SPACE SURVEILLANCE:

LESSONS LEARNED FROM THE IRIDIUM-COSMOS COLLISION

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ABSTRACT

On 2009 February 10, Iridium 33 (an operational US communications satellite in low-Earth orbit) was struck and destroyed by Cosmos 2251 (a long-defunct Russian communications satellite). This is the first time since the dawn of the Space Age that two satellites have collided in orbit. Working directly with Iridium and the US Strategic Command to recreate, analyze, visualize, and deconflict future probable collisions from the expanding clouds of debris, the AGI-CSSI team has gained new insights into the threats and mitigation techniques for this very real problem.

To better understand the circumstances of this event and the ramifications for avoiding similar events in the future, this paper provides a detailed analysis of the predictions leading up to the collision, and it looks in detail at the collision, the evolution of the debris clouds, and the long-term implications for satellite operations.

The only public system available to satellite operators for screening for close approaches, SOCRATES, did predict this close approach, but it certainly was not the closest approach predicted for the week of February 10. Our analysis includes limitations of screening close approach events using two-line element sets and specific examples for the Iridium constellation of how current limitations affect decision making for satellite operators.

Analysis of the collision event, along with the distribution of the debris relative to the original orbits, will be presented to help develop an understanding of the geometry of the collision and the near-term evolution of the resulting debris clouds. Additional analysis will be presented to show the long-term evolution of the debris clouds, including orbital lifetimes, and estimate the increased risk for operations conducted by Iridium and other satellite operators in the low-Earth orbit environment.

The final portion of the paper will look at how collaborative efforts, such as the current Data Center operations supporting SOCRATES-GEO and SOCRATES-LEO, might be used to reduce the overall risk of similar events in the future.

1. INTRODUCTION

In the report issued 2009 February 10 at 15:02 UTC, SOCRATES [1] predicted a close approach of 584 m between Iridium 33 and Cosmos 2251. This was not the top predicted close approach for that report or even the top predicted close approach for any of the Iridium satellites for the coming week. But, at the time of predicted close approach (16:56 UTC), Iridium 33 suddenly went silent. The US Space Surveillance Network (SSN) subsequently reported that they were tracking debris clouds in both the Iridium 33 and Cosmos 2251 orbits, confirming a collision.

This is the first time two satellites are known to have collided on orbit. While Cosmos 2251, a Russian communications satellite, is thought to have ceased operations about two years after it was launched in 1993, Iridium 33 was part of the operational Iridium constellation of 66 satellites at the time of the collision.

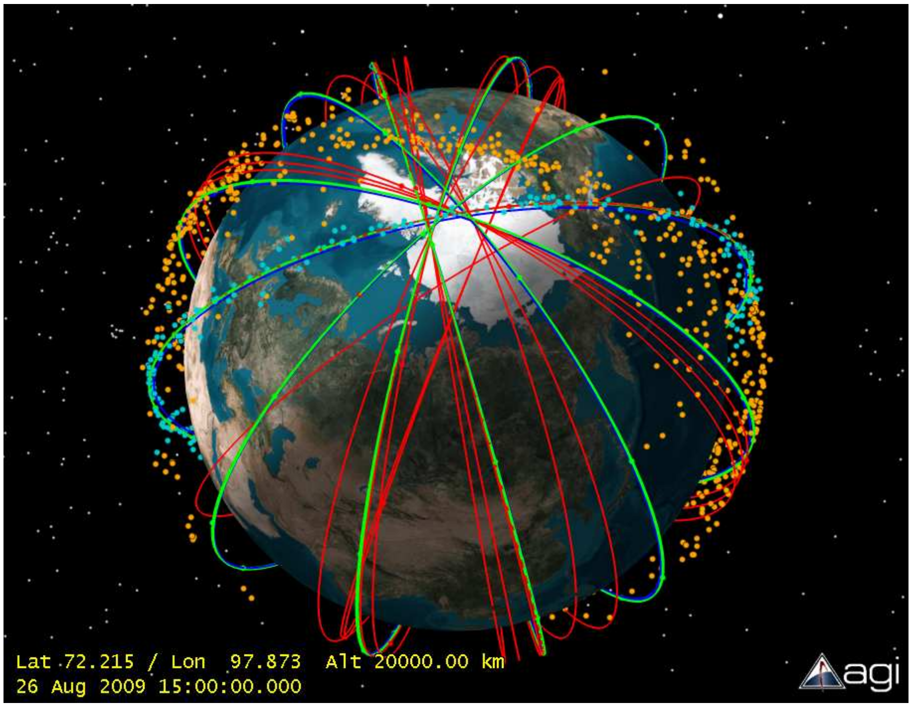

Fig. 1. Current Iridium Constellation and Collision Debris Clouds.

As of 2009 August 26, the SSN has cataloged 406 pieces of debris (16 pieces of which have already decayed from orbit) associated with Iridium 33 and 960 pieces of debris (32 pieces of which have decayed) associated with Cosmos 2251. Fig. 1 is provided to give a sense of the current relationship between the Iridium constellation and the resulting debris clouds. It shows the current Iridium constellation with the orbits for the operational satellites shown in green, the spares shown in blue, and the inactive satellites shown in red. The Iridium 33 debris is shown in light blue and the Cosmos 2251 debris is shown in orange.

2. TRACKING A COLLISION

There has been much discussion about why this collision wasn't reported in SOCRATES or why Iridium didn't act on the information provided in SOCRATES. In reality, SOCRATES did predict a close approach between Iridium 33 and Cosmos 2251 at the time of the actual collision in each of the 14 reports in the week leading up to the event. None of these, however, made the Top Ten list. It is instructive to see just what SOCRATES reported to help understand the limitations of the data used by that system and what needs to be done to improve these types of screenings. Starting with the report on February 4 at 04:01 UTC and continuing right up to the report issued on February 10 at 15:02 UTC, SOCRATES did predict a close approach between Iridium 33 and Cosmos 2251 at between 16:55:59.670 and 16:55:59.990 UTC. As can be seen in Fig. 2, the predicted close approaches ranged from 117 m to 1.812 km over that interval.

That graph shows the predicted minimum range for the closest conjunction in each report, the closest Iridium conjunction, the closest Iridium 33 conjunction, and the conjunction with Cosmos 2251. The variability of the predictions over the week before the collision speaks to the inherent uncertainty in the two-line element set (TLE) data used to make the predictions. While Report Number 5 (February 6 at 04:02 UTC) did predict a close approach of 117 m, the predicted close approach grew to 1.243 km the very next day.

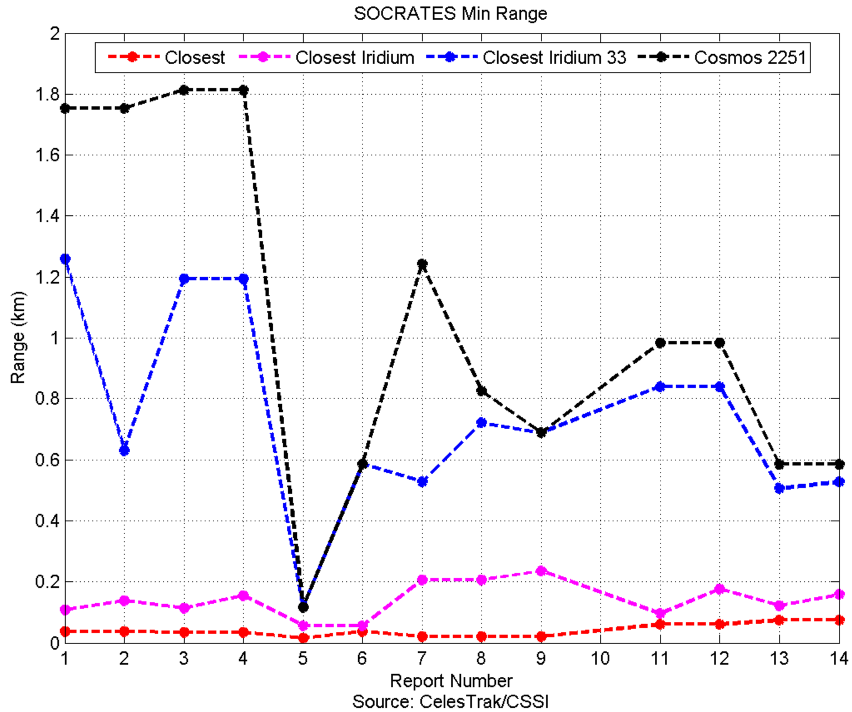

Fig. 2. SOCRATES Min Range.

In fact, as can be seen in Fig. 2, the Cosmos 2251 conjunction is not even the closest predicted conjunction for Iridium 33 in most of the reports, much less for the entire Iridium constellation. Looking at the relative rankings of these conjunctions can help understand the limitations in using conjunction reports based on data as inaccurate as the TLEs.

Fig. 3 shows the rankings in each SOCRATES report for the Iridium 33-Cosmos 2251 conjunction in the total report, against all Iridium conjunctions, and for all Iridium 33 conjunctions. Over the 14 reports, the overall ranking ranges from a low of 1,611 in Report Number 3 to a high of 11—again just the very next day. At the time of the collision, it was ranked 152 overall.

Looking at the rankings against all Iridium conjunctions gives a sense of the magnitude of the problem for Iridium—or any satellite operator—in trying to screen with TLEs. The Iridium 33-Cosmos 2251 collision ranges from a low ranking of 149 in Report Number 3 to a high ranking of 2 in Report Number 5, with an average ranking of 64. Over this interval, Iridium 33 saw between 10 to 15 times each week when something was predicted to come within 5 km of it—out of the 1,007 to 1,095 such predicted conjunctions for the entire Iridium constellation. Determining that the predicted conjunction for Iridium 33 and Cosmos 2251 was more significant than the many dozens of other Iridium conjunctions for that week is simply not possible using the TLE data.

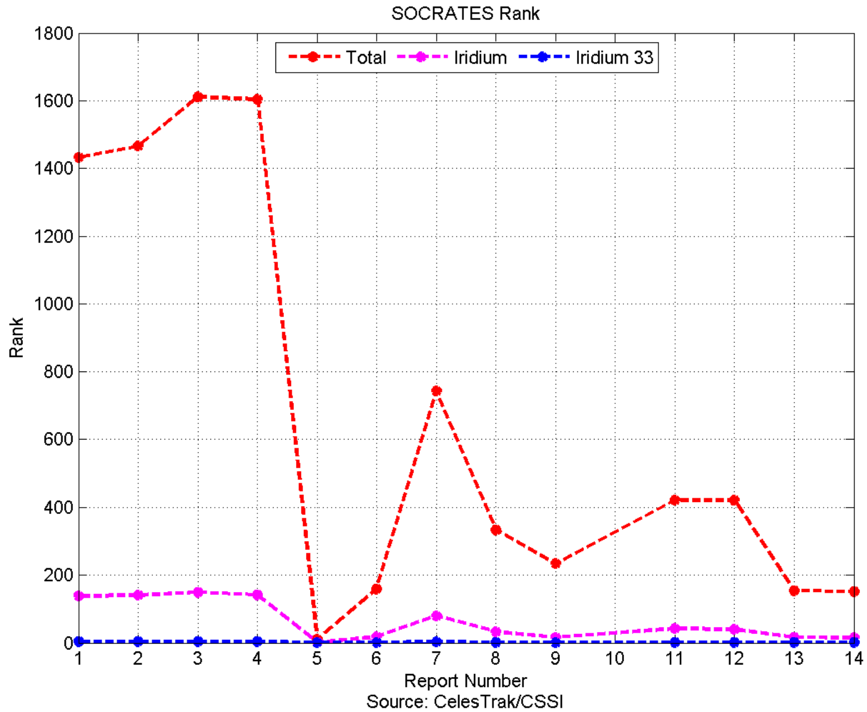

Fig. 3. SOCRATES Rank (All).

So does that mean it isn't possible to provide meaningful conjunction screening for satellites operators? No. SOCRATES was actually set up to demonstrate several key points:

- That it is possible, using off-the-shelf software, standard orbital data, and basic computer hardware to automatically screen large numbers of satellite (over this interval, we screened 2,946 payloads against between 11,761 and 11,848 total objects) and provide access to the reports via a standard web interface.

- To help people understand that close approaches with satellites in Earth orbit are not uncommon events. Over the period examined here, between 11,169 and 11,493 conjunctions were reported each week—over 1,600 times a day. Even though each conjunction has a low probability of occurrence, over time, a collision with an operational satellite was bound to happen.

- To illustrate the need for better data to reduce the uncertainty in conjunction predictions, thereby enabling satellite operators to work to protect their assets. Better data is available—directly from satellite operators and from the US and other governments. Our SOCRATES-GEO effort [2] has shown the advantages of operators working together and sharing their best orbital data to reduce risks of collisions, but a more open data sharing policy and wider participation is needed to make this process even better.

3. ANATOMY OF A COLLISION

The following figures illustrate the geometry of the collision of Iridium 33 and Cosmos 2251.

Fig. 4 shows the orbital geometry just at the time of the collision (based on the predicted time of closest approach in the last SOCRATES report) at 16:55:59.806 UTC. In this figure, Iridium 33 is moving from the bottom to the top of the image, while Cosmos 2251 is moving from the upper left to the lower right. It can be seen that the objects collided at nearly right angles over northern Russia.

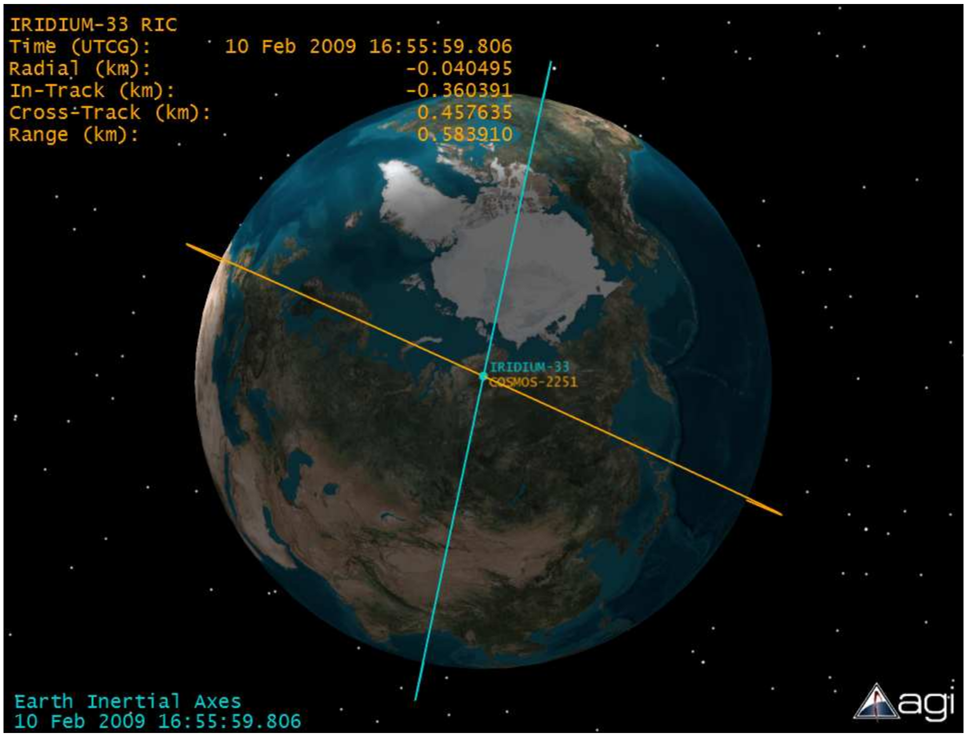

Fig. 4. View of Iridium 33 and Cosmos 2251 Orbits at Time of Collision.

Fig. 5 shows the initial evolution of the debris cloud just 10 minutes later. This figure uses the first TLEs released by Air Force Space Command as each debris piece was added to the public catalog. Since not all of the debris lines up well at the time of the collision due to limitations of the data (e.g., some of the pieces were just cataloged and are being propagated backward several months), the data was filtered to only show those objects within 100 km of the original parent objects at the time of the collision. That left 209 of the 406 pieces of Iridium 33 debris and 553 of the 960 pieces of Cosmos 2251 debris (762 of the total 1,366 pieces of debris).

Fig. 6 shows the evolution of the debris clouds 180 minutes post-collision, almost two revolutions later. The spread of each debris cloud around its respective orbit is already becoming apparent.

In an attempt to develop a better understanding of the actual collision geometry for this event, a 3D plot was generated of the relative velocities of each piece of debris with respect to its parent object using Satellite Tool Kit (STK). Fig. 7 provides a static view of the result.

Examination of the interactive 3D scenario shows large out-of-plane relative velocity components, the apparent result of coupling of the two masses, despite the hypervelocity nature of the collision. There are also a large number of pieces of Cosmos 2251 debris with significant radial (downward) relative velocities, although it is not apparent why this situation would be the case. It is hoped that the availability of this data set will help researchers with expertise in hypervelocity impacts develop a more complete description of the collision geometry for this event.

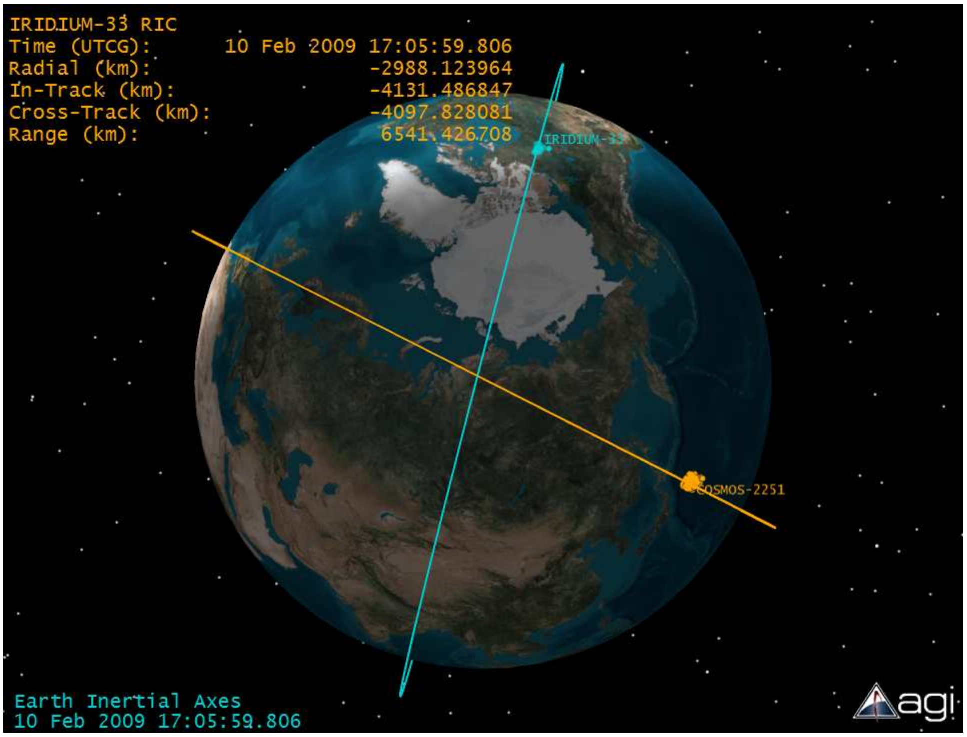

Fig. 5. View of Iridium 33 and Cosmos 2251 Debris 10 Minutes Post-Collision.

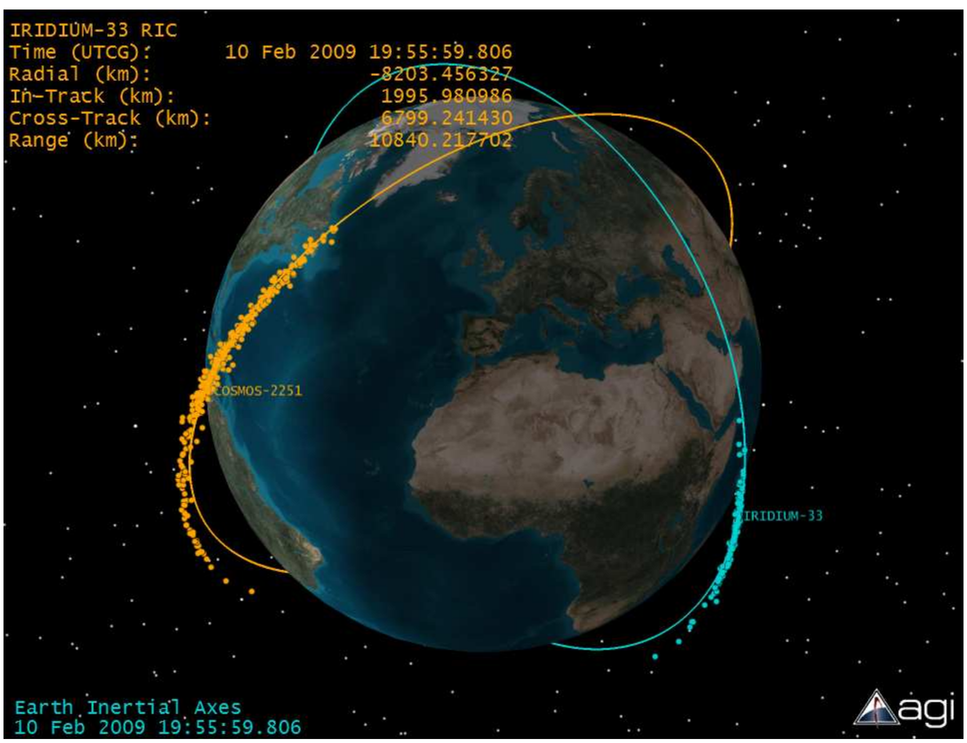

Fig. 6. View of Iridium 33 and Cosmos 2251 Debris 180 Minutes Post-Collision.

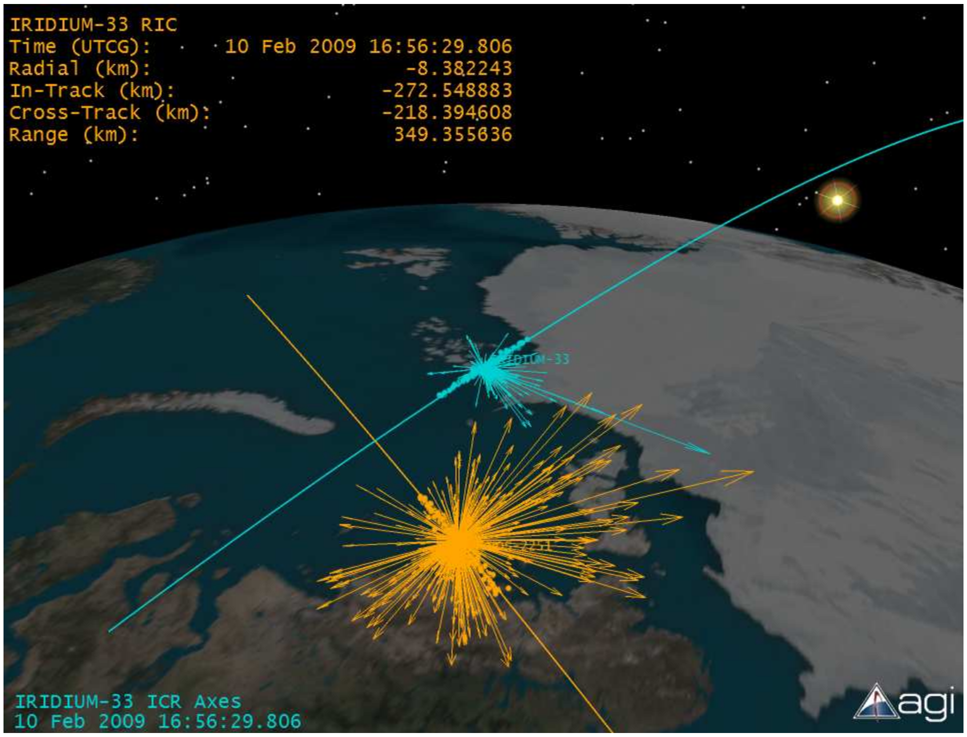

Fig. 7. 3D Plot of Debris Relative Velocities.

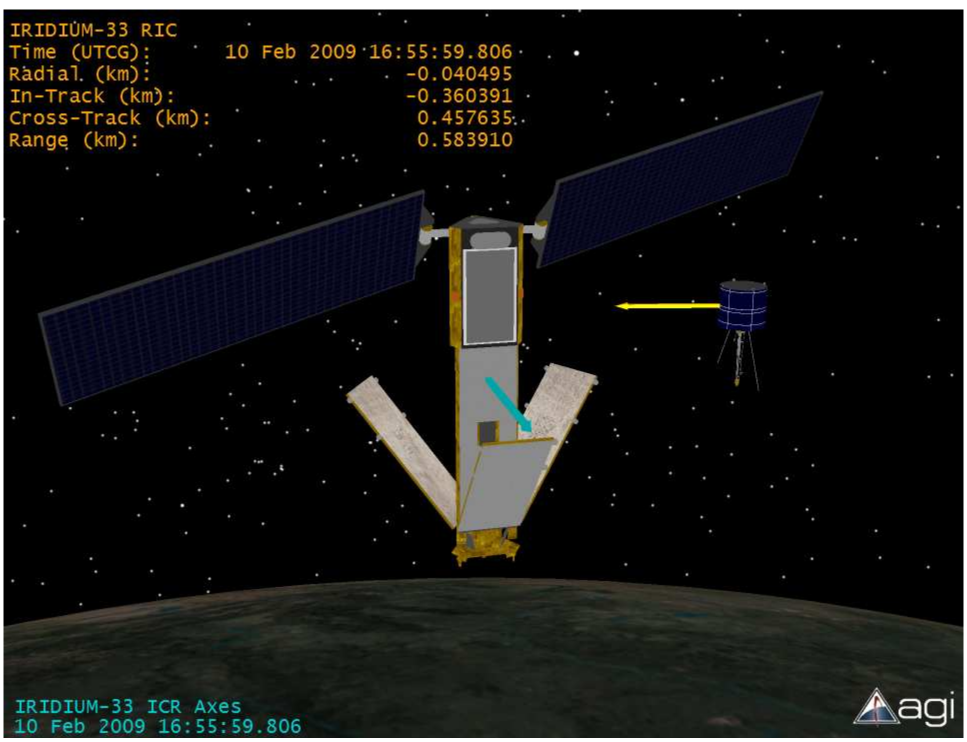

Fig. 8. View of Iridium Satellite Showing MMAs (Bottom).

Video captured by Kevin Fetter [3] on 2009 March 12 provides additional insight into the collision geometry for this event. His video shows the main piece still associated with Iridium 33 in the SATCAT (NORAD Catalog Number 24946) followed by the inactive Iridium 28 satellite. The double flashes from Iridium 33 suggest that at least two of the MMAs (Main Mission Antennas, seen at the bottom of the satellite in Fig. 8) on that object survived the collision relatively intact.

The video was taken from Brockville, Ontario, Canada (44.6062 N, 75.6910 W) looking at 8h 45m RA, +04° 56' Dec between 00:54:03 and 00:54:26 UTC. Detailed analysis of the video verifies the basic conditions of this observation, including that the necessary visibility conditions were satisfied.

4. IMPACT ON THE SPACE ENVIRONMENT

Loss of the Iridium 33 satellite and its near-term impact on users of the Iridium constellation, while significant, only hints at the long-term implications of this event. A search of SOCRATES on 2009 August 5 shows 154 conjunctions (within 5 km) between the 66 operational and 8 spare Iridium satellites and Iridium 33 debris and another 33 conjunctions between the 30 operational and 6 spare Orbcomm satellites and Iridium 33 debris, over the upcoming 7-day period. Looking at Cosmos 2251 debris, there are a further 334 conjunctions with Iridium satellites and 108 with Orbcomm satellites. And there are many other satellites which operate in this orbital regime seeing similar increases in the number of conjunctions, as well.

Unfortunately, the problem will not be getting better any time soon. Fig. 9 and 10 show the distribution of the debris clouds for Iridium 33 and Cosmos 2251, respectively. Each dot represents the apogee and perigee height of each object listed in the public catalog on 2009 August 26. Objects just below the 800-km apogee line (horizontal) represent objects which were knocked into lower orbits as a result of the collision, while those just to the left of the 800-km perigee line (vertical) represent objects which were knocked into higher orbits. More of the Iridium 33 debris appears to have been knocked into higher orbits while more of the Cosmos 2251 debris seems to have been knocked into lower orbits.

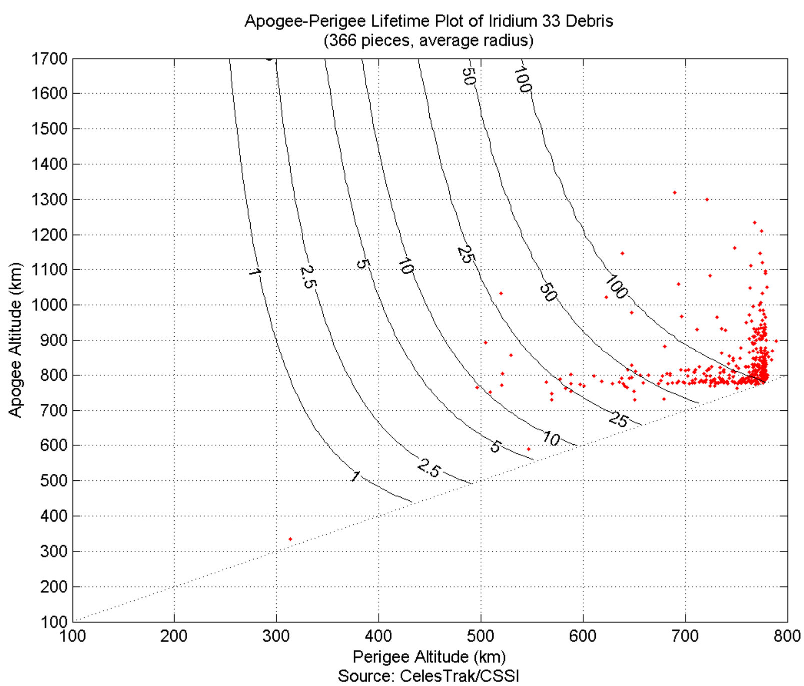

Fig. 9. Apogee-Perigee Lifetime Plot of Iridium 33 Debris (Average Size).

Overlaid onto the plots of orbital distributions are contours of the expected orbital lifetime values (in years) for objects with the same average physical characteristics. Objects to the left of the first contour should decay within 1 year of 2009 August 26 while those to the right of the last contour are predicted to be in orbit 100 years from now.

For the Iridium 33 debris, over half of it is beyond the 100-year contour. For the Cosmos 2251 debris, several dozen pieces (beyond those which have already decayed) should reenter in the next couple of years, but significant numbers will likely remain in orbit 25–50 years from now.

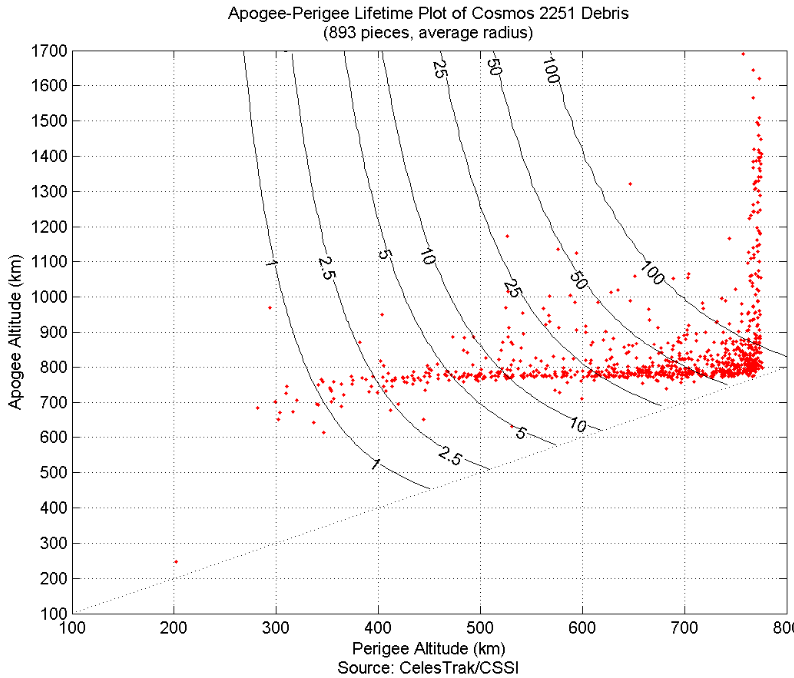

Fig. 10. Apogee-Perigee Lifetime Plot of Cosmos 2251 Debris (Average Size).

These contours are based on the average characteristics of the objects cataloged to date. To determine those characteristics, the overall dry mass and volume of each original object, Iridium 33 and Cosmos 2251 (as shown in Table 1), was used to compute the average mass and volume of the resulting debris.

Table 1. Pre-Collision Satellite Characteristics.

Satellite	Number of Pieces	Total Volume (m^3)	Dry Mass (kg)	Inclination (deg)
Iridium 33	406	3.388	556	86
Cosmos 2251	960	7.841	900	74

Interestingly enough, the average volume yields an almost identical size of 12.5 cm radius for the Iridium 33 debris and 12.6 cm radius for the Cosmos 2251 debris (likely a result of the limiting sensitivity of the radar sensors in the US Space Surveillance Network). The average masses are also close, with the average being 1.369 kg for Iridium 33 debris and 0.938 kg for Cosmos 2251 debris (consistent with the original average densities of the two spacecraft). The orbital lifetime contours were generated using the Lifetime Tool in Satellite Tool Kit (STK). The average area-to-mass ratios resulting from the data in Table 1 (assuming the objects to be spherical) were used together with a grid of orbits, each of which were initialized for the selected apogee and perigee (using the inclination from Table 1), and assuming the argument of perigee, right ascension of the ascending node, and mean anomaly were all zero (sensitivity analysis of these assumptions showed measurable differences but did not significantly affect the overall results). A coefficient of drag of 2.2 was assumed for all calculations.

As was done in our analysis of the Chinese ASAT test debris [4], the Jacchia-Roberts atmospheric model was used (again after performing sensitivity analysis on the results). The latest Schatten predictions from March 2009 through

May 2039 were used to estimate future space weather conditions. Orbital lifetime predictions were evaluated looking forward 150 years (which means the Schatten predictions were repeated, as needed, to span this interval).

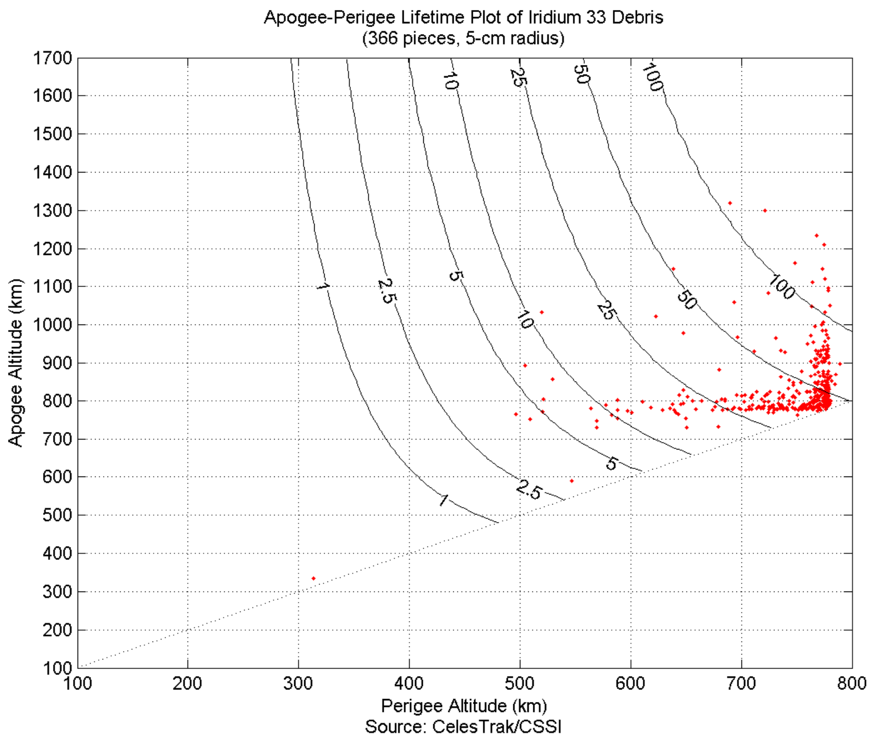

Fig. 11. Apogee-Perigee Lifetime Plot of Iridium 33 Debris (5-cm Radius).

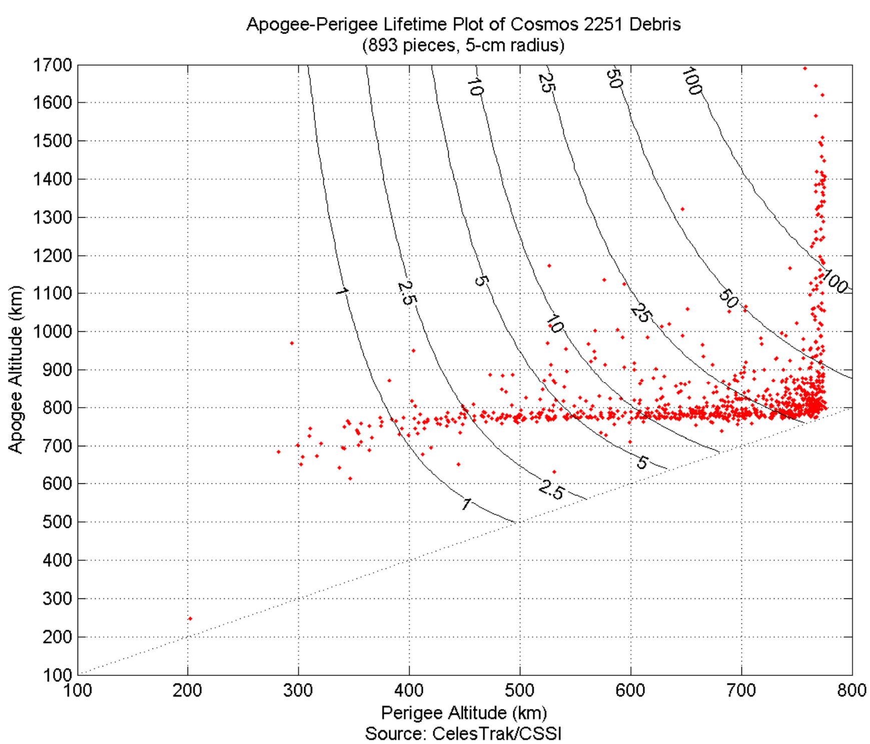

Fig. 12. Apogee-Perigee Lifetime Plot of Cosmos 2251 Debris (5-cm Radius).

For objects smaller than the average value, the orbital lifetime contours shift to the right, and for objects larger than the average value, the contours shift to the left. Fig. 11 and 12 show the results assuming debris of the same average density as the original satellite but now using a radius of 5 cm (the approximate limit of the US Space Surveillance Network radar sensors). This is the equivalent of increasing the ballistic coefficient (C_DA/m) by a factor of 2.56 (the area-to-mass ratio varies as the inverse of the spherical radius for a constant density), so it could also account for variability in the estimates of the coefficient of drag or density. Fig. 11 and 12 likely represent a best case for the decay of the cataloged debris from this collision.

5. MITIGATION THROUGH COLLABORATIVE SURVEILLANCE

The result of future catastrophic collisions could be devastating to the operational space environment. As mentioned above, one of the key reasons for developing SOCRATES was to demonstrate to the space community just how common orbital close approaches are in the existing orbital environment. This was apparent even before the Chinese Anti-satellite (ASAT) test and the Iridium-Cosmos collision added thousands of more pieces of debris to an already-crowded orbital environment. Figure 13 shows how the amount of orbital objects has jumped as a result of these debris-generating events between 2007 and 2009.

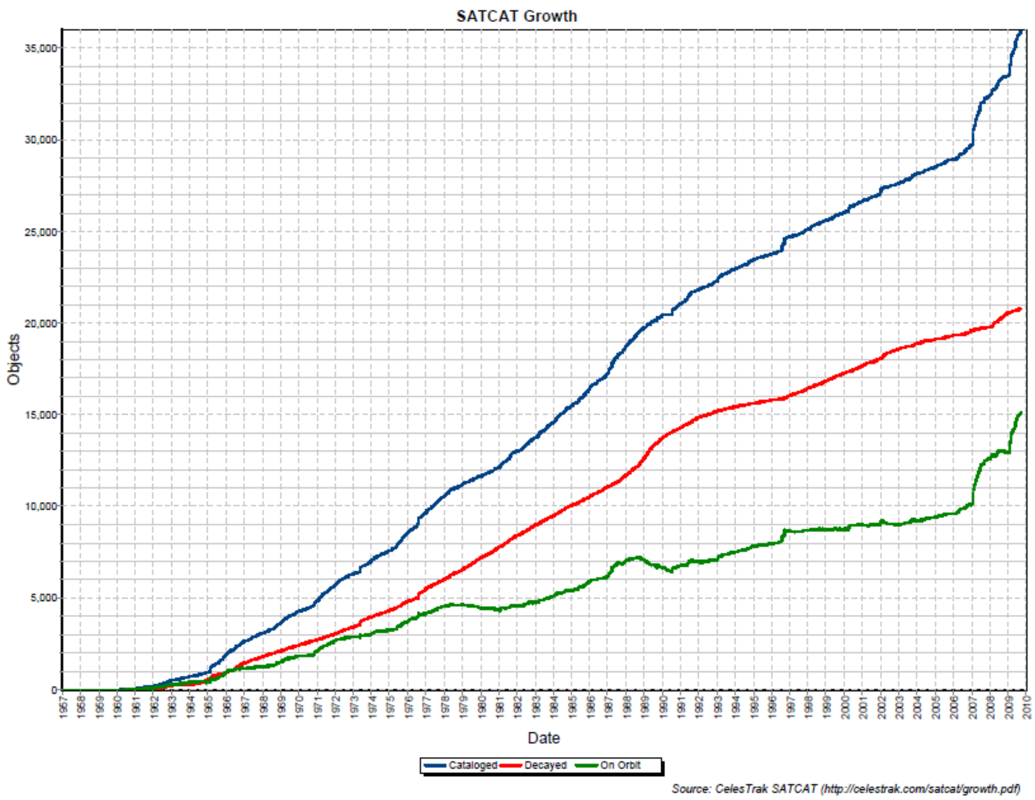

Fig. 13. Growth of the SSN SATCAT showing all cataloged, decayed and remaining on-orbit objects [5].

With the potential for future collisions growing with every new launch, immediate steps need to be taken to mitigate the risk of future collisions. While SOCRATES is a useful demonstrator of the power of existing commercial technology like the STK Conjunction Analysis Tool (STK/CAT) from Analytical Graphics, Inc to predict orbital conjunctions, there are limitations to SOCRATES because the system currently only uses publicly available TLE data which has several limitations because they were not designed to perform this task. Notably, the published TLEs include orbital uncertainties on the order of several kilometers in LEO and several tens of kilometers in GEO, due to the passive nature of the tracking systems. In addition, maneuvers of operational satellites cause the TLEs to become outdated and have been shown to result in cross-tagging of satellites. Satellite operator data, such as that provided by Iridium, can be an order of magnitude more accurate.

Fig. 14. shows positions of three Intelsat geostationary satellites as predicted by SSN public TLEs (shown in red) and Intelsat-generated ephemerides (shown in green). The figure shows not only positional errors on the order of hundreds of kilometers, but also the re-ordering of IS-3R and IS-11 in the respective data sets.

As discussed above, while the SOCRATES system was able to predict a close approach between Iridium 33 and Cosmos 2251 for the week leading up to the impact, the validity of these results have generally been in question since the source ephemeris data comes from the public SSN catalog. Had accurate ephemerides of the Iridium operators, combined with the best data from the SSN, shown that a close approach was imminent, it is likely that preventative measures would have been taken. Unfortunately, the most accurate tracking data for active satellites is often closely held only by the satellite operators.

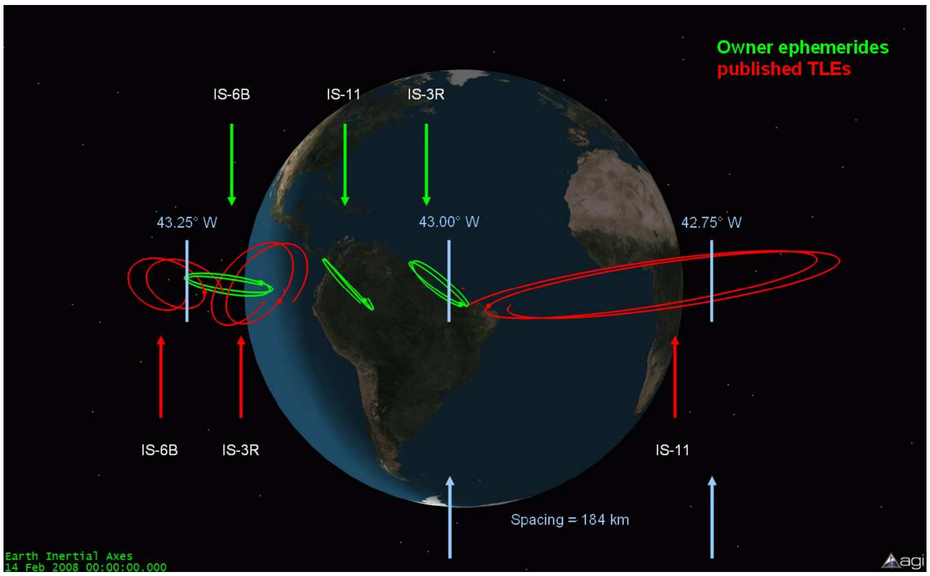

Fig. 14. Comparison of public TLEs and operator-owned ephemerides.

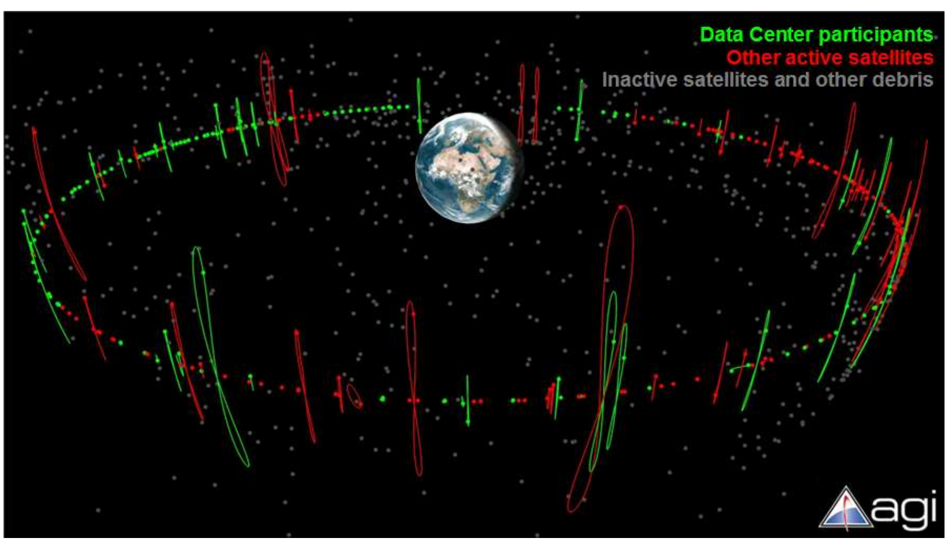

Fig. 15. Current SOCRATES GEO data center participation.

It was this fact that led the CSSI team to consider the use of collaborative conjunction analysis to create the next generation of SOCRATES, SOCRATES-GEO and the more recent SOCRATES-LEO projects. Using neutral, and confidential data centers, the CSSI team started collecting proprietary ephemeris for geostationary satellite operators to include high-fidelity ephemeris in their daily STK/CAT conjunction analysis runs. These high-fidelity data sets allow these advanced SOCRATES systems to predict close approaches much more accurately and generate automatic warnings to the satellite operators involved. They can then work together to generate a collision mitigation strategy with maneuver planning tools like STK/Astrogator.

Following the success of SOCRATES-GEO which at the time of this authoring has **11** active participants providing data for 152 active satelllite (a mapping of SOCRATES-GEO participants can be seen in Fig. 15.), CSSI has embarked upon the early stages of the SOCRATES-LEO project in an effort to determine if data sharing in the near-Earth environment can lead to further enhancements in the prediction and mitigation of collisions with active payloads and other orbiting objects.

6. CONCLUSIONS

The collision of Iridium 33 and Cosmos 2251 is a prime example of the consequences of not being good stewards of the near-Earth space environment. Not only was an operational communications satellite lost, but many thousands of pieces of debris larger than 1 cm were produced, putting many other communications and earth resources satellites in similar orbits at increased risk for many decades to come.

Space-faring nations must be more proactive toward reducing the amount of material launched into or left in Earth orbit. All satellites will eventually fail and satellite operators simply cannot expect natural forces to remove them in a timely fashion. The international community must continue to work toward establishing and adopting standards for mitigating the generation of space debris.

Until such time as someone can come up with a cost-effective way to actively remove space debris from orbit, the international community must also work more closely together to share orbital information to improve overall space situational awareness, with the goal of mitigating the risk of collision to other operational satellites. While the SOCRATES-GEO and new SOCRATES-LEO services—offered by the Center for Space Standards & Innovation (CSSI) through the GEO and LEO Data Centers—are already supporting 15 satellite operators by screening over 250 active satellites, progress in this area has been far too slow.

The ultimate success of these risk mitigation services depends on the fullest participation of all satellite operators—together with existing space surveillance systems—to provide the best space situational awareness picture possible. After all, why wouldn't we want to share the best orbital information available if we thought it would have helped avert this collision and its consequences? Without this type of cooperation, our chances of avoiding a repeat of this event are limited. And, until then, we will have no idea of whether simply sharing data would have made it obvious that this event was exceptional or if some more ambitious cooperative undertaking is necessary.

6. REFERENCES

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