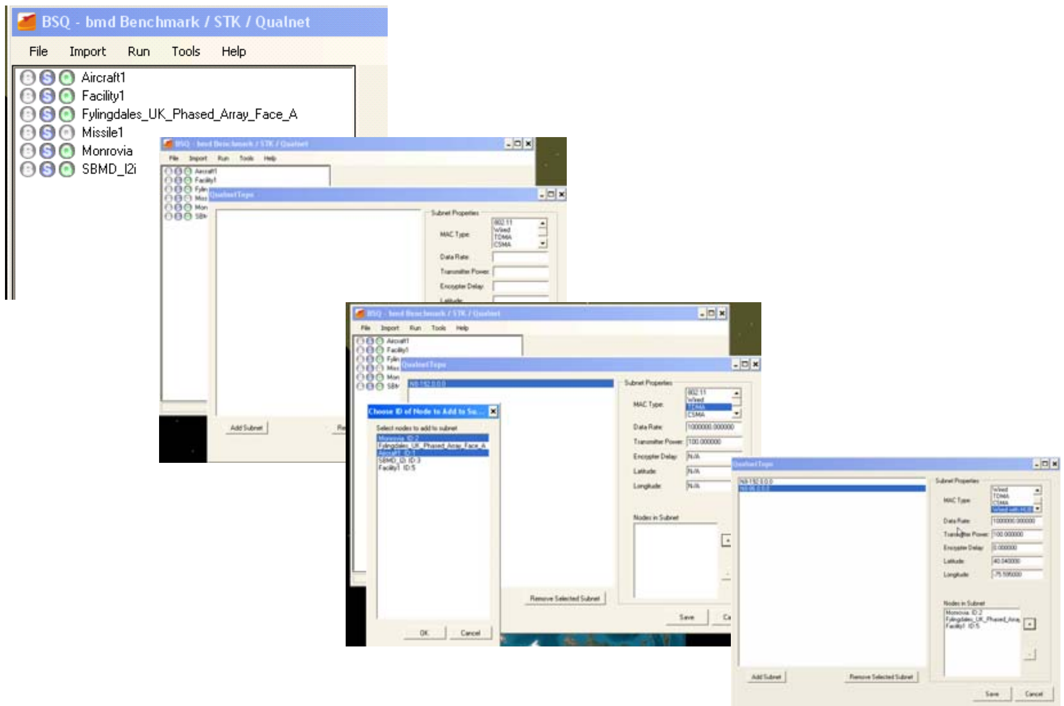


Figure 23   Synthesizing communication analysis

Returning to the interface we developed, we import the STK scenario into QualNet, as shown by the green circles in the leftmost screen of Figure 23. We can create rudimentary network topology with our interface. One can create wired, wireless, and hybrid subnets among the objects in the scenario, invoking a variety of widely used protocol stacks. In this mode of operation, all communication device characteristics are invoked within QualNet. They need not be, and in fact are not, the same as those in STK. QualNet overrides all but the physical accesses.

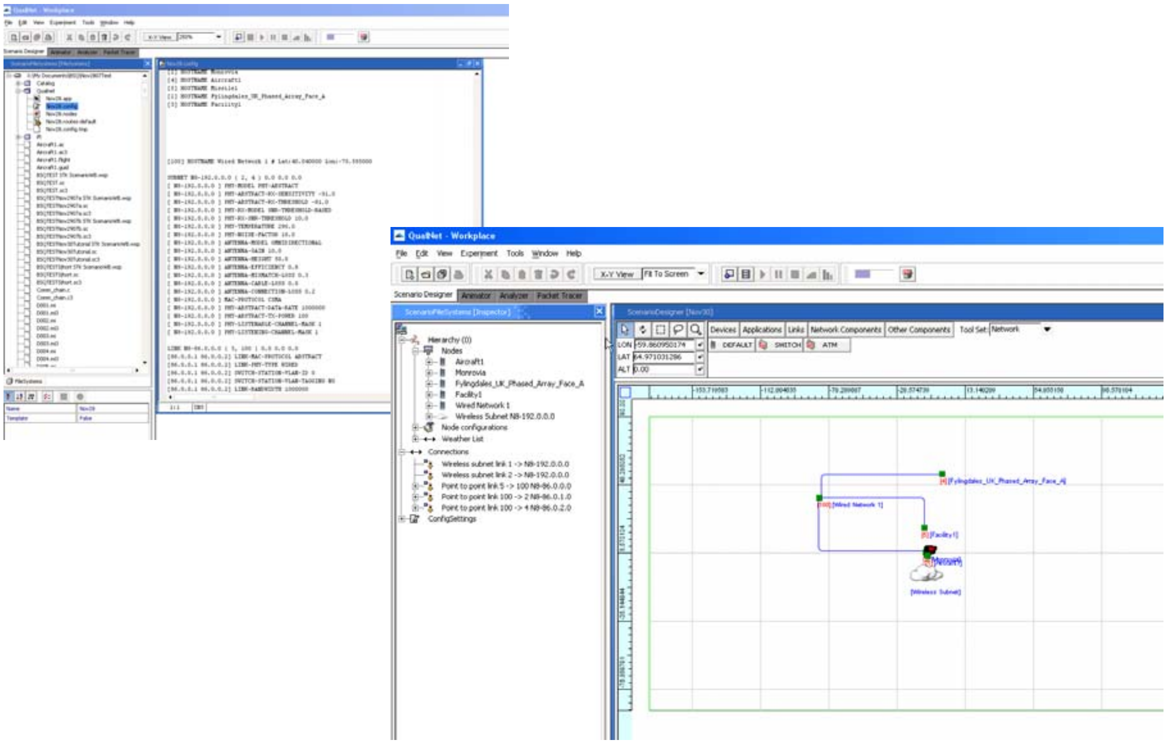


Figure 24 QualNet Analysis Work Flow

Figure 24 shows the scenario as represented in QualNet. The upper left demonstrates the file hierarchy and the content of one of these files. The lower screen shows the scenario as the QualNet GUI would present it. Clouds are wireless subnets, and flags are waypoints corresponding to object mobility.

There will be no communication unless applications are invoked at the top of the OSI hierarchy. In the world of network engineering and analysis, an application has nothing to do with the actual information content of the transmissions. An application parses and formats the information into messages. As the transmission moves down the OSI hierarchy to the physical world, the messages are apportioned among packets, error correction schemes such as checksums are applied, and eventually a bit stream emerges, encoded on a carrier in the physical layer.

The next step is creating applications and examining the actual information transfer. This is the point of departure for physical layer schemes best suited to a given problem set.

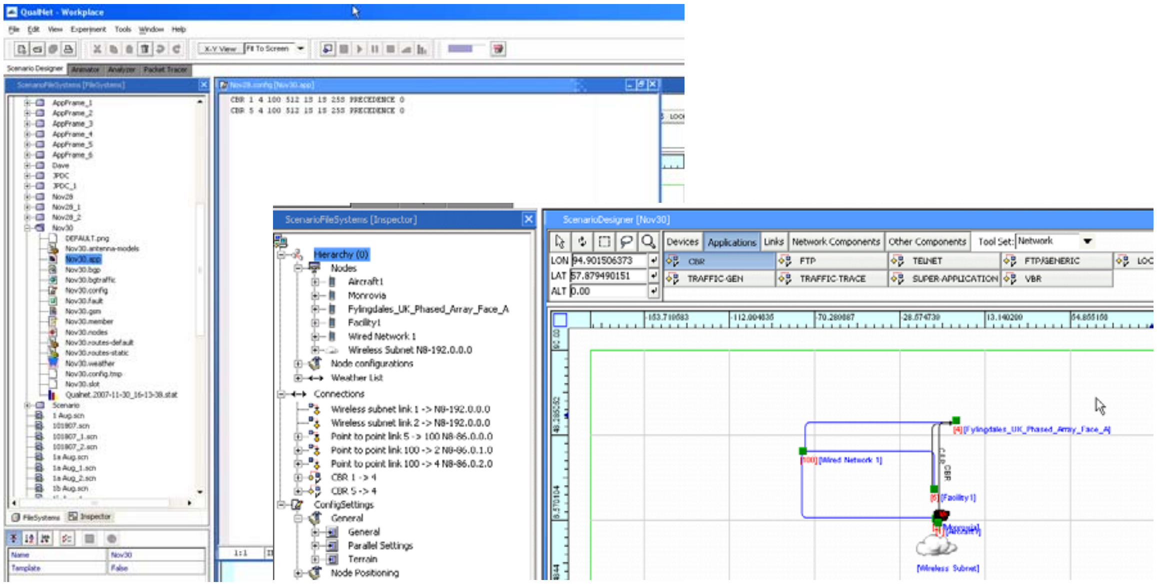


Figure 25 Invoking Applications

Figure 25 shows a constant bit rate application invoked through QualNet. The screen on the left shows the supporting application specification, characterized by the number of elements to be sent, the size of each element, the start time for the transmission, and the frequency at which elements are transmitted. There are also variable bit rate applications, and applications that correspond to industry standards such as IP or FTP.

This is the point of departure for different analysis paths suited to the problem of interest. The question is, "How are applications created that correspond to the communication relevant to the scenario?"

Day-to-day, communication among entities will be scheduled, generally arranged through interface control documents. There should be little or no contention among transmissions, and standard information transmission applied can be applied continuously or on a schedule. In this case, analysis completely within the communication network simulation environment is appropriate.

This is not what we are interested in. We seek responses to events whose evolution, if not their occurrence, is unplanned.

In this case, we let the STK physical layer prevail, employing the network simulation to impose constraints and processes above the physical layer. To do this we must confirm or arrange for the QualNet physical layer to be much less restrictive than the STK physical layer, and we use the fully constrained access reports to generate CBR applications only when all constraints (platform, sensor, and radar of transmitter/receiver) are met. This circumvents the complications of non-coincident object models and diversely distributed properties. We let one simulation environment or the other control the physical layer.

There are circumstances in which this approach is insufficient. For example, when the network schema exploits "cross layer" interactions in which route finding processes affect physical layer phenomena.

In this section we described the work flow and tools developed to examine the mission chain from event, through perception, to processing, communications, and actionable tracks. The next section presents a representative analysis.

REPRESENTATIVE ANALYSIS OF A DEBRIS EVENT

We demonstrate our analysis technique and work flow with the scenario previously described. It is, clearly, completely fictitious in order not to resemble in any way past events or any for which one might infer future capabilities. We intercept from Seattle a retrograde satellite in an elliptical orbit with 800 km apogee and 300 km perigee. We position sensor systems in Hawaii, Seattle, and Tel Aviv. Figure 26 illustrates the event shortly after intercept.

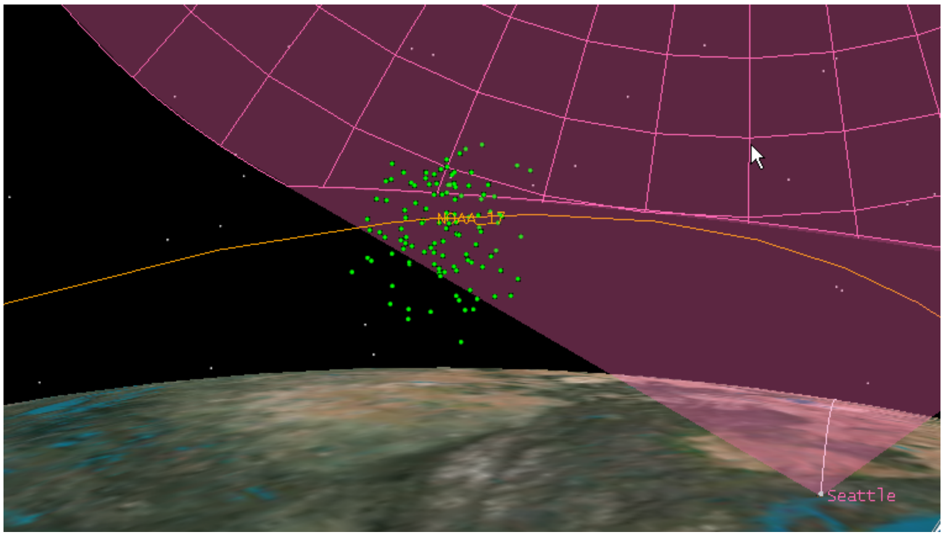


Figure 26 Debris environment shortly after impact

There are 114 debris fragments with radar cross sections from -5 dbsm to -20 dbsm.

There are many measures of effectiveness. For example, how long should it take for the entire system of sensors or any single sensor to perceive all of the debris particles? At what rate are observations accrued on a given object?

Figure 27 shows the epoch times at which accesses to the debris elements occurs.

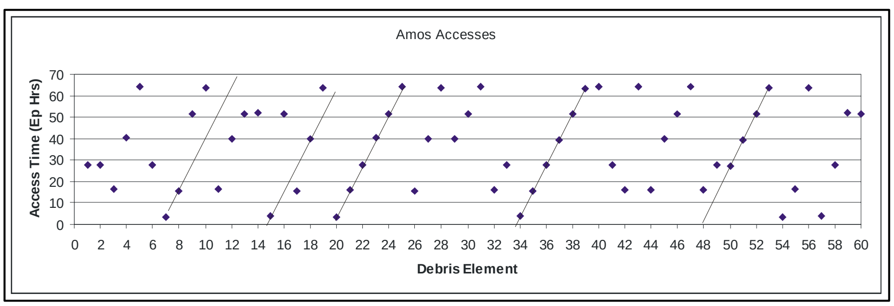


Figure 27 AMOS access to debris elements

Every one of the sixty largest objects can be observed within 70 hours of the event. However, many of these objects can be accessed only once during that interval. The reader can infer much more from this simple presentation. For example, object number 6, one of the largest is perceived only once, and that late in the interval shown. Depending on the duration of each access and the orbit determination scheme, generally there are not enough observations on most objects to determine a confident mean orbit. The value of this kind of analysis for anticipatory planning and contingency response is obvious.

Line of sight and volumetric coverage are necessary, but, as we show below, not sufficient to claim meaningful observation. Figure 28 compares unconstrained volumetric sensor access to the debris distribution compared to constraining access to abstracted radar constraints. We stress that this is not just filtering objects smaller than a prescribed threshold. The analysis invokes a rich set of constraints on the ability of a radar to perceive an object, including antenna characteristics, pulse integration, and energy distribution. Of course, this single sensor would never be sufficient to characterize and respond to this debris event. However, it is clear that the utility of this sensor could easily be overestimated.

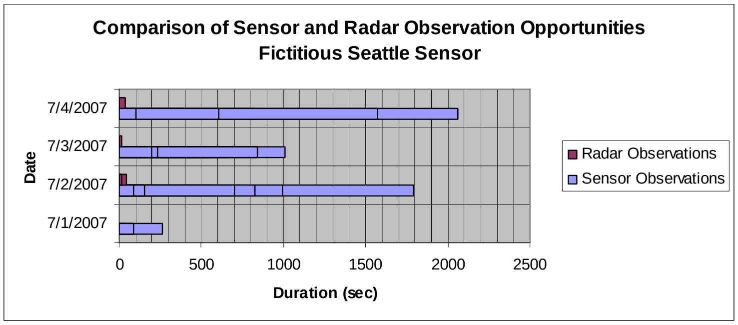


Figure 28 Sensor Only and Sensor with Radar Observation Opportunities

Next, we ask how well one could accrue observations of a single element of the debris field in order to characterize it and estimate its orbit. Figure 29 depicts sensor volumetric and radar constrained access to a single, large, persistent debris element.

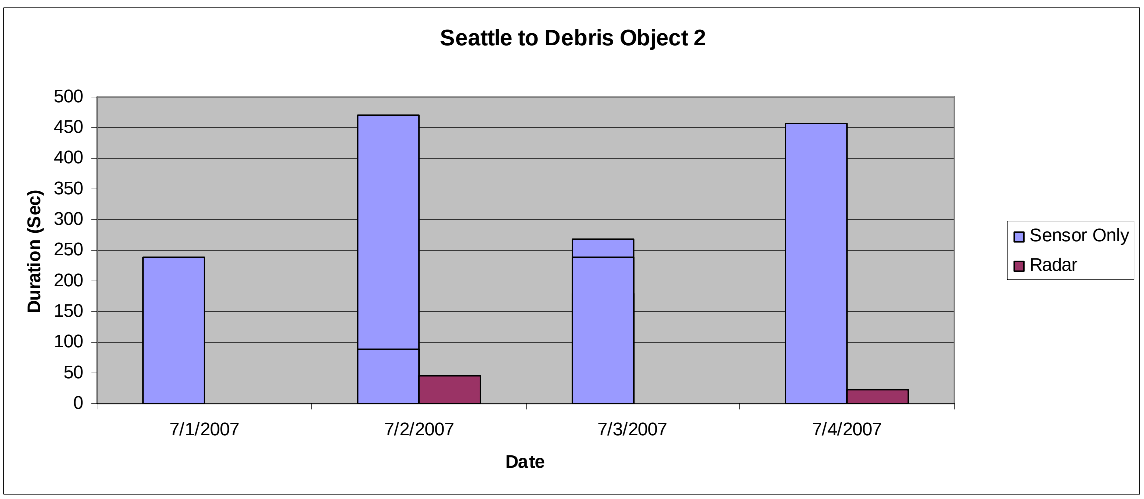


Figure 29 Possible versus Feasible Observations of a Single Debris Element

Sensor only observations are a set of possible data gathering opportunities, but data can be acquired only when radar constraints are met. We call this the feasible set. There is a great difference between possible and feasible.

The final question is, "How well can observations be communicated or shared?" Limited communication at the beginning of space surveillance is the major reason for the data transfer schemes we still use. How much more information could be shared today? How much more rapidly might analysts estimate orbits? The network simulation can answer these questions. Figure 30 and Figure 31 depict some of these outcomes.

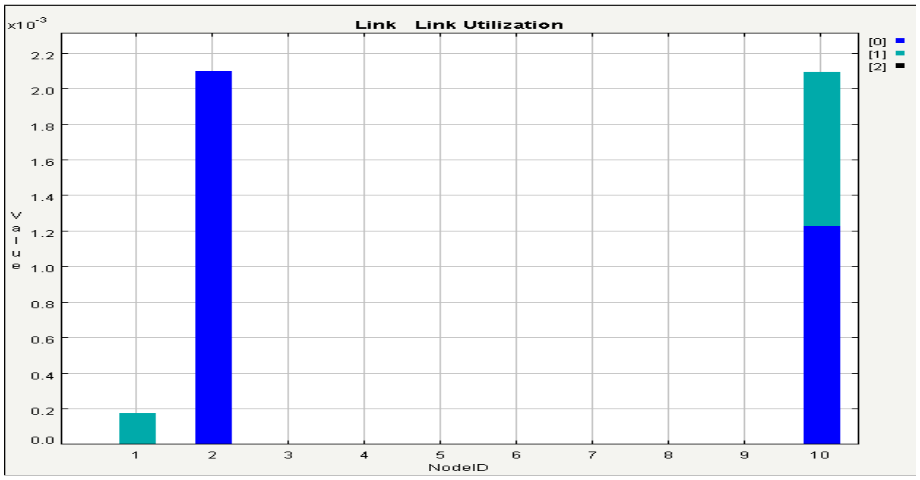


Figure 30 Link Utilization

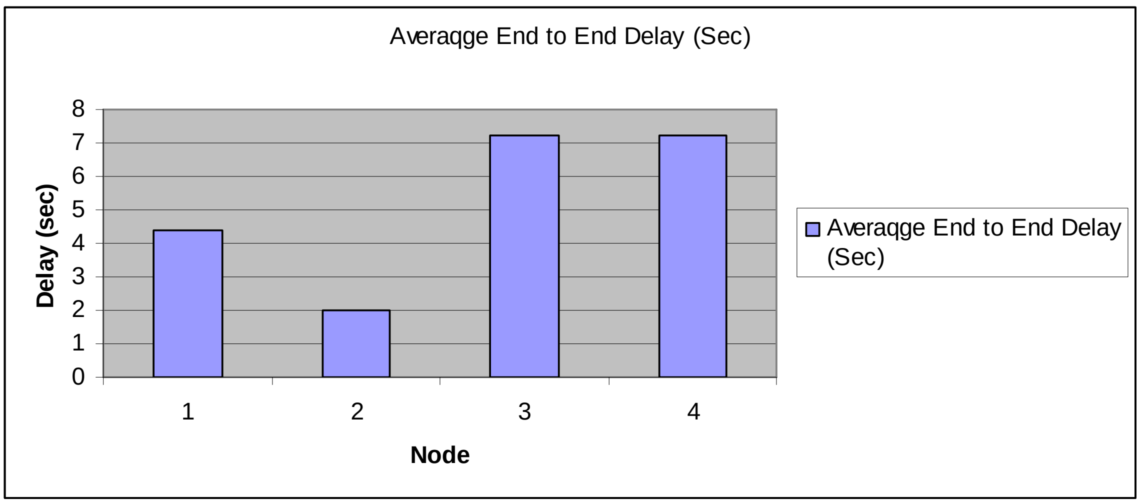


Figure 31 Latency

CONCLUSIONS

We have described a work flow and collection of analysis tools with which the capability of a space surveillance network against orbital debris events can be predicted. The procedure uses only commercial and Government off the shelf software. Our approach encompasses the entire mission sequence from event initiation, through detection, orbit estimation, communications, and mitigation planning. It should be useful for collaborative space surveillance and data sharing essential to safe and productive space observations. No tool set or process relieves the analyst of understanding the issue of interest. The manner in which simulation elements should interact depends on the nature of the problem.

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