# Subsequent Assessment of the Collision between Iridium 33 and COSMOS 2251

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## ABSTRACT

On February 10, 2009, a collision between the operational Iridium 33 and the derelict COSMOS 2251 promoted policy changes, ushering a new era of collision assessment and avoidance. The data sufficiently capable of collision assessment of well tracked objects was the numerically integrated Special Perturbation (SP) model of the High Accuracy Catalog (HAC), which at the time was restricted from the public but used internally by the group then known as the Joint Space Operations Center (JSpOC) for conjunction detection. The HAC alone, however, could not delineate the conjunction risks of operational and maneuverable satellites as it did not incorporate operator measurements, maneuver histories, or maneuver plans. The JSpOC did not know Iridium's independent tracking or maneuver plans and Iridium did not have access to the HAC. Each party, Iridium and the JSpOC, needed the other half of the information to know a collision was probable. Discussed will be a revisit of the collision using combined data not available at the time, informing the effectiveness of changes made since 2009.

## 1. OVERVIEW

At 16:55:59.82 UTC on February 10, 2009, a collision between the operational Iridium 33 and the derelict COSMOS 2251 promoted policy changes to usher a new era of collision assessment and avoidance. At the time, only General Perturbation Two Line Element sets (TLEs) were released publicly by the U.S. Government (USG). The simplified analytical model and lack of a corresponding covariance were insufficiently accurate and precise for satellite collision avoidance. The data sufficiently capable of collision assessment of well tracked objects was the numerically integrated Special Perturbation (SP) model of the High Accuracy Catalog (HAC), which at the time was restricted from the public but used internally by the group then known as the Joint Space Operations Center (JSpOC) for conjunction detection.

The HAC alone, however, could not delineate the conjunction risks of operational and maneuverable satellites as it did not incorporate operator measurements, maneuver histories, or maneuver plans. Eight hours before the conjunction, Iridium 33 fired its hydrazine thruster twice to raise the semimajor axis by 8.3 meters for station- keeping. Iridium did not know that COSMOS 2251, as modelled in the HAC, was on the end trajectory of that maneuver. The JSpOC did not know Iridium maneuvered because no mechanism existed for willing commercial and foreign operators to inform them, and 8 hours was too short a time to uncooperatively detect the maneuver. Each party, Iridium and the JSpOC, needed the other half of the information to know a collision was probable.

The resulting collision led to immediate policy changes to correct this communication shortcoming. Recognizing the importance to space safety, Iridium worked with the JSpOC and 18th Space Control Squadron to identify minimal necessary components of Special Perturbation (SP) data from the HAC while security concerns over comprehensively useful data were addressed. From relative state vectors to redacted Orbit Conjunction Messages (OCMs), known as Conjunction Summary Messages (CSMs) to external operators, this process evolved into the 95% capture screening volumes with results shared via the new CCSDS Conjunction Data Message (CDM), which effectively contains the information provided in the precursor CSM. Equally important, all Iridium maneuvers since 2009 are included in ephemerides and shared with the USG, which returns data of the secondary objects in conjunction with those ephemerides. With help gleaned from the NASA Conjunction Assessment Risk Analysis (CARA) team, Iridium implemented a collision assessment process to reduce the risk of future collisions.

In 2011, the JSpOC and Iridium recreated SP versus SP and SP versus Iridium ephemerides screenings, using historical data, to ascertain the effectiveness of preventing the 2009 collision using the then current data sharing of CSMs and analysis tools[26]. That review both underscored how the data could prevent future collisions between large objects but also served as a caution for setting action thresholds and addressing covariance realism. The facts of the collision, as known by the those who operated Iridium 33, and summary of the recreated screening results are presented along with a discussion of how additional improvements since 2011 aid collision avoidance.

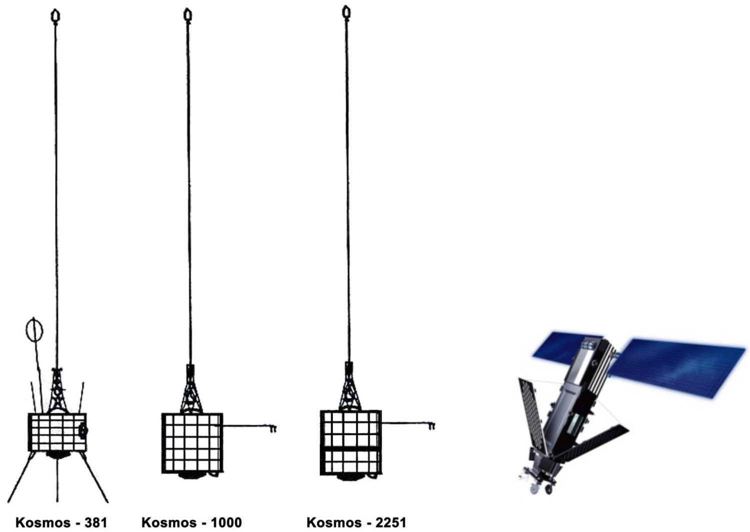


Figure 1: COSMOS 2251, a Strela 2M, and Iridium 33 on the right (estimated approximate scale)

## 2. THE IRIDIUM© CONSTELLATION

Consisting of 6 planes of 11 satellites each, Iridium is a global crosslinked telecommunications constellation inclined at 86.4 deg. Each plane is spaced by 31.587 deg in RAAN (with a seam of 22.065 between the counter- rotating planes 1 and 6). Iridium is controlled to an exact mean period of 6028 seconds, equivalent to about a 775 km mean altitude, and maintained in a frozen orbit with perigee at the north pole and a frozen eccentricity of 0.00127. The epoch for the constellation targets in mean elements was and continues to be, 27 years later for block 2, June 1, 1996. The first launch was in 1997 and the constellation was completed in 1999. Launched on a Russian Proton out of Baikonur, Iridium 33 was inserted into plane 3 slot 3 of the constellation in September 1997. Five years earlier, COSMOS 2251 had been launched from Plesetsk[9].

The original control box for the block 1 constellation was +/- 6 km along track, but that box was expanded to +/- 100 km in 2007 to accommodate solar sailing at high solar beta angles. The block 1 satellite's thrusters were all posigrade thrusters, mounted on the satellite's spine, and solar radiation pressure on the reflective angled main mission antennas raised the semimajor axis during periods of low atmospheric drag[25]. The station-keeping strategy changed to maintaining the relative separation of in-plane satellites, flying planes together to maintain crosslinks, and allowing them to drift backward during solar sailing and forward during stronger atmospheric drag, when control authority returned to also regroup the satellites[6]. In early February 2009, Iridium plane 3 was regrouping prior to the next cycle of solar sailing.

## 3. COLLISION ASSESSMENT BEFORE 2009

By the time of Iridium's first launch, the old mantra and defense that space is big was already questioned. Iridium funded collision assessment advances, including but not exclusively those of Dr. Kenneth Chan, whose acknowledgements in his 2008 book include sponsorship by Joe Pizzicaroli at Iridium [4]. Additional research from the Aerospace Corporation and internal development created an extensive well of knowledge to quickly pivot to active collision assessment later in 2009.

Unfortunately, prior to 2009 the available data could not be effectively used for collision assessment. Missing was sufficiently accurate data for the secondary objects. At the time, only two-line element (TLE) sets were accessible from the USG for propagation by the analytic Simplified General Perturbation 4 (SGP4) model. TLEs did not include covariance for computing Probability of Collision (Pc) and understood to have 1-2 km of error at epoch before propagation. Efforts to uncover the missing covariance[23] and combine operator ephemerides with TLE data were made, including that of Dr. T.S. Kelso[17], to whom Iridium contributed data for some of his testing. The larger errors over higher fidelity numerical propagation models, however, led to an untenable number and size of maneuvers. Iridium's own internal ephemerides and TLE-based collision assessment also could not be used operationally.

## 4. THE COLLISION

On Monday, February 9th, 2009, a station-keeping maneuver for Iridium 33 was created for it to join its plane grouping before the next solar sailing cycle. To maintain Iridium 33's frozen orbit, the maneuver consisted of 2 "burns," spaced 180 degrees apart in argument of latitude, of one hydrazine thruster. Each burn itself contained 2 short successive pulses spaced for the nutation of the momentum wheel, but effectively represented an impulsive $\Delta V$. Table 1 contains the commanded inputs of Revolution Number, Argument of Latitude, and $\Delta V$. Time, duration, and an estimated achieved $\Delta V$ were determined by the vehicle.

| Center Time | Rev Number | Argument of Latitude (deg) | $\Delta V$ (m/sec) | Duration (sec) |
|---|---|---|---|---|
| 2009-02-10 07:10:33.195 | 59739 | 135 | 0.0021685 | 3 |
| 2009-02-10 08:00:47.190 | 59739 | 315 | 0.0021685 | 3 |

Table 1: Predicted Iridium 33 thruster firings

Late on the morning of February 10th, Iridium's Mission Planning and Orbit Analysis Shop was debating a venue for lunch when the Mission Director called. Lunch would instead be pizza ordered in. Iridium 33 had dropped crosslinks at 16:56 (later refined to 16:55:59.82) UTC ascending over Siberia. Secondary link passes were scheduled, and a recovery from a single event upset, clock error, or other non-fatal injury was expected. However, contact at the first ground visibilities were inexplicitly missed. Worse, the author was shown a text message from Joe Pizzicaroli, who noted that T.S. Kelso's SOCRATES[16] TLE-based conjunction tool showed a conjunction with COSMOS 2251 near the time of lost crosslinks. While TLEs were insufficiently accurate to prevent collisions, they were accurate enough, combined with missed passes, to indicate more than correlation. The mood soured.

A collision was confirmed following contact with the JSpOC, and the initial inquiry expanded into discussions of how to prevent a future occurrence. By a meeting in early April of 2009, a solution that would be recognizable today existed on a white board. Iridium would send predicted station-keeping ephemerides along with post- maneuver ephemerides to the JSpOC. The JSpOC would provide daily collision screening reports with the SP vector and SP covariance. Iridium acquiesced to accept a 200 m by 1 km by 1 km pizza box but was requesting 2 km by 10 km by 10 km, a screening volume goal later gained and surpassed. Iridium would check the conjunctions against a twitch factor (became Pc), inform JSpOC within 2 hours and submit mitigation ephemerides. The JSpOC would provide a special screening report for mitigation ephemerides within 2 hours. Outside this loop, Iridium ephemerides would be compared against JSpOC's and calibrated, if necessary, to ensure "knowledge synch." By 2011, CSMs, OCMs with just the Pc (calculable from the remaining information) and exact measurement times redacted, were shared. By 2012, a request for the 95% capture screening volume was approved (0.5 km by 12 km by 12 km for "LEO3," perigees $>$ 750 km and $<$ 1200 km). By 2019, the operator ephemerides screening volume is now 2 km by 25 km by 25 km. Updates are three times a day.

Although unfortunate that a Black Swan event was required to instigate change, the collision led to a rethinking of what USG space tracking data can be shared with commercial and foreign operators. In 2011, the 18th Space Control Squadron approved an Orbit Data Request to "replay" the Iridium 33 event using archived data and the processes then in place.

## 5. THE PRE-MANEUVER ASSESSMENT

In 2011, CSMs for conjunctions using just the HAC were created for the 7th, 8th, 9th, and 10th of February 2009. Iridium shared ephemerides and the maneuver plan as they would have done for the maneuver planned on the 9th. The CSM for the 10th, would have been created post-maneuver with knowledge of the maneuver, so the 18th SCS truncated their batch orbit estimate to only contain measurements after the maneuver as was then the practice. The 18th SCS/SDS at the JSpOC, now CSpOC with the 19th SDS, do not accept maneuver plans into orbit determination

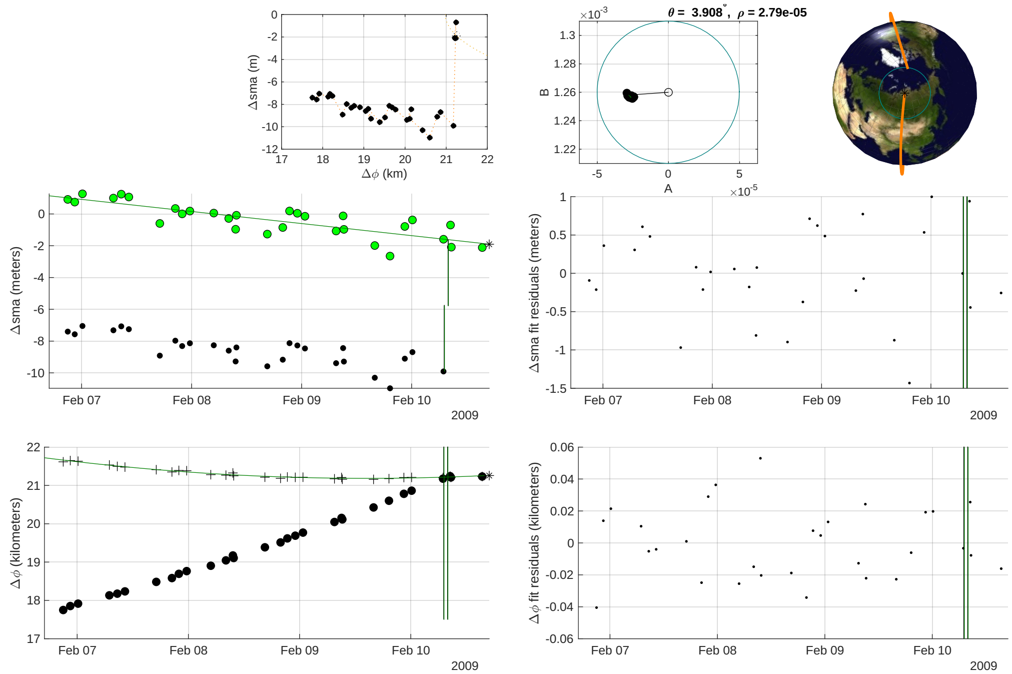

Figure 2: Iridium 33's orbit in mean elements at the time of the collision. Three line-of-sight ground passes provided range measurements following the 2 station-keeping burns, denoted by the two vertical green lines in the burn corrected fit.

but instead ignore measurements prior to these known but unmodelled forces. Iridium then combined the provided CSMs with archived Iridium orbit estimates and ephemerides, clearly indicating the original maneuver plan would have been rejected had the same data been available in 2009.

In 2011, 2019 and now refreshed again in 2023, Iridium's current software was used to resurrect the archived data and assessed with the latest capabilities that could be applied to the old data. First, Iridium's initial process since 2010 (either via automated software or a mechanized process directed by a flight dynamics engineer) is to analytically create burns that meet station-keeping requirements while minimizing the probability, and when possible, the plausibility of collisions using the data for the next 7 days (currently with a large screening volume of 25 by 25 by 2 km). Iridium uses Chan's and now also Elrod's probability methods to efficiently map the solution space (Fig. 3). After a maneuver is chosen, it is numerically propagated with a high-fidelity model and the resulting ephemerides re-checked against all conjunctions and submitted to the 18th SCS/SDS via space-track.org.

Each of the 4 CSMs are treated four different ways. The source of the secondary object remains that of the CSM for all, but simply adjusted via rectilinear motion for small changes in the time of close approach (TCA). The 1st method is the raw CSM with the primary object data unmodified from the source CSM. The 2nd method is to numerically backpropagate the primary object data in the CSM to before the maneuver, apply the maneuver, and then repropagate forward to TCA, slightly adjusting again for the resulting new TCA. This is not operationally done at Iridium and just serves to gauge the then realism of the JSpOC covariance, but with a caveat that maneuver error has not been applied to the covariance. The 3rd method propagates an Iridium Orbit Estimate with covariance to TCA, inserts it into the CSM, and readjusts for the new TCA. This is routinely done operationally. The 4th method is to also insert an Iridium Orbit Estimate into the CSM, but instead of using the covariance from the orbit determination process, polynomials are used to construct a covariance that statistically and conservatively models the observed self-consistency errors. The latter is also used operationally, but the 3rd method is favored as ideal, creating realistic covariance from a well-tuned orbit determination process. However, for block 1, the orbit determination process was known to create overly optimistic covariance, so the 4th method was the default. For all methods, the hard body radius used for Iridium 33 is 3.942 meters. For COSMOS 2251, the hard body radius has never been satisfactorily established, but 16 meters is used as derived from the drawing in Fig. 1 from [2], a 2.04 meter diameter from [28], and no contradicting information in a reference closer in time to the source Soviet technology[8]. Other artistic depictions show a shorter boom, but the

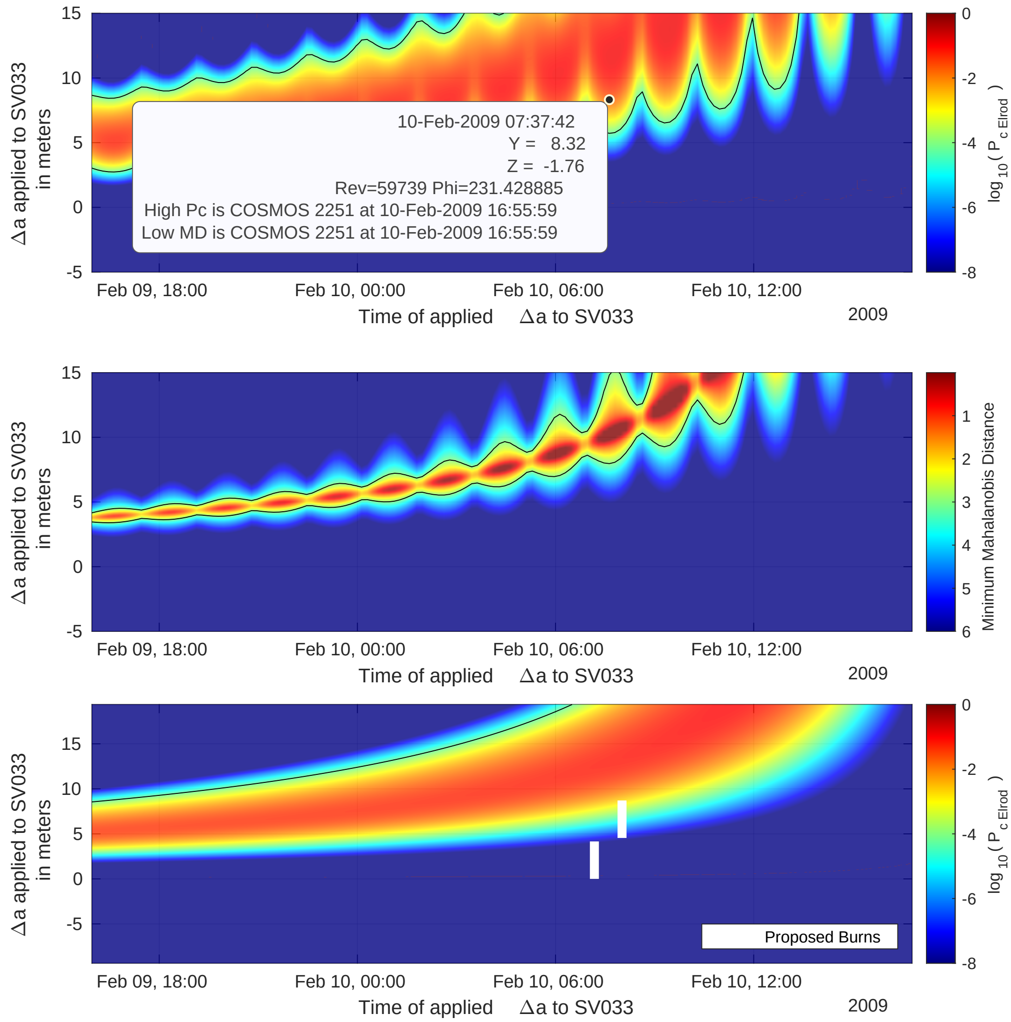


Figure 3: Analytical application of the burn against the CSM with an Iridium orbit estimate indicates both a high plausibility of a collision (middle, Mahalanobis Distance) and probability of collision (top, Pc Elrod). The undulating depiction at top only applies to Iridium's later practice of unbalanced burns to improve radial separation. In 2009, Iridium only used balanced burns to preserve frozen eccentricity, so the simplified analytic curves would have been best depicted smooth, as shown on the bottom.

quality of the computer generated graphics may not be commensurate as historical source material for a satellite series first flown in 1970 [18]. The results for Iridium 33 are shown in Table 2 below. A Pc above a threshold of 1e-4 is denoted in bold, though maneuvers seek to avoid surpassing 3.1e-6, or the same reduction from threshold of 1.5 orders of magnitude for a mitigation maneuver as now documented as a best practice[21][14][5].

Six probability methods are shown, the 2D methods of Chan[4], Elrod[7], and Foster (numeric quadrature)[10], a simple numerical integration of the 2D Pc via quadrature implemented in 2009, NASA CARA's adjustment for cross-correlation of the 2D Pc[3], and NASA CARA's 3D Pc [11] that also includes cross correlation. As could be expected for 2 large objects, the Chan Pc differs in some cases because the combined hard body radius is close to the limitation of 1/10 the covariance for this conjunction. The limitation is known[1] and operationally handled by switching to another method when it applies. For this time of lower atmospheric drag, removing cross-correlation did not affect results. An important caveat, though, is the Energy Dissipation Rate method was used because the CSM data did not contain the Dynamic Consider Parameter (DCP) Forecast uncertainty and DCP sensitivity vector values available in CDMs today since ASW version 19.2. The measured, rather than the unrecorded predicted, space weather indices were also used but, again, the values were stable enough at the time that the difference appears unimportant to explore. Also

Table 2: Probability of Collision Using "Replay" Data

| Primary | Secondary | $P_{c2D}$ Chan | $P_{c2D}$ Elrod | $P_{c2D}$ Foster | $P_{c2D}$ Numeric Quad. | $P_{c2D}$ Cross Correlation | $P_{c3D}$ |
|---|---|---|---|---|---|---|---|
| Simulated Creation 2009-02-07 20:00:00 | | | | | | | |
| JSpOC | JSpOC | $1.3E-31$ | $1.2E-23$ | $1.2E-23$ | $1.2E-23$ | $1.2E-23$ | $1.2E-23$ |
| JSpOC w/Thrust | JSpOC | $2.7E-22$ | $2.8E-15$ | $2.8E-15$ | $3.0E-15$ | $2.8E-15$ | $2.8E-15$ |
| Irid OD Cov | JSpOC | $6.8E-17$ | $1.1E-11$ | $1.1E-11$ | $1.2E-11$ | $1.1E-11$ | $1.1E-11$ |
| Irid Constr. Cov | JSpOC | $1.0E-04$ | $\mathbf{2.5E-04}$ | $\mathbf{2.5E-04}$ | $\mathbf{2.5E-04}$ | $\mathbf{2.5E-04}$ | $\mathbf{2.5E-04}$ |
| Simulated Creation 2009-02-08 20:00:00 | | | | | | | |
| JSpOC | JSpOC | $1.5E-37$ | $9.5E-27$ | $9.5E-27$ | $1.0E-26$ | $9.5E-27$ | $9.5E-27$ |
| JSpOC w/Thrust | JSpOC | $1.6E-19$ | $2.4E-11$ | $2.4E-11$ | $2.6E-11$ | $2.4E-11$ | $2.4E-11$ |
| Irid OD Cov | JSpOC | $7.2E-18$ | $7.5E-11$ | $7.5E-11$ | $8.0E-11$ | $7.5E-11$ | $7.5E-11$ |
| Irid Constr. Cov | JSpOC | $\mathbf{5.8E-04}$ | $\mathbf{1.2E-03}$ | $\mathbf{1.2E-03}$ | $\mathbf{1.2E-03}$ | $\mathbf{1.2E-03}$ | $\mathbf{1.2E-03}$ |
| Simulated Creation 2009-02-09 20:00:00 (Day Manuever was Planned) | | | | | | | |
| JSpOC | JSpOC | $4.9E-69$ | $2.6E-51$ | $2.6E-51$ | $3.0E-51$ | $2.6E-51$ | $2.6E-51$ |
| JSpOC w/Thrust | JSpOC | $4.1E-18$ | $1.0E-08$ | $1.0E-08$ | $1.1E-08$ | $1.0E-08$ | $1.0E-08$ |
| Irid OD Cov | JSpOC | $3.7E-07$ | $\mathbf{1.0E-03}$ | $\mathbf{1.0E-03}$ | $\mathbf{1.1E-03}$ | $\mathbf{1.0E-03}$ | $\mathbf{1.0E-03}$ |
| Irid Constr. Cov | JSpOC | $\mathbf{3.0E-02}$ | $\mathbf{3.3E-02}$ | $\mathbf{3.3E-02}$ | $\mathbf{3.3E-02}$ | $\mathbf{3.3E-02}$ | $\mathbf{3.3E-02}$ |
| Simulated Creation 2009-02-10 15:40:00 | | | | | | | |
| JSpOC | JSpOC | $\mathbf{4.9E-04}$ | $\mathbf{4.9E-04}$ | $\mathbf{4.9E-04}$ | $\mathbf{4.9E-04}$ | $\mathbf{4.9E-04}$ | $\mathbf{4.9E-04}$ |
| JSpOC w/Thrust | JSpOC | $\mathbf{1.1E-03}$ | $\mathbf{1.1E-03}$ | $\mathbf{1.1E-03}$ | $\mathbf{1.1E-03}$ | $\mathbf{1.1E-03}$ | $\mathbf{1.1E-03}$ |
| Irid OD Cov | JSpOC | $\mathbf{7.0E-04}$ | $\mathbf{7.4E-02}$ | $\mathbf{7.4E-02}$ | $\mathbf{7.5E-02}$ | $\mathbf{7.4E-02}$ | $\mathbf{7.4E-02}$ |
| Irid Constr. Cov | JSpOC | $\mathbf{7.5E-02}$ | $\mathbf{7.8E-02}$ | $\mathbf{7.8E-02}$ | $\mathbf{7.8E-02}$ | $\mathbf{7.8E-02}$ | $\mathbf{7.8E-02}$ |

considered by default but not shown were the collision consequences[12][20], which could not evaluate as anything but catastrophic with the generation of two large debris fields. Since 2012, the categorization in the Iridium process gives such a conjunction the greatest weight for mitigation.

Unsurprisingly, using data only from the JSpOC did not rise above a risk threshold of 1e-4 until the 10th and only then because it used knowledge of the Iridium maneuver to truncate the fit span to measurements after the maneuver, expanding the covariance large enough to result in a high Pc. Applying the predicted Iridium maneuver to the JSpOC solution also did not trigger the threshold, but maneuver error wasn't added. Using Iridium's raw orbit estimate from the orbit determination process did not trigger until the 9th, but that was also the day the burn was planned. The overly optimistic covariance was also a known limitation for block 1 and the reason for applying a conservative model of covariance growth. Iridium orbit determination uses ranging measurements from line-of-sight passes, which are necessarily dense for maintaining continuous communication traffic with the ground. The Kalman filter for block 1 was well-tuned for feeding the a priori estimate for the next pass within minutes to hours, but covariance propagation performance days in the future deviated from realism. To compensate, constructed covariance derived from recent self-consistency of orbit estimation propagation to subsequent orbit estimates were used. For Iridium 33, the standard deviations to construct the conservative covariance were $U = 20$, $V = 120\Delta t + 60$, $W = 20$ meters, for respectively the radial, in-track, and cross-track coordinates with $\Delta t$ in days. These values were always checked that they included the JSpOC variations from Iridium estimates as well. That compensation would have flagged the conjunction as early as the 7th, the earliest data from the 2009 conjunction recreated from archives in 2011.

By the 9th, the day the maneuver was planned, it would have been clear the maneuver resulted in unacceptable risk. If, for some reason, no information was available until the 10th after the maneuver, the risk would have been abundantly clear. Even after the maneuver, there would have been time to react if data were shared. Iridium is crosslinked and mission vehicles can be commanded at any time. Iridium Block 1 had a 6-minute lock-out prior to burn execution, planning and upload took about 15 minutes, so 21 minutes after the final 15:24 Iridium orbit estimate, at 15:45 UTC, a mitigation burn could have executed by a half orbit before TCA. Fortunately, the need today for such last-minute reactions are minimized by longer 7-day screenings within a large volume of 25 by 25 by 2 km.

Results reaching beyond the commonly cited probability threshold of 1e-4 required knowledge that the maneuver occurred and, certainly, covariance for both objects. Even the result sourced only from the JSpOC CDM on the 10th surpassed the threshold because knowledge of the burn was later used to truncate the fit span. While some additional details have been presented here, the overall conclusion itself is not new to those who have been able to review similar data after the event[22]. The point is repeated here, though, lest the learned retrospection of data sharing be eclipsed by the immediate recollections of the actual day—that the Iridium 33 conjunction did not then stand out as high risk [15][24]. The latter was indeed historically true *beforehand* but only because the respective views were incomplete that day, not because the separate data, when merged, were lacking.

## 6. THE REFINED POST-MANEUVER ASSESMENT

The previous results revolved mainly around the operational cadence of what would/could have been done. The following results involve enough effort and computation that it would have been unreasonable to perform, at least in 2009, after the maneuver but before the collision. First, the predicted maneuver executed but wasn't recorded. The vehicle computed thruster pulses onboard for a requested delta V at an argument of latitude, and the nominal record of executed pulses was scheduled to be downloaded after the collision. The maneuver wasn't calibrated. No error was applied to the prediction for block 1, though the constructed conservative covariance for realism was large in comparison to the typical errors. Second, three separate passes existed after the maneuver to facilitate that calibration if combined in a least squares batch orbit estimate. Both required careful evaluation outside of the nominal automation and activities that could have taken place that day.

Table 3: Post-maneuver refined probability of collision

| Primary | Secondary | $P_{c2D}$ Chan | $P_{c2D}$ Elrod | $P_{c2D}$ Foster | $P_{c2D}$ Numeric Quad. | $P_{c2D}$ Cross Correlation | $P_{c3D}$ |
|---|---|---|---|---|---|---|---|
| Simulated Creation 2009-02-10 15:40:00 | | | | | | | |
| Irid OD Cov | JSpOC | **4.9E − 01** | **5.6E − 01** | **5.6E − 01** | **5.6E − 01** | **5.6E − 01** | **5.6E − 01** |
| Irid Constr. Cov | JSpOC | **1.8E − 01** | **1.8E − 01** | **1.8E − 01** | **1.8E − 01** | **1.8E − 01** | **1.8E − 01** |

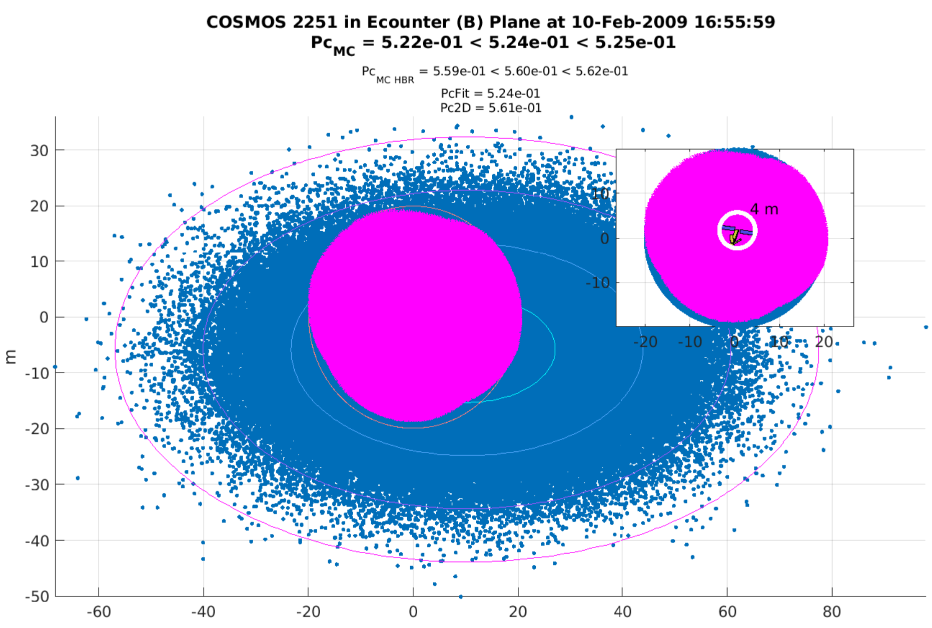


Figure 4: Brute Force Monte Carlo from batch orbit estimate after maneuver.

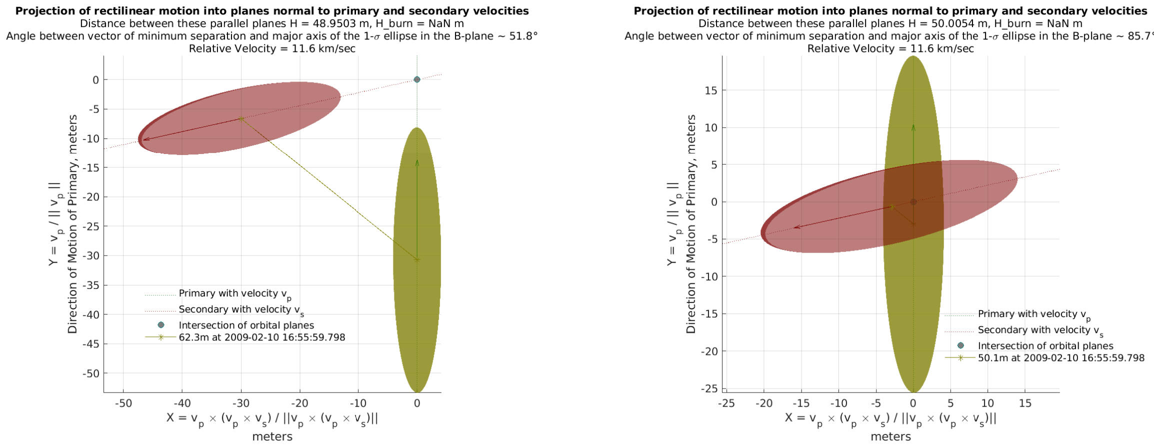


Figure 5: The projective plane containing relative motion without maneuver calibration, left; with calibration, right.

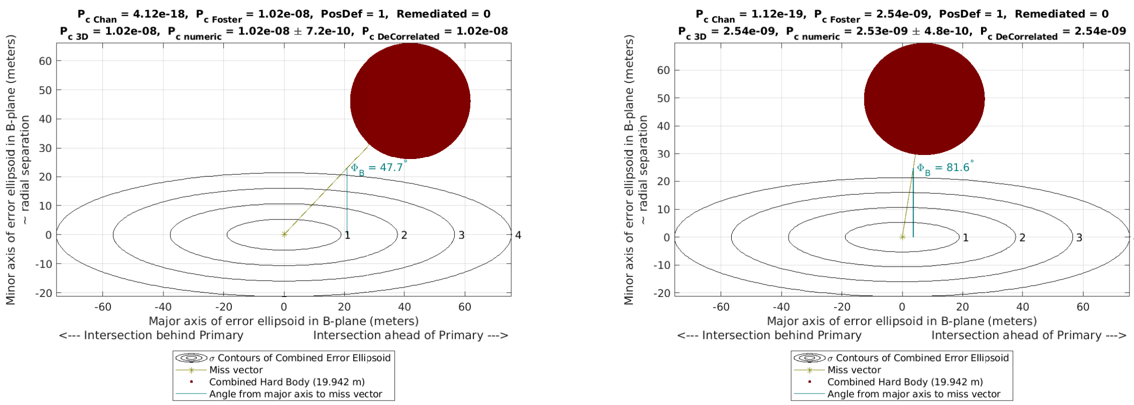


Figure 6: B-plane view of the JSpOC CSM from the 9th with the predicted burn added, left; measured burn, right.

Combining measurements with a batch estimate of the 3 available passes following the maneuver results in an 11.8-meter miss distance. In Table 3, fortunately not unexpected for a known collision, the result is a 56% chance of being inside the combined hard body radius, also verified by a brute force Monte Carlo in Fig. 4 which not surprisingly matches given the relative velocity of 11.6 km/sec is well within the short-term encounter assumptions used for the 2D Pc. The block 1 system used a Maneuver Efficiency Factor, which using an anchor of a batch orbit estimate before and after the maneuver was estimated as 0.8692. The result of that factor, when applied to the JSpOC CSM for the 9th, is shown in Fig. 5 as aligning the primary and secondary satellites in the projective plane containing the relative motion, thus shrinking the miss distance to just that of the radial component.

The day the maneuver was planned, the 9th, is then reconsidered with the MEF to see if that missing error could explain the lower probability assessment for the one method of repropagating the JSpOC estimate with the burn. Again, this is an exercise outside nominal operational use, but one that could illuminate the possibility the covariance was overly optimistic. Applying the MEF to this method leads to shrinking the miss distance from 62 meters to 50 meters with a probability of 2.5e-9. Fig. 6 illustrates the problem with the low results. Though the in-track and cross-track components are brought close to zero, like the results with an Iridium orbit estimate, the radial component remains, again like the results with an Iridium estimate. However, whereas the radial component of Iridium's covariance is large enough to bridge the radial gap and present a high probability of collision, the radial component of the JSpOC is too small. That leaves a couple possibilities: the JSpOC covariance was too optimistically tight, or the assumed hard body radius is wrong. Absent the discovery of scaled renderings better than that of Fig. 1 from [2], sensitivity analyses such as Fig. 7 are needed to consider safe clearance.

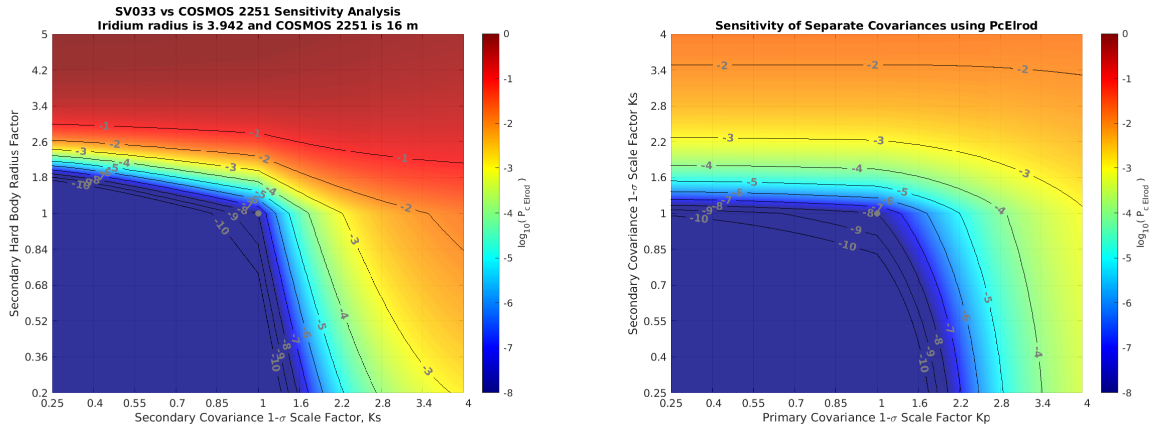


Figure 7: Sensitivity of hard body radius vs. secondary covariance scale factor, left; secondary vs. primary covariance scale factors, right

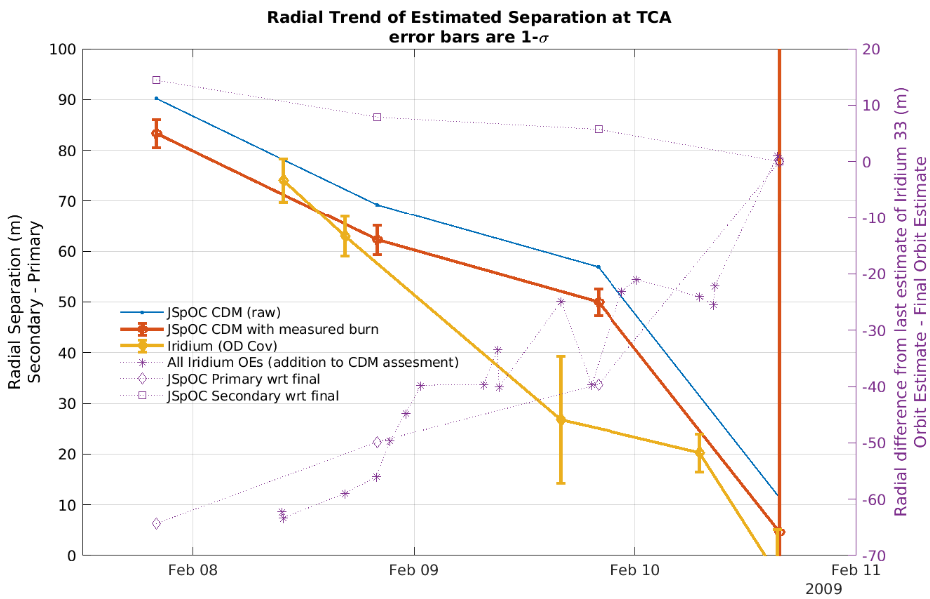


Figure 8: Radial changes in JSpOC and Iridium data indicate Iridium 33 rising over model predictions.

Such a method to compensate for these lower probabilities due to tight covariance is to accommodate covariance under or over sizing by applying scale factors separately to the primary and secondary covariance. CNES has been an advocate of these covariance adjustments by a Kolmogorov-Smirnov test of the Chi-squared distribution of squared Mahalanobis distances[19]. Such application is not attempted here because of the small data set collected in 2011 prior to the maneuver. Today's cadence of 3 updates a day for seven days prior to TCA can produce a better set for such a statistical test. A simple plot, however, of primary and secondary scaling factors in Fig. 7 within the plausible extent determined by CNES yields probabilities meeting criteria. The method appears capable of compensating with sufficient data.

While appropriately sized covariance or sensitivity considerations can compensate, the radial separation is seen in methods both using all Iridium data for the primary as well as the Iridium maneuver applied to JSpOC data. Furthermore, Fig. 8 shows decreasing radial separation as measurements approach TCA. Iridium data rises to the final solution approaching TCA. Similarly, the JSpOC solution itself shows the primary rising and the secondary falling slightly towards the final solution. Both suggest an unmodelled force affecting the shape of the orbit. One candidate could be the radiation pressure for which Iridium block one was also famous in another form, the same producer of the Iridium flares off the main mission antennas. While solar radiation pressure was modelled by Iridium, it was an addendum that didn't include a full plate model for the Kalman filter during block 1. Such models were offline analyses[6]. The JSpOC didn't use any plate models. In mid-beta the solar radiation pressure was small compared to atmospheric drag, but it would have been unbalanced. Unless the gravity gradient boom of COSMOS 2251 was much longer than depicted, the radial offset suggests the importance of covariance sized to encompass forces outside the model.

Of course, the resolution of this curious bias in radial separation was not needed to decide against a maneuver. The only method that didn't rise above a Pc threshold of 1e-4 was the one method never routinely used—back propagating the solution of the external data provider with a matched force model and repropagating with the maneuver applied. All other routinely used methods, with larger covariance than the JSpOC solution, clearly flag the maneuver. Iridium's initial work to utilize JSpOC data later in 2009 addressed the need to avoid overly optimistic covariance with the constructed covariance for block 1. For block 2, both the covariance from orbit determination, calibrated with the appropriate amount of state noise, and the constructed covariance technique are used but usually yield equivalent results.

## 7. CONCLUSION

The replay of data was clearly against the maneuver of Iridium 33 on February 10th. Had the data been available then, the processes adopted afterwards would have prevented it. Though this assessment included later technical improvements such as the 3D Pc and covariance decorrelation, no technical advance developed after 2009 was necessary to detect the risk. The 2D Chan Pc or integration of the 2D Pc by numerical quadrature were both known and immediately implementable by Iridium. When reflecting upon the Iridium 33 collision and future improvements to collision assessment and avoidance, the data shows policy cannot be ignored. The data existed. In one bucket, Iridium orbit estimates with covariance and a plan to maneuver for station-keeping. In the other bucket, JSpOC orbit estimates with covariance of all tracked objects. That no one could predict and stop the collision is because no one shared their bucket.

## 8. FUTURE CONSIDERATIONS

The replay demonstrates a collision between a maneuverable object and a non-maneuverable is preventable today. A collision between two maneuverable objects is also preventable, but as the replay demonstrates, only if the data of both parties are shared with the other. There are some technical questions and ideas about coordination[13][27], but they build on a policy of sharing and transparency. Commercial and foreign operators who cooperate with the current solution of the 18th/19th U.S. Space Defense Squadron via space-track.org, the future U.S. Office of Space Commerce solution TRaCCS, the European SST solution, or existing entities such as the non-government Space Data Center, have the necessary basis for that cooperation if the proliferation of data lakes acts in a federated manner. The concern for policy makers is earth orbit is a global resource, populated by satellites from all nations, some of which have barriers to cooperation. Though most conjunctions remain with debris, Iridium today has a few conjunctions with such isolated operators, a category of conjunctions waiting to be the next Black Swan. A lesson of Iridium 33 is that reliance upon hindsight is not the best instigation of change.

## 9. ACKNOWLEDGEMENTS

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## 11. APPENDIX MEASURED SPACE WEATHER INDICES FROM CELESTRAK

```
# -------------------------------------------------------------------------------------------------------------------------
#                             SPACE WEATHER DATA
# -------------------------------------------------------------------------------------------------------------------------
#
# See http://celestrak.com/SpaceData/SpaceWx-format.asp for format details.
#
# FORMAT(I4,I3,I3,I5,I3,8I3,I4,8I4,I4,F4.1,I2,I4,F6.1,I2,5F6.1)
# -------------------------------------------------------------------------------------------------------------------------
#                                                                                              Adj     Adj   Adj   Obs   Obs   Obs
# yy mm dd BSRN ND Kp Kp Kp Kp Kp Kp Kp Kp Sum Ap  Ap  Ap  Ap  Ap  Ap  Ap  Ap  Avg Cp C9 ISN F10.7 Q Ctr81 Lst81 F10.7 Ctr81 Lst81
# -------------------------------------------------------------------------------------------------------------------------
#
2009 02 07 2395 11  3 20  3  0  3  3  0  0  33   2   7   2   0   2   2   0   0   2 0.0 0   0  69.2 0  67.9  67.2  71.1  69.6  69.4
2009 02 08 2395 12  0  0  3  0  0  0  0  3   7   0   0   2   0   0   0   0   2   0 0.0 0   0  69.3 0  67.9  67.3  71.2  69.6  69.4
2009 02 09 2395 13 17  3  0  0  0  3  0 10  33   6   2   0   0   0   2   0   4   2 0.0 0   0  68.8 0  67.9  67.3  70.7  69.6  69.4
2009 02 10 2395 14  3  3  0  3  3  3  3  7  27   2   2   0   2   2   2   2   3   2 0.0 0   0  65.8 0  68.0  67.3  67.6  69.6  69.4
```

## 12. APPENDIX: KEY CONJUNCTION DATA FOR 9TH

Relevant elements of the conjunction data resurrected from February 9th used in the assessment.

```
"Creation Date:" 2009-02-09T20:00:19.000000
JSpOC CSM
TCA: 2009-02-10T16:55:59.798000
Iridium 33
ITRF Position/Velocity (m,m/s): -2.961368970e+05 2.139834382e+06 6.813319413e+06
                                -4.276033580e+02 -7.088663168e+03 2.202742231e+03
UVW Position Covariance (m^2):
7.0410e+00 7.2360e+00 -1.4500e+00
7.2360e+00 5.1140e+02 -1.1460e+00
-1.4500e+00 -1.1460e+00 1.6640e+01
COSMOS 2251
ITRF Position/Velocity (m,m/s): -2.959592990e+05 2.139972561e+06 6.813343383e+06
                                -6.985040501e+03 2.011980267e+03 -9.328477630e+02
UVW Position Covariance (m^2):
2.3000e+01 2.1600e+01 5.3870e+00
2.1600e+01 3.2140e+02 7.1100e-01
5.3870e+00 7.1100e-01 2.5690e+01

Iridium Orbit Estimate, propagated to Epoch: 2009-02-10T16:55:59.815508
ITRF Position/Velocity (m,m/s): -2.961383471e+05 2.139961754e+06 6.813312007e+06
                                -4.276694703e+02 -7.088558347e+03 2.202963878e+03
UVW Position Covariance (m^2):
1.5785e+02 2.1293e+03 1.9844e+01
2.1293e+03 3.2898e+04 2.4713e+02
1.9844e+01 2.4713e+02 1.1811e+01

Iridium Adjusted Orbit Estimate, propagated to Epoch: 2009-02-10T16:55:59.815508
ITRF Position/Velocity (m,m/s): -2.961383472e+05 2.139961752e+06 6.813312008e+06
                                -4.276694705e+02 -7.088558347e+03 2.202963879e+03
UVW Position Covariance (m^2):
4.0000e+02 0.0000e+00 0.0000e+00
0.0000e+00 3.4172e+04 0.0000e+00
0.0000e+00 0.0000e+00 4.0000e+02
```