Space Debris Birth to Death
Analysis from Concern to Consequences

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Abstract: We present the space debris operational process in the context of real circumstances that would have required early assessment, prompt warning, and responsive mitigations. We have applied several widely used collision and explosion models to the prompt debris environment, short term moderation of the debris cloud through reentry, mid-term assessment of conjunctions with operational satellites, and identification of the long term persistent aftermath. We provide distributions of fragment sizes, masses, and radar cross sections which we use to identify the trackable population and the remaining population which is either imperceptible to space surveillance radars. We examine predicted conjunctions between FY1C Debris (Catalog 31473)/Meteor 2-2, FY1C Debris (31379)/Meteor 2-12, and ISIS-2/Cosmos 2271. These illustrate early assessment of collision probability and consequences, triage among high probability conjunctions to conduct additional analysis judiciously, and the consequences of collisions between objects of disparate masses. We highlight deficiencies in essential analytical tools and databases. We offer guidance for further investigation and seek better capabilities to serve this important need.

Introduction: The purpose of this paper is to share our experience dealing with real events and debris environments for several years. Using trusted tools and techniques and the best data available to us, we have developed processes for perceiving encounters that might create dangerous space debris, assessing the consequences of those encounters, and developing plans to mitigate consequences. Working these tasks frequently and for several years, we have learned painfully the deficiencies in the array of models and simulations these tasks require. We have also developed mitigations, but not solutions, to insufficient and poor quality of orbit data. Many of the tools and techniques employed in this paper have been exposed in previous presentations and publications[1,2,3,4,5,6.]. We advise readers to consult those references for details.

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[1] Finkleman, D., Oltrogge, D.L. Faulds, A. and Gerber, J.., "Analysis of the Response of A Space Surveillance Network to Orbital Debris Events," Paper AAS 08-127, 2008 AAS/AIAA Astrodynamics Specialist Conference, Galveston, TX 27-31 January 2008.

[2] Finkleman, D. and Oltrogge, D.L., "Short Term Consequences of Orbital Debris Events (An Orbital Debris Toolset)," AIAA 2008-6777, AIAA/AAS Astrodynamics Specialist Conference, Honolulu, HI, August 2008.

[3] Oltrogge, D.L., and Finkleman, D., Consequences of Debris Events in Geosynchronous Orbit, AIAA 2008-7375, AIAA/AAS Astrodynamics Specialist Conference, Honolulu, HI, August 2008

[4] Kelso, T.S., and Alfano, S., "Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES), AAS 05-124, AAS/AIAA Space Flight Mechanics Conference, Copper Mountain, CO, Jan 2005

[5] Alfano, S., Collision Avoidance Maneuver Planning Tool, AAS-05-308, AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, August 2005

[6] Kelso, T.S., "Improved Conjunction Analysis via Collaborative Space Situational Awareness," Advanced Maui Optical and Space Surveillance Technologies Conference, Wimea, Maui, HI, September 2008.

This paper opens an important space debris operational research area, the world-wide, collaborative, real time response to any event that might impair space activity with debris. There is a significant body of work assessing long term collision risks in order to plan missions, accommodate potential evasive maneuver, and design for survivability.[7] Concerned satellite owner/operators embrace detailed analyses of threats to their own satellites[8]. Diligent operators are also sharing high quality, responsive orbit data to avoid encounters among themselves[9]. None take the broad, synoptic perspective or explore the consequences of the events should they occur.

The Debris Mitigation Sequence: The operational process begins with space surveillance and situational awareness. Assuming adequate surveillance and orbit data that it produces, one next examines the likelihood of conjunctions among orbiting objects. One then determines which events, if any, might have serious consequences. These are investigated in greater detail with estimates of the debris environment that might be created and the evolution of that environment during the critical first few days. This guides selecting courses of action. Many of the most serious events involve debris or inoperable satellites, some in orbit for decades. The only courses of action are in response to the environment the event might create, such as warning likely impact areas on the Earth or maneuvering satellites vulnerable to secondary collisions.

In our work, a conjunction is when two orbiting objects are in close proximity. How close is subjective, although a quantitative threshold may be established based upon the probability that the two objects will actually make contact. Contact between the two objects is a collision. Few conjunctions result in collisions. The degree of contact further qualifies each collision. Subsequently we explore the degree of "involvement" of each object that participates in a collision.

Unfortunately, space surveillance and situational awareness are not sufficient to support responsive debris operations. It is well documented that there are not enough sensors contributing to the process. Many potentially significant objects are not perceived by the sensors. Sensors do not report the number of observations necessary for confident orbit estimation with quantified uncertainty. Conjunction assessment and debris mitigation require more and better data than is currently produced.

There are many approaches to determining the significance of conjunctions. They all rely on the degree of uncertainty in the result as a consequence of imprecise measurements and models or hypotheses that unavoidably do not represent physics completely (measurement and process noise). Some satellite operators envelope the satellite most of interest within a three dimensional volume large enough to encompass the greatest uncertainty in orbit estimates. The uncertainty is inferred from experience rather than from measurement calibrations and extensive analysis of state significance. NASA encloses the space shuttle in a rectangular paralleliped 20x40x40 km. Any orbit that intersects this volume represents a potential collision. ESA's paralleliped is 20x50x20 km for the International Space Station (ISS) and the Automated Transfer Vehicle (ATV). These approaches aggregate in the keepout volume the uncertainties in all potential colliders. These approaches have also been developed for specific satellites at risk and do not apply well to other satellites. Another approach is to infer the 3x3 position covariance for each object and envelope each in that ellipsoid, taking ellipsoid tangency as the measure of risk. Simple algorithms reveal whether the ellipsoids touch without determining where they might touch. Finally, there are true probability based approaches that quantify the probability of body to body contact. These techniques recognize the pivotal significance of covariances. Lacking covariance information, they construct covariances without physical significance through statistical analysis of the history of two line element sets. CNES, the Aerospace Corporation, and AGI have made significant contributions to probability based

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[7] Klinkrad, H., Space Debris, Models and Risk Assessment, Springer-Praxis Publishing, ISBN 30540-25448, 2006

[8] Peret, L., Legendre, P., Delavault, S., and Martin, T., "Detection of orbital debris collision risks for the Automated Transfer Vehicle," 20th International Symposium on Space Flight Dynamics, Annapolis, MD, September 2007.

[9] Burzykowska, Anna, "The State of Space Security Workshop, January 24, 2008, A Summary Report," Space Policy Institute, Elliot School of International Affairs, George Washington University, Washington, DC, January 2008.

conjunction assessment for all satellites. The non-covariance-based techniques are exceptionally conservative and have a high false alarm rate. Maneuver decisions lacking covariance information and analysis are arguable and might increase risk.

The SOCRATES[10] technique for determining the probability of body-to-body technique developed by Alfano and Kelso is well described in the literature. Chan explains the underlying mathematics in his recent book[11]. If the statistics of the two bodies are independent, the covariance of one body with respect to the other in barycentric coordinates is the sum of the two independent covariances in the inertial frame. This reduces the problem to determining the volume of the combined covariance ellipsoid contained within a tube whose cross section is the maximum extent of one body circumscribed about the other. The fact that the event occurs rapidly with respect to changes in either orbital velocities or covariances makes the tube straight. This volume can be represented by a Rician Integral, and it appears often in communication research. But, we usually don't know the covariances. There is a value of the combined covariances for which the probability of body to body contact is a maximum. This requires no knowledge of the true covariances, but it is a very optimistic estimate. The true probability might be orders of magnitude less. Nonetheless, events with a high maximum probability are subjectively the most threatening.

Currently, SOCRATES determines the covariance independent maximum probability of body-to-body contact of objects whose osculating positions predicted by a suitable propagation technique are within a specified distance of each other. Any orbit data and propagator can be used. In its present form SOCRATES employs Two Line Element Sets and SGP-4 because most orbit data is provided in that formalism. The separation thresholds are 5 km in LEO and 50 km in GEO. SOCRATES applies over all orbit regimes. Actual probabilities can be estimated if covariances are specified. The probabilistic process is incorporated in the STK AdvCat utility. The reader must understand that the SOCRATES LEO product is the maximum probability that the two bodies would intersect if they were to pass within 5 km of each other. The mean orbits and osculating positions are uncertain. Regardless of the magnitude of measures of uncertainty (such as the one sigma deviation from the stated position), there is always a probability that they could suffer excursions greater than the separation between the orbits. This is a deep subject, and there is much literature and ongoing research. We refer the reader to the references for greater depth.

We also observe from continuing analyses of close approaches that covariances, whether inferred or stated, tend to place the encounter in the dilution region, where conjunction probability decreases with increasing covariance. This occurs because the locations of the satellites are so uncertain that the probability of their being in the same place at the same time is small. The rate of change of probability with combined covariance is much less in the dilution region than in the undiluted region, where conjunction probability decreases because we are very certain that the satellites stay close to their predicted locations. The real probability could still be several orders of magnitude less than the maximum probability although often still above the threshold for concern. Probabilities of 10^{-4} cause concern in LEO, and 10^{-7} is a common threshold of concern in GEO.

The potential consequences of collisions among satellites are widespread. Not only is there a prompt and pervasive debris environment, but there may be additional collisions with that debris. Some of the debris will reenter, and there will be risks on the surface of the Earth. Many fragments will persist for a very long time, increasing the long term risk to large satellites. Responding to potential collisions must consider the consequences.

The fundamentals of fragmentation have been obscured as interest in space debris grew even though that science predates space operations by more than a century. Ultimately, there is a great deal of empiricism, but the relationships among material or structural characteristics and fragment size and mass distribution are based on sound physical reasoning.

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[10] Kelso, T.S., and Alfano, S., "Satellite Orbital Conjunction Reports Assessing Threatening Encounters in Space (SOCRATES), AAS 05-124, AAS/AIAA Space Flight Mechanics Conference, Copper Mountain, CO, Jan 2005

[11] Chan, F.K., Spacecraft Collision Probability, The Aerospace Press, ISBN 978-1-884989-18-6, 2007

There are several regimes each of which requires different physical hypotheses: slow approaches in which only plastic deformation might occur, fast approaches in which induced stresses cannot be dispersed during the encounter period, and extremely hypervelocity encounters in which matter disassembles more rapidly than stresses can be created. These might be characterized by the ratio of the propagation speed for stress waves within the material and the relative velocity of the two objects.

The essential observation is that fracture and fragmentation occur as a stress relief mechanism. The energy of the fragments depends on strain energy stored in the materials as a result of the impact. Maximum entropy principles very similar to those in statistical mechanics reveal physical consequences confirmed by experiments such as the Poisson distributions of fragment sizes and the binomial distribution of likely fracture sites. The two most important underlying facts are that there is a fundamental minimum fragment size determined by the microscopic structure of the materials and that the size scale of larger fragments depends on the possible distribution of stress concentrations and fracture sites, determined by the characteristics of the overall structure. The distribution should be bimodal, the particular velocities of the fragments are due to strain energy release, and (at least for ductile materials) the fragment size distribution should have a definite cutoff at a minimum fragment size.[12] The approaches of Chobotov and Spencer and the NASA Evolve model as modified in our previous papers satisfy these observations.

We present the analysis process in the context of recent real world conjunction possibilities. Individual owner/operators can determine the vulnerabilities of their satellites and the risks they can bear better than anyone. Our perspective is synoptic. We are trying to mitigate debris in general, not protect an individual satellite. Therefore, we aggregate satellite fragmentation across all kinds of satellites through a generic fragmentation model. The tools and techniques we employ are representative. They have been best for us, but others will surely prefer other models. The work flow and observations we present are the result of having worked with these matters for several years. Some of our guidance is founded soundly on data and theory. Some is empirical, justifiably only because it has worked so far.

Long term propagation is also a problem. Two line element sets grow increasingly inaccurate the farther in the future they are propagated from their epoch. The positions and velocities predicted by TLE's are precise but very inaccurate. Most propagation schemes suffer numerical imprecision or require painfully small integration steps to retain accuracy. All techniques are inappropriate to estimate orbit lifetime based on long term propagation. Most orbit lifetime assessments use the rate at which orbital energy is dissipated due to nonconservative forces to bound orbit lifetime. Finally, reentry prediction is an immature science. The long term consequences of an event can only be handled through aggregated population analyses. Specific propagation such as that in SOCRATES is unsuitable for long term debris analysis.

The purpose of vigilance and assessment is to act in order to mitigate consequences. Often the objects that might collide are dead, and no direct mitigation is possible. In that case, the best we can do is to warn those who might be at risk, provide them with the best information possible, and burden them with deciding what to do. Occasionally one or both partners can be maneuvered. Techniques exist for determining the magnitude and direction of thrusts necessary to diminish the probability of collision within the time available. Figure 1[13] demonstrates the outcome in a specific instance. The presentation is very user friendly. Locii of constant total delta V are circles. The elliptical island contours are locii of constant probability for the geometry and orbits of interest. The intersections are the state changes necessary to achieve a given probability a given time from the predicted conjunction. In this case, the probability of conjunction would be approximately one in a thousand without maneuver. Maneuvers of 0.4 m/sec could lower the probability of collision by four orders of magnitude. This approach also gives the direction of the maneuver. There is little guidance for maneuver direction if covariances are not known. Some past maneuvers might have been in the wrong direction and increased collision probability rather than reduced

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[12] Grady, D.E. and Kipp, M.E., Dynamic Fracture and Fragmentation, Chapter 8, High Pressure Shock Compression of Solids, Asay, J.R., and Shahinpoor, M., eds, Springer-Velag, New York, 1993

[13] Alfano, S., Collision Avoidance Maneuver Planning Tool, AAS-05-308, AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, August 2005

it. The circular mound and the elliptical island intersect in a contour that encompasses a range of probabilities for the same delta V, depending on the direction of the thrust.

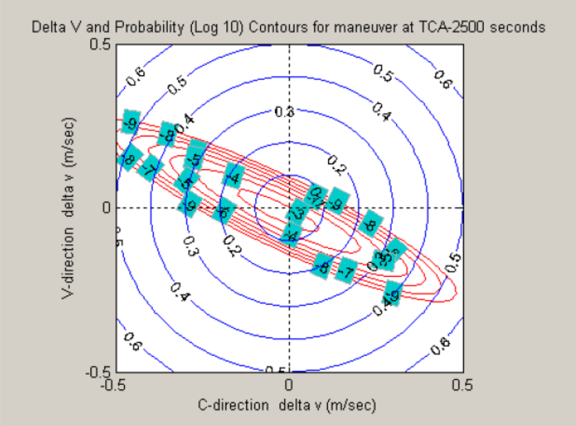
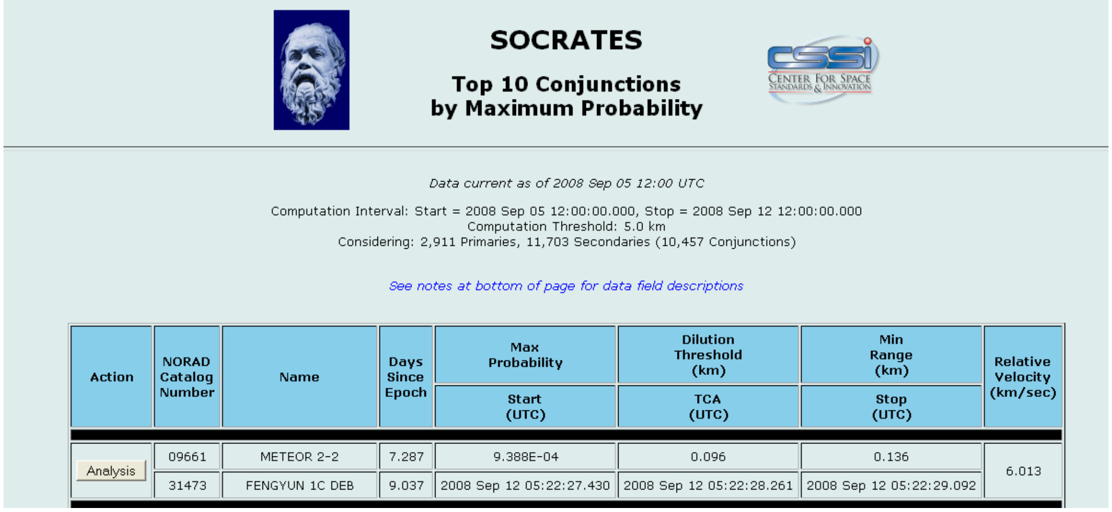


Figure 1: Two dimensional delta velocity required to achieve a desired probability of collision starting a specified time before the closest approach.

A Day in the Lives of Satellites:

Our day of conjunction analysis, 5 September 2008, begins with SOCRATES conjunction analysis. The conjunction with highest maximum probability is shown in Figure 2.   The highest probability conjunction involves Meteor 2-2 and Feng Yun 1C debris (Catalog Number 31473).



SOCRATES

Top 10 Conjunctions by Maximum Probability

Data current as of 2008 Sep 05 12:00 UTC

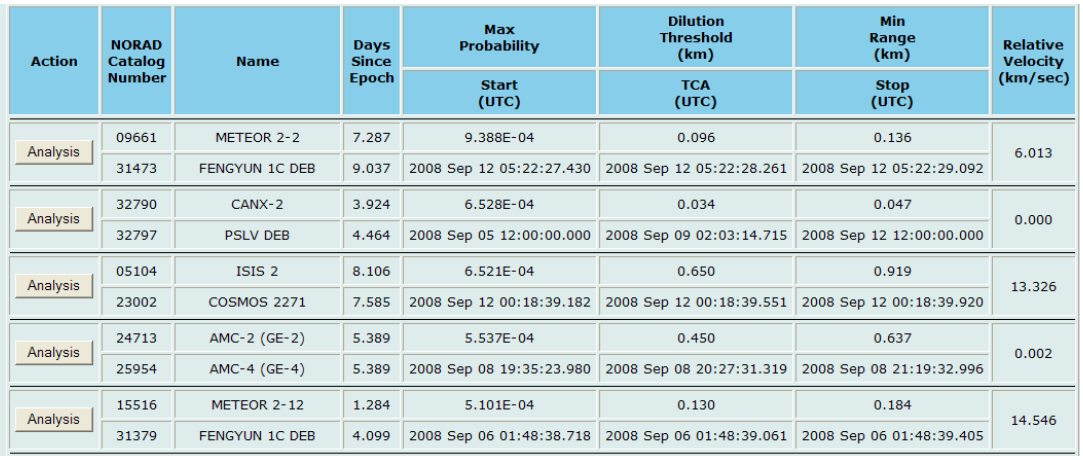
Computation Interval: Start = 2008 Sep 05 12:00:00.000, Stop = 2008 Sep 12 12:00:00.000
Computation Threshold: 5.0 km
Considering: 2,911 Primaries, 11,703 Secondaries (10,457 Conjunctions)

See notes at bottom of page for data field descriptions

Action	NORAD Catalog Number	Name	Days Since Epoch	Max Probability	Dilution Threshold (km)	Min Range (km)	Relative Velocity (km/sec)
				Start (UTC)	TCA (UTC)	Stop (UTC)	
Analysis	09661	METEOR 2-2	7.287	9.388E-04	0.096	0.136	6.013
	31473	FENGYUN 1C DEB	9.037	2008 Sep 12 05:22:27.430	2008 Sep 12 05:22:28.261	2008 Sep 12 05:22:29.092	

Figure 2: SOCRATES highest maximum probability conjunction on 5 Sep 2008

We interpret this information based on our experience with such events. The preponderance of high probability conjunctions occurs at high latitudes and in the Southern Hemisphere. This phenomenon occurs because high inclination satellite orbits “pinch” at high latitudes. Much persistent FY1C debris is also at relatively high inclination because FY1C was a meteorological satellite in Sun synchronous orbit. Next we recognize that most of these high inclination, Southern Hemisphere events involve FY1C debris and that such debris is probably much less massive than this Meteor (3800 kg). The supporting TLE’s are both more than a week old; hence the conjunction assessment is inaccurate. In addition, the dilution threshold for the combined covariance is very small, and the inaccuracy in the orbit propagated from TLE’s probably pushes the encounter farther into the dilution region, where the probability is smaller than the maximum. The location of the conjunction implies that promptly reentering objects will fall in the Pacific. Both collision partners are inactive. No missions will be directly compromised. The disparity in masses means that most of the debris will remain around the orbit of the Meteor. We conclude that despite being the highest maximum probability for this day, *the conjunction is not a strong threat and no action is necessary.*



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	31473	FENGYUN 1C DEB	9.037	2008 Sep 12 05:22:27.430	2008 Sep 12 05:22:28.261	2008 Sep 12 05:22:29.092	
Analysis	32790	CANX-2	3.924	6.528E-04	0.034	0.047	0.000
	32797	PSLV DEB	4.464	2008 Sep 05 12:00:00.000	2008 Sep 09 02:03:14.715	2008 Sep 12 12:00:00.000	
Analysis	05104	ISIS 2	8.106	6.521E-04	0.650	0.919	13.326
	23002	COSMOS 2271	7.585	2008 Sep 12 00:18:39.182	2008 Sep 12 00:18:39.551	2008 Sep 12 00:18:39.920	
Analysis	24713	AMC-2 (GE-2)	5.389	5.537E-04	0.450	0.637	0.002
	25954	AMC-4 (GE-4)	5.389	2008 Sep 08 19:35:23.980	2008 Sep 08 20:27:31.319	2008 Sep 08 21:19:32.996	
Analysis	15516	METEOR 2-12	1.284	5.101E-04	0.130	0.184	14.546
	31379	FENGYUN 1C DEB	4.099	2008 Sep 06 01:48:38.718	2008 Sep 06 01:48:39.061	2008 Sep 06 01:48:39.405	

Figure 4: Highest maximum probability conjunctions predicted on 5 September 2008

We move down the hit parade, examining each of the highest probability conjunctions in turn. The second highest involves the Canadian Nanosatellite Experiment (CANX), a microsatellite lofted by the Indian Polar Satellite Launch Vehicle (PSLV). These objects appear in the hit parade often. Their close proximity and negligible relative velocity imply that they are in an enduring metastable Hill's equation ellipsoidal oscillation. They are also small. This event is also not a concern. The next highest probability is ISIS 2 and Cosmos 2271. These are large objects but also both inactive. The TLE's are old, but the closing velocity is high. This event remains in consideration. The next highest probability event involves two satellites that are under active control and flying in formation. It is not a concern.

Finally, the Meteor 2-12/FY1C (31379) conjunction has a high closing velocity with an oblique geometry. This event has appeared before, but not recently. The TLE's are much fresher than those for the putatively highest probability event on this day. Meteor satellites are massive, and the closing velocity is highest on the list. The encounter is again over the Antarctic, so that prompt debris reentry may not be a serious issue. Both objects are dead, and no mitigating maneuvers are possible. The event will also not be observable, a particular deficiency given that most of the highest probability collisions occur over the Antarctic. Meteor 2-12 is massive (3800 kg).

It is also unfortunate that we do not know the mass of the FY1C debris fragment. Intense observation and orbit determination can reveal only the entire ballistic coefficient, inextricably connecting mass, atmospheric density, and projected area. However, past parametric analyses demonstrate that the average mass per fragment for collisions between two bodies of diverse mass varies little beyond the threshold of about 10 kg for the small collision partner[14]   We expect meaningful results for a fragment mass of 10 kg or greater.

Therefore, we focus first on this conjunction, which is the highest probability event with consequences that might be of concern. This is a subjective assessment, but it illustrates that every diligent operator must understand the limitations of the data and models he uses. Applying techniques and information without understanding the problem is wasteful and inefficient.

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[14] Finkleman, D. and Oltrogge, D.L., "Short Term Consequences of Orbital Debris Events (An Orbital Debris Toolset)," AIAA 2008-6777, AIAA/AAS Astrodynamics Specialist Conference, Honolulu, HI, August 2008.

Our work flow produces a wealth of pertinent information. According to our models and assuming 30% involvement of the large collision partner and 100% of the small one, we predict a total of 3787 fragments a few of which are massive as shown in Figure 4.

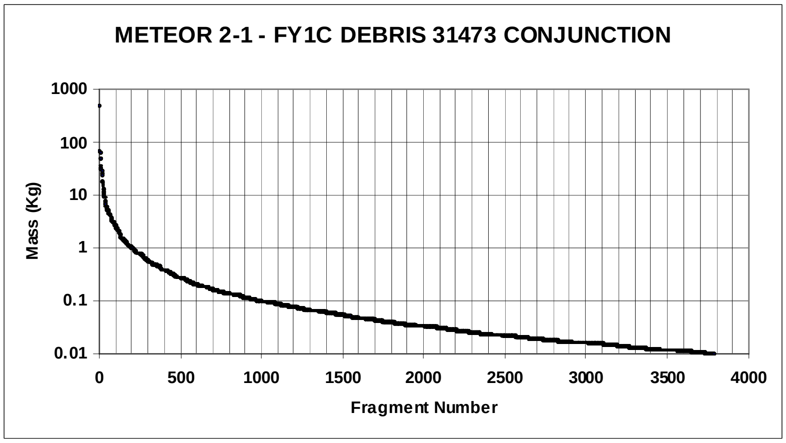

Figure 4: Meteor 2-1/FY 1C (31473) Fragment Mass Distribution

Figure 5 is the distribution of radar cross-sections predicted by the NASA RCS2Size model. The model is empirical, and it aggregates data over all reasonable radar bandwidths. A large fraction of the debris population is unobservable with current radars in normal operating modes (threshold of -20 dbsm at 1000 km).

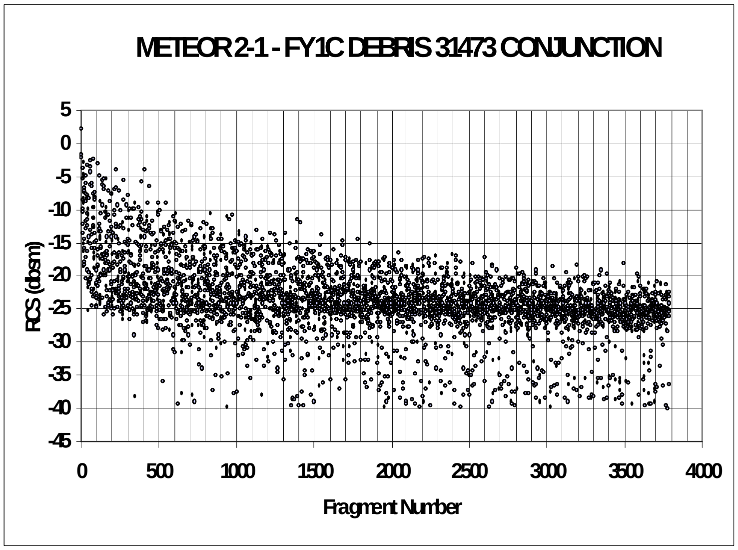

Figure 5: Meteor 2-1/FY 1C Fragment Radar Cross Section Distribution

Subsequent close approach analyses shows that no active satellites are threatened in the near term. Therefore, our only action is vigilance.

We return to the ISIS-2/Cosmos 2271 event, which we temporarily triaged because its supporting TLE's were old. Although the probability of conjunction is not the highest for the day, and given the age of the TLE's is likely not as high as the Meteor 2-12 event, this conjunction involves two satellites, not just a satellite with a piece of debris. ISIS-2, launched in 1971, mass is 264 kg. Cosmos 2271, launched in 1991, is massive, 6600 kg. This event is likely to have the greatest consequence within the hit parade.

Figure 6 shows the consequences of the ISIS-2/Cosmos 2271 collision assuming Cosmos 20% involved and ISIS 30% involved. We predict 6336 fragments, one of which has a mass of 1864 kg. 1016 fragments reenter in less than one revolution but 4264 have lifetimes greater than six months. The dense ring contains mainly fragments from the involved elements of the satellites. The lighter, less dense rings are debris from the uninvolved elements of both satellites.

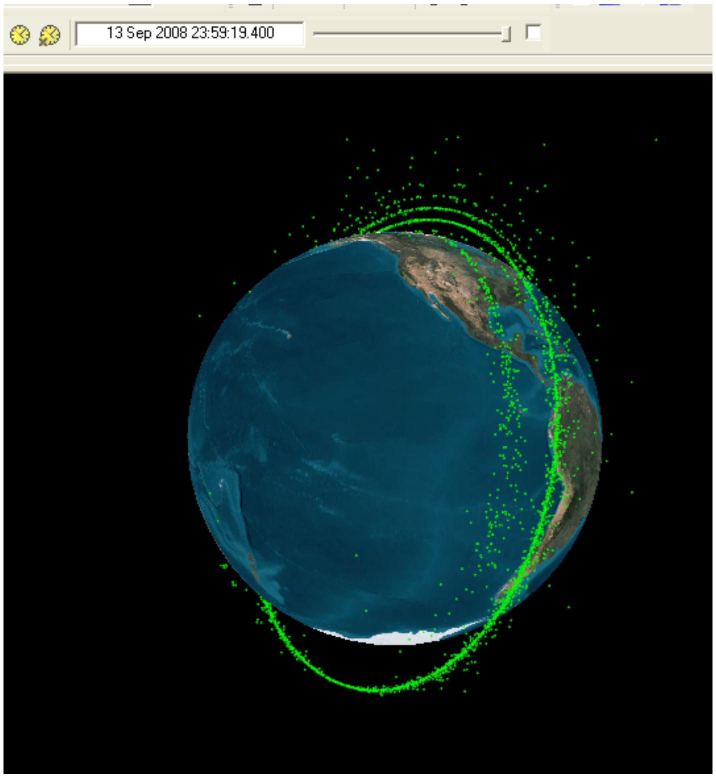

Figure 6: ISIS-2/Cosmos 2271 Consequences approximately 36 hours post collision.

Figure 7 is the Gabbard plot for this event. It is characteristic of the collision of objects of diverse mass. Much of the debris is injected into highly eccentric orbits. The apogees of fragment orbits cluster around Cosmos 2271 altitude.

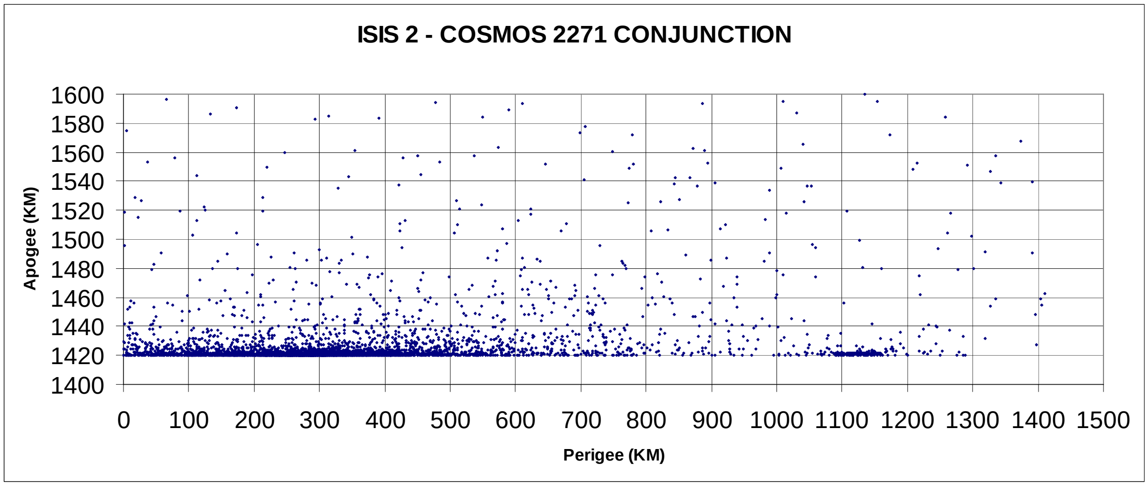

Figure 7: Gabbard (Apogee-Perigee) Plot for the ISIS-2/Cosmos 2271 Conjunction

RCS analysis predicts that 1586 fragments very likely would be unobservable with current systems, including several masses greater than 1 kg.

Figure 8 shows the space surveillance network opportunities to observe the largest fragment got the first two post-event revolutions. The sequence of observations is: Cobra Dane, Clear (each face in turn), Thule, Globus II, PARCS, Cape Cod, Millstone Hill, …

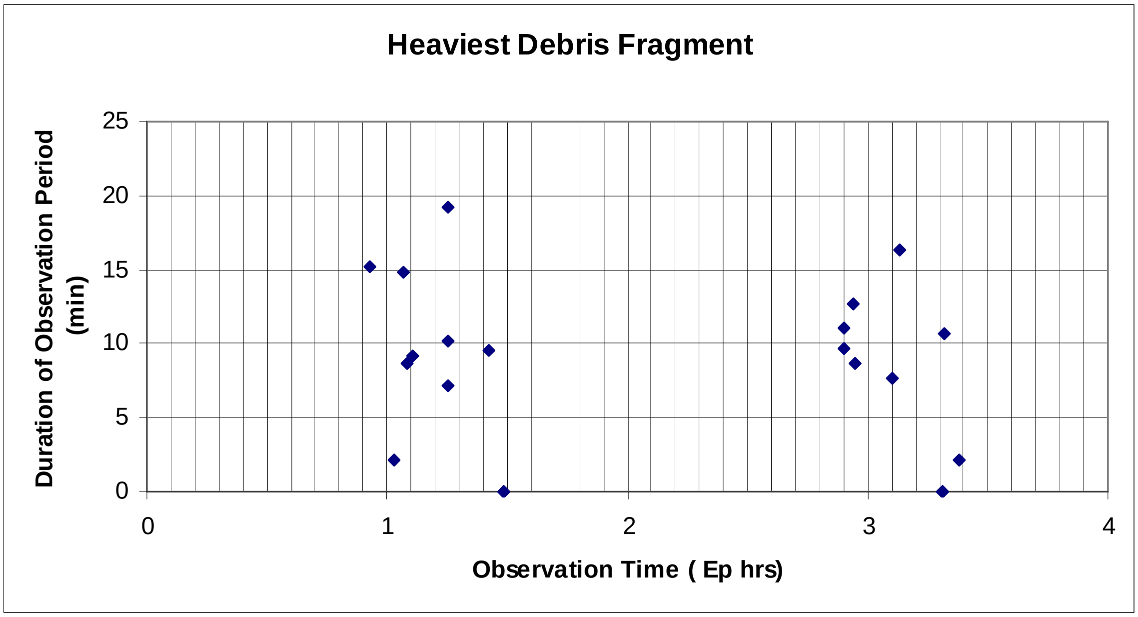

Figure 8: Perception of the most massive fragment of the ISIS-2/Cosmos 2271 Conjunction

Since there are so many massive fragments and more than a thousand fragments reenter promptly, we trace the paths of reentering objects to identify regions on the Earth most at risk. Figure 9 identifies those areas.

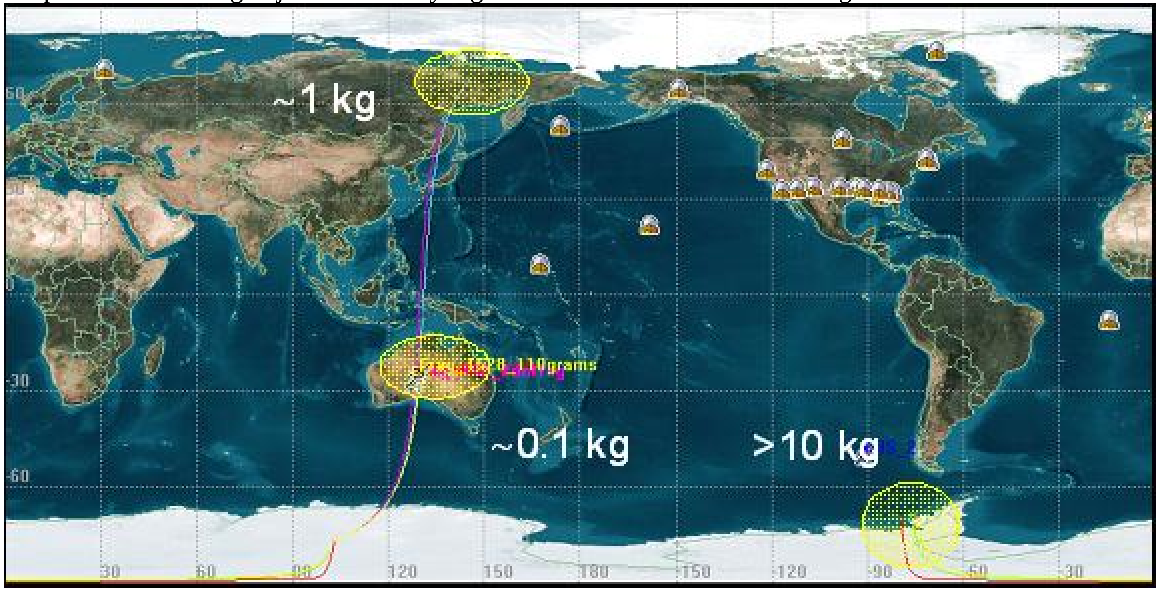

Figure 9: Areas at risk from prompt reentry of fragments from the ISIS-2/Cosmos 2271 Conjunction

Conclusions:

These few representative analyses illustrate the importance of understanding the limitations of the process. We have found that the highest maximum probability conjunctions are not always the greatest threats. We have learned that the probability estimates must be interpreted considering the age of supporting TLE's, the location of the conjunction, the characteristics of the two objects, and several other practical factors. We also observe that such events produce significant numbers of reasonably massive fragments that will not be perceived. Our actions should reflect the existence of this phantom population.

We have demonstrated an operational process to deal with space debris from birth to death. Few if any debris mitigation and management guidelines can be implemented or verified without such tools. We are confident that many readers would choose other propagation and debris generation approaches, but none have yet appeared in this synoptic context to the best of our knowledge. Very, very few estimated conjunctions actually occur. We are confident that the outcome of those that do will not map directly onto our predictions. However, the approach we present can provide guidance for dealing with future events as well as incentive for further research.