Collision Risk Assessment for Derelict Objects in Low-Earth Orbit

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ABSTRACT

Massive, defunct objects in low-Earth orbit (LEO) pose a unique and significant threat to the space environment. Potential collisions between rocket bodies and non-operational satellites are the most significant potential source of debris-generating risk in LEO, as they represent the bulk of the uncontrollable mass and orbit in congested regions.

A first step in addressing this problem is characterizing the risk. In this paper, we study the clusters of several hundred objects orbiting between 750 km and 1000 km. These clusters are comprised of predominantly Russian rocket bodies and satellites, but also include newer massive satellites such as Envisat. We investigate close approaches between objects in the clusters, rather than conjunctions with smaller pieces of debris. LeoLabs performs automated full-catalog conjunction screening using high-precision ephemerides, a first-of-its-kind service.

We perform a statistical analysis of conjunction events for objects in these clusters and summarize the number of events and the relationship between miss distance and probability of collision. We present several case studies analyzing close conjunctions of less than 100 meters between objects in these clusters. Using LeoLabs' high-precision orbital solutions on these objects in the days leading up to the time of closest approach (TCA), we analyze trends in the orbital solutions, miss distances, and probability of collision (Pc) for several events in order to evaluate the consistency of the solutions and predictions. We compare results to analyses performed with two-line element sets (TLEs) issued by the US Air Force's Combined Space Operations Center (CSpOC), along with CSpOC high-precision special perturbation (SP) ephemeris.

This analysis portrays one use case of how new commercial radar systems can be applied to provide responsive insights useful for management of the debris population.

1 INTRODUCTION

Collisions between rocket bodies and non-operational satellites are the most significant potential future source of debris-generating risk in Low-Earth Orbit (LEO), as they represent the bulk of the uncontrollable mass and orbit in congested regions. These non-maneuverable objects also orbit within regions with a significant number of massive, operational satellites. A collision between any two of these massive objects, or even between one of these objects and a piece of smaller debris, could significantly increase the collision risk for operational satellites. Clusters of hundreds of derelict rocket bodies and satellites exist above 750 km, with a combined mass of over 1000 tons. Individually, objects with masses of over 1000 kg are not uncommon. In some regimes, such as the cluster of Cosmos satellites and their parent upper stage SL-16 rocket bodies orbiting at around 850 km altitude, each with cross-sections close to or larger than 10 m^2, payload masses of over 3000 kg and rocket body masses of over 8000 kg have repeated close approaches and will continue to do so over their lifetime. While most of these large objects were put into orbit in the 1970s, 1980s, and 1990s, upper stages continue to be left in orbit, and defunct satellites add to the uncontrolled mass in the region. The low-drag environment ensures that these objects will remain in orbit for centuries without intervention from robotic de-orbiting missions.

The impact of a collision between two of these large objects on the LEO environment cannot be understated: it has been shown that a collision between two of these massive objects could (a) double the amount of trackable debris in LEO [1] and result in significant growth in the LEO debris population [2], (b) triple the risk to operational satellites from sub-10 cm debris, which would be untrackable with current space situational awareness (SSA) capabilities [1], (c) present significant additional burden for collision avoidance on operational satellites [1], and (d) overall result in a 10% average reduction in the lifetime of satellites in the 650-1050 km altitude range [3]. The importance of this topic led to the Massive Collision Monitoring Activity (MCMA) [4], which is an effort to monitor and characterize close approaches between clusters of large, defunct objects in LEO greater than 700 kg in mass. Initial results focused on four clusters of massive defunct objects centered at 775 km, 850 km, 975 km, and 1500 km, covering about 500 objects and about a third of the non-operational mass in LEO [4]. The MCMA activity has since been extended to cover other large objects in similar altitude regimes, some of which include operational satellites [5].

The MCMA experiment involves the use of general perturbation (GP), specifically SGP4, two-line element sets (TLEs) shared publicly via space-track.org. These TLEs are generated by the US Air Force's 18th Space Control Squadron (18 SPCS), which is located at the Combined Space Operations Center (CSpOC) at Vandenberg Air Force Base in California. The data is derived from the US Space Surveillance Network (SSN), which tracks and catalogs objects from LEO to GEO. The CSpOC also produces data using special perturbations (SP) analyses, but these data and the covariances needed for collision risk assessment are not generally publicly available, and risk assessment for conjunctions between two non-operational objects is not generally performed. As part of the MCMA effort, some additional analysis of events has been made available from the 18 SPCS.

Beginning in 2016, LeoLabs began tracking objects in LEO and offering commercial services to operators. Since March 2019, LeoLabs has been assessing and recording close approaches for all objects in the catalog, paying special attention to objects in the clusters identified as part of the MCMA experiment. In this paper, we perform detailed analyses of some close approaches where information from LeoLabs' system, from the CSpOC TLEs, and from the CSpOC SP ephemeris are available. In Section 2 we review these datasets, in Section 3 we present some statistical results based on LeoLabs' datasets, and in Section 4 we investigate some case studies in detail. We summarize our findings in Section 5.

2 DATA SOURCES

2.1 LeoLabs Tracking Data

LeoLabs utilizes a network of two radar systems: the Poker Flat Incoherent Scatter Radar (PFISR) located near Fairbanks, Alaska, and the Midland Space Radar (MSR) located near Midland, Texas. This network, the radar systems, and the radar performances has previously been described [10]. Today LeoLabs' network regularly tracks more than 10,000 objects in the LEO public catalog. These radars track objects at inclinations of 30° and higher, and objects that have an equivalent RCS of roughly a 10-cm sphere or larger. They revisit prioritized objects between 1 and 2 times per day on average, and revisit most objects at least once every 1-2 days. Beginning in 2019, LeoLabs will build additional radars, located at sites around the world, that will increase this revisit rate and detect smaller debris. The first of these advanced radars is located in New Zealand and called the Kiwi Space Radar (KSR).

Observations from the radar systems include high precision range, Doppler, and signal strength, which are used to derive data products such as satellite ephemerides. An example of such a detection is shown in Fig. 2.1, which is an observation of a rocket body from KSR. Radar measurements are automatically calibrated and validated [10]. Ephemerides are provided with calibrated covariances, which are validated using well-tracked objects with known precision ephemerides [11] as well as statistical analyses using the overlap statistics of propagated states [12]. Validation studies have also been performed with satellite operators and a recent study has looked at tracking performance on small satellites [13].

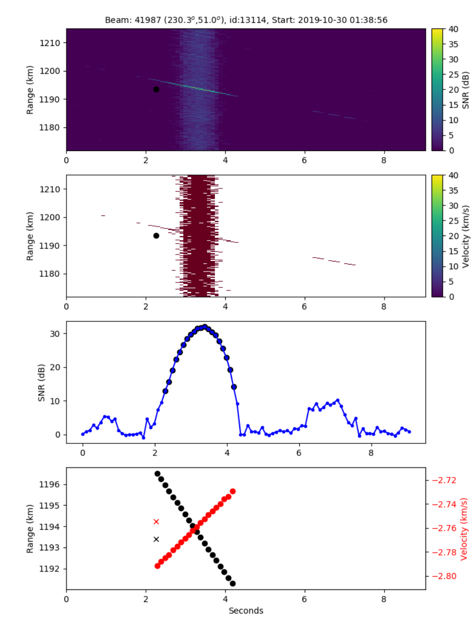

Fig. 2.1. Detection of a rocket body at the Kiwi Space Radar (KSR). (Top) SNR as a function of range and time; (Second) Doppler as a function of range and time; (Third) Peak SNR as a function of time; (Bottom) Extracted range and doppler measurements.

LeoLabs is continuously developing new products and features. Of most relevance to this work is its conjunction screening service, which allows operators to automate the process of conjunction assessment and maneuver planning [14]. Operators can screen planned or generated ephemerides using LeoLabs' screening API and retrieve the results in industry-standard formats programmatically within seconds of screening. The operator can input parameters such as covariances, hard-body radius (HBR), and screening volumes. While the results are retrievable via the API, the web-based platform includes automated reports showing visual representations of the conjunctions.

LeoLabs services also include the ability to prioritize objects of interest. For satellite operators, this may be useful in collecting additional data in the days leading up to a close-approach situation. Additional data on the secondary can refine the uncertainties and probability of collision for high-risk conjunctions, leading to more effective planning for maneuvers. LeoLabs tools are all API-driven and are designed to integrate with operational tools to promote effective and automated satellite operations.

Beginning in early 2019, LeoLabs began screening for conjunctions. Object states are updated after every pass over one of LeoLabs' radar sensors. On every state update, for any object (regardless of operational state or object type), an 8-day ephemeris is generated and screened against the entire catalog. Events within 100 km are analyzed for probability of collision (Pc), Mahalanobis distance (Md), and miss distance. If the event meets certain criteria, it is stored and available for download or for further analysis. Typically, 20 to 30 million conjunctions are generated on a daily basis, and 500,000 to 1M are stored on a daily basis in LeoLabs backend database. An example of the type of information derived from this dataset is shown in Fig. 2.2, which depicts the highest risk conjunctions on any given day (left panel) as well as the ability to drill down to understand specific high-risk events (right panel). In this study, we use events stored as part of the conjunction screening process to analyze the collision risk assessment for rocket bodies and defunct satellites in LEO.

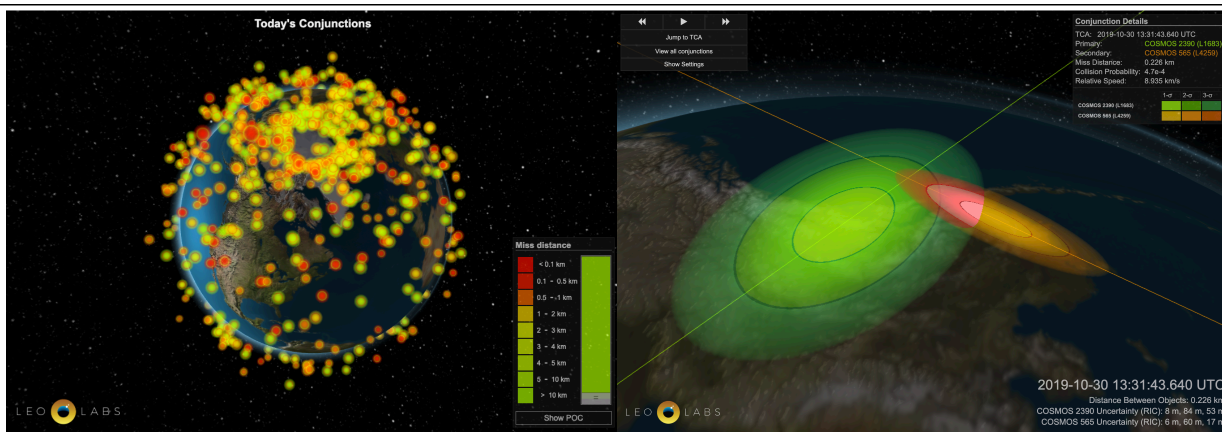

Fig. 2.2. (Left) Snapshot of LeoLabs' Today's Conjunctions dashboard which highlights high risk (high Pc or low miss distance) conjunctions on a daily basis. (Right) A snapshot of a single conjunction showing uncertainty ellipsoids and their overlapping regions.

2.2 CSpOC Two-Line Element Sets

The genesis of TLEs was motivated in the 1960s by a need for an efficient way to depict the state of a satellite's orbit and to predict its future state. The TLE is used by a simplified perturbations model (i.e., SGP4, etc.) that provides reliable forward propagation but with limited accuracy. This process is highly useful for maintaining a catalog of objects and tasking ground-based sensors to re-acquire and update the object's orbital state [6]. However, the TLE format and simplified propagator makes the TLE a poor tool for conjunction assessment. While TLEs cannot provide sufficient accuracy for collision avoidance maneuvers, they statistically provide an efficient way to depict general encounter dynamics between orbital objects.

2.3 CSpOC Special Perturbations Analysis

Special perturbations (SP) propagators numerically apply detailed force models to predict the future state of a satellite using a state vector representation of a satellite's state (i.e., x, y, z, x, y, and z) in contrast to TLEs and SGP4 that use Keplerian elements. The SP process includes many more and more precise characterization of forces that can affect the evolution of a satellite's orbit (e.g., solar radiation pressure, high order geopotential terms, etc.). Generally, even using the same initial radar observations, an SP process can provide significantly more precise orbit state estimation and propagation than SGP4 using TLEs. Further, the use of SP enables both position and velocity covariance determination for a specific orbit processing while covariances are not even calculated for TLEs; for

TLEs, there are simply generalized uncertainty levels ascribed to TLEs that vary by orbital regime and the actual uncertainty values do not have a universally agreed upon level.

Table 3.1. Summary of cluster events detected by LeoLabs over a roughly 8-month period from March to October 2019. Probability of collision results are computed using a combined 5-meter hard-body radius.

	775 km Cluster	**850 km Cluster**	**975 km Cluster**
Number of objects	101	75	314
Approximate Total Mass (US Tons)	162	311	408
Number of events <1 km, <500 m, <100 m miss distance	227, 38, 0	104, 28, 2	1862, 410, 22
Number of events >10^{-6}, >10^{-5}, >10^{-4}, >10^{-3} Pc	98, 22, 2, 0	44, 6, 2, 0	684, 118, 24, 6
Expected number of collisions per month	1.2 x 10^{-4}	5.3 x 10^{-5}	3.3 x 10^{-3}
Mean years between collisions for cluster objects	676	1577	25

3 OVERALL STATISTICS

Approximately 8 months of data were used for this study, during the time period from roughly March to October 2019. Conjunctions between cluster objects were recorded if they met certain Pc or miss distance thresholds. A summary of the results for the clusters of objects at 775 km, 850 km, and 975 km is shown in Table 3.1. and cumulative distributions as a function of miss distance and probability of collision are shown in Fig. 3.1. Note that these events are close approaches between cluster objects only, and do not include the very large number of conjunctions with smaller objects and debris. Each of the events, if they were to result in a collision, would be catastrophic and result in a huge increase in the LEO debris population.

Cluster 775 is comprised of 101 objects weighing over 160 tons, including 44 paired Cosmos satellites and their upper stage rocket bodies launched in the 1970s, 1980s, and 1990s, along with newer massive objects such as Envisat and Worldview 2. Cluster 850 is comprised of 75 objects with over 300 tons of total mass, including 18 large Cosmos satellites and their upper stage SL-16 rocket bodies with physical dimensions of about 11 meters by 4 meters, about 24 Meteor weather satellites, and other large operational satellites such as SPOT 3 and NOAA weather satellites. Cluster 975 is the largest cluster, at 314 objects and over 400 tons of total mass, most of which again are paired Cosmos satellites and upper stages.

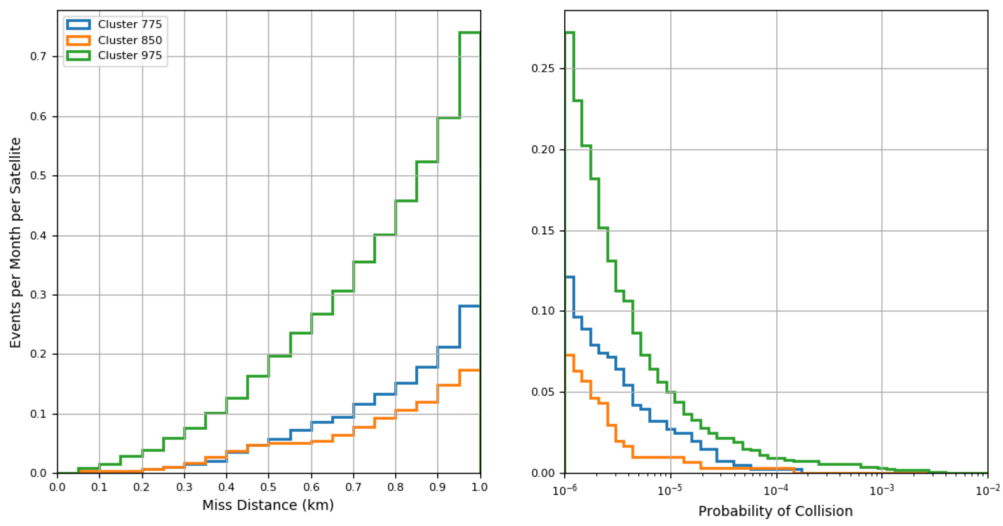

Fig. 3.1. Histograms for the dataset described in Section 3. (Left) Cumulative distribution of events per month per satellite as a function of miss distance. (Right) Inverse cumulative distribution of events per month per satellite as a function of probability of collision.

Over the 8-month study, as summarized in Table 3.1, over 200 events, 100 events, and 1800 events were detected with final miss distances less than 1 km in clusters 775, 850, and 975, respectively. In cluster 975, 22 events (or roughly three per month) were detected with final miss distance less than 100 meters. In terms of probability of collision, the 8-month data set leads to a mean time between cluster objects of 676 years, 1577 years, and 25 years for in clusters 775, 850, and 975, respectively. This number, of course, is highly sensitive to the hard-body radius, or HBR, used to compute Pc. A doubling of the HBR, as may be reasonable especially for the 850 km cluster, would decrease the mean years between collision numbers by a factor of 4.

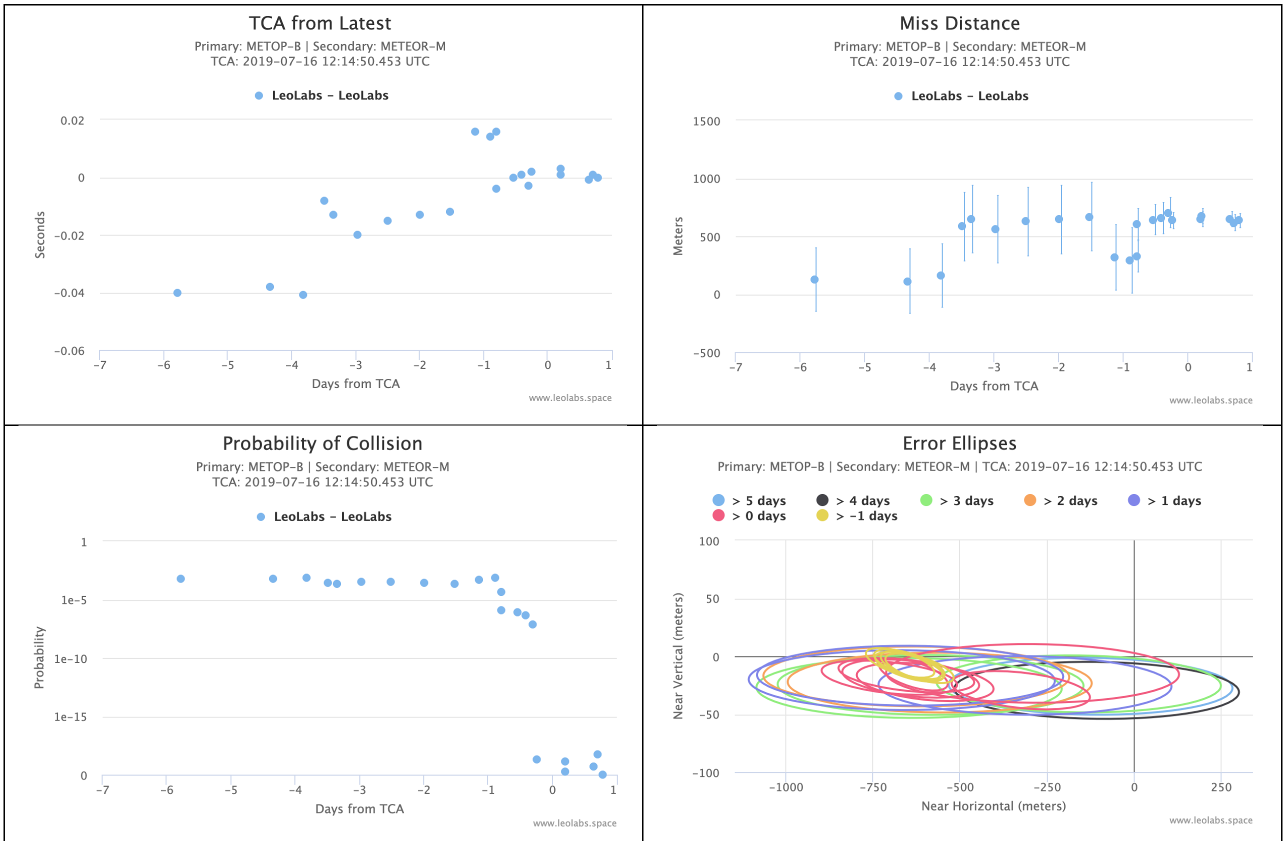

Fig. 4.1. LeoLabs' event analysis for a conjunction between METEOR-M and METOP-B on 16 July 2019. (Top left) TCA change as a function of time. (Top right) Miss distance with 1-sigma RMS uncertainty as a function of time. (Bottom left) Probability of collision as a function of time. (Bottom right) One-sigma error ellipses in the conjunction plane, color coded by days before TCA.

4 CASE STUDIES

In this section, we report on specific events where we compare the collision risk analysis obtained by LeoLabs and from the TLE-based analysis described previously. In two of the three cases analyzed, we also obtained results from CSpOC using their definitive special perturbation (SP) ephemeris.

4.1 Event 1: Two large operational satellites at 820 km altitude

This event represents a close but low-risk conjunction between two operational satellites – ESA meteorological satellite METOP-B (38771) and Russian meteorological satellite METEOR M (NORAD ID 35865), on 16 July 2019. The satellites orbit at approximately 820 km altitude in circular, roughly 99° inclination orbits. METEOR-M has a radar cross-section (RCS) of approximately 4 m^2 as reported by LeoLabs, and a mass of 2755 kg. METOP-B has an RCS of approximately 12 m^2 as reported by LeoLabs, and a mass of over 4000 kg.

LeoLabs' Conjunction Analysis Report for this event is available at https://platform.leolabs.space/conjunctions/reports/11044327. This event was identified by LeoLabs approximately 6 days before the time of closest approach (TCA) and thereafter LeoLabs updated the event 22 times. LeoLabs' conjunction analysis for this event is summarized in Fig. 4.1. The TCA evolved by only about 40 milliseconds over the 6 days leading up to TCA. The final miss distance reported by LeoLabs was approximately 635 meters with a relative speed of about 7.5 km/s. The final Pc of the event was close to 0; this low Pc is due to the small uncertainties on the object states at TCA. However, just one to two days before TCA, the Pc was significantly higher, close to 10^{-3} (note this Pc calculation is computed using a combined hard-body radius, or HBR, of 5 meters).

The change in Pc is clearly evident in the uncertainty ellipses shown in the bottom right panel of Fig. 4.1. As time progresses, the ellipses trend slightly to the left in the conjunction plane, and close to TCA shrink in size narrowing in on the horizontal miss distance of about 650 meters. This shift and the resulting separation may have been due to an in-track change in one of objects, which may have conceivably been caused by a maneuver. This separation is especially easy to visualize in the 3D view shown in Fig. 4.2. Note, however, that the overall change in separation is encompassed within the uncertainties propagated to TCA.

A comparison between LeoLabs results, the CSpOC results derived from TLEs, and the CSpOC definitive SP ephemeris is shown in Table 4.1. The final probability of collision for LeoLabs is significantly lower than CSpOC's, however this is likely because of the change in Pc in the day leading up to TCA. The TCA and relative velocity from LeoLabs solutions are in excellent agreement with the results derived from CSpOC TLEs, and the LeoLabs miss distances are in excellent agreement with the CSpOC definitive solutions (well within uncertainties). The CSpOC TLE-derived miss distances, are in considerable disagreement with the LeoLabs and CSpOC definitive solutions. It is noteworthy that the TLE-derived miss distance was very consistent over time, varying between only 101 and 114 meters over the course of 6 days. This case clearly demonstrates that consistency does not imply accuracy. Nevertheless, comparing the definitive solutions, this case demonstrates strong consistency between LeoLabs and CSpOC with the additional updates provided by LeoLabs allowing for refinement in Pc in the 24 hours leading up to TCA.

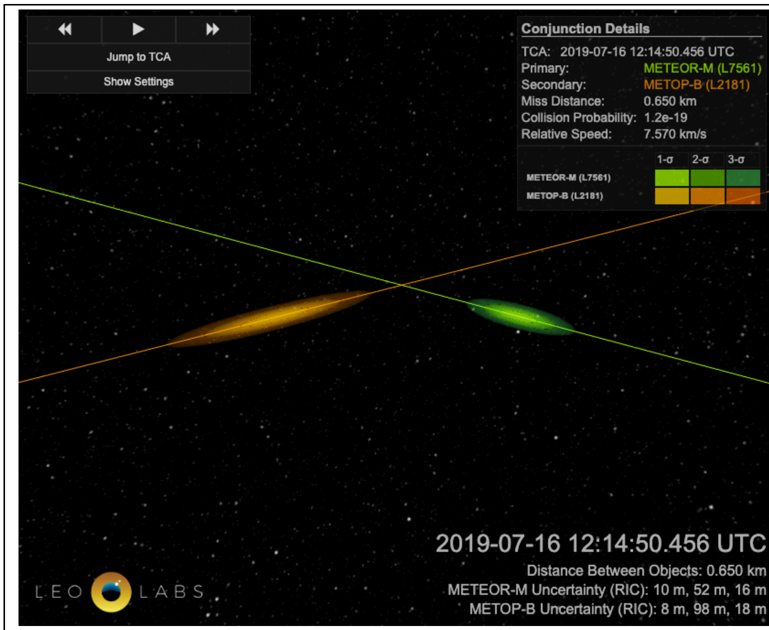

Fig. 4.2. LeoLabs' visualization of the conjunction highlighted in Section 4.1 in three-dimensions, at TCA.

Table 4.1. Comparison between LeoLabs and CSpOC solutions for the event described in Section 4.1. The solutions are compared between LeoLabs, CSpOC TLEs, and CSpOC analysis from the definitive SP ephemeris.

Data Source	**TCA (UTC)**	**Probability of Collision**	**Relative Speed (km/s)**	**Miss Distance (m)**	**Radial Miss (m)**	**In-Track Miss (m)**	**Cross-Track Miss (m)**
LeoLabs	2019-07-16 12:14:50.453	6.4 x 10^{-21}	7.570	637	8.3	547.8	324.9
CSpOC (TLE)	2019-07-16 12:14:50	N/A	7.569	101	79	55	32
CSpoC (Def)	Unknown	1.25 x 10^{-3}	Unknown	712	18	612	362

4.2 Event 2: Satellite and parent upper stage rocket body

The second event that we will explore in detail is a conjunction between COSMOS 2322 (NORAD ID 23704) and an SL-16 rocket body (NORAD ID 22285). LeoLabs' Conjunction Analysis Report for this event is available at https://platform.leolabs.space/conjunctions/reports/5226403. As is commonly the case for this class of satellites, there are frequent repetitive conjunctions between the payload and the upper stage that deployed the satellite, making for a dangerous scenario with significant risk over the lifetime of the two objects. The objects have a combined mass of over 11,000 kg and a LeoLabs-reported RCS of approximately 8 m^2 for both objects (note that the CSpOC reported RCS is nearly twice as large for the payload). The two objects are observed to come in close proximity roughly every 2 months, with repeated close encounters over several orbits. The closest approach detected to date (beginning in March 2019) is the one described here.

On 21 May 2019, the objects came within approximately 95 meters of each other with a closing speed of nearly 14 km/s as reported by LeoLabs. LeoLabs initially detected the event approximately 6.5 days before TCA, and updated the event with 29 new, unique conjunction data messages (CDMs) in the days leading up to TCA. The TCA (not shown) evolved by less than 0.1 seconds over this time period. Fig. 4.3 (top left) shows the miss distance evolution and demonstrates the stability of the predictions along with a reduction in uncertainties as the propagation time decreased. The probability of collision (top right panel) shows a fairly stable Pc over that time period, in the range 10^{-6} to 10^{-7} – i.e., despite the objects having a very small miss, the small uncertainties at TCA results in a relatively low Pc. However, the Pc in this regime is very sensitive to the uncertainties and HBR. Shown in the bottom right panel of Fig. 4.3 is a sensitivity analysis of Pc, where we can see that a doubling of the uncertainty and a doubling of the HBR results in a nearly 6000 times increase in Pc (or an overall probability of collision in the range 0.01-0.1%). This was a high-risk conjunction that will likely repeat itself numerous times over the lifetime of the two objects.

A 3D snapshot in shown in Fig. 4.4. Unlike the event described in Section 4.1, the objects are not separated in-track at TCA by an appreciable amount. Instead, the miss is largely in the radial direction. The tight radial uncertainties afforded from LeoLabs' radar ranging measurements results in the low Pc for this event.

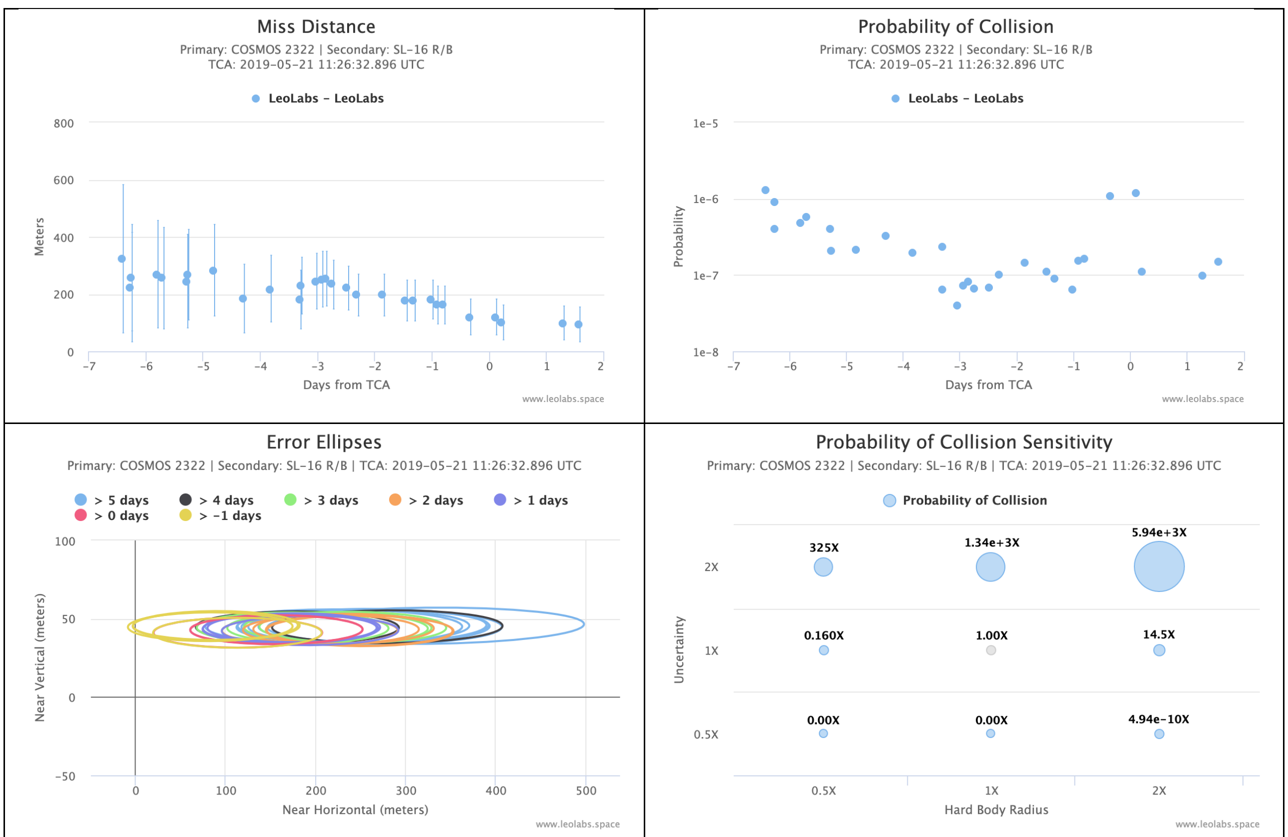

Fig. 4.3. LeoLabs' event analysis for the conjunction between COSMOS 2322 and an SL-16 rocket body on 21 May 2019, described in Section 4.2. (Top left) Miss distance with 1-sigma RMS uncertainty as a function of time. (Top right) Probability of collision as a function of time. (Bottom left) One-sigma error ellipses in the conjunction plane, color coded by days before TCA. (Bottom right) Probability of collision sensitivty analysis.

A comparison of the results from LeoLabs and CSpOC for this event is shown in Table 4.2. The comparison between LeoLabs and CSpOC definitive solutions again show good agreement: a largely radial and cross-track miss with a total separation distance of about 90 meters at TCA, within the error bounds of LeoLabs solutions (and presumably CSpOC's as well, but these were not available). The TLE-derived solutions show a larger miss and again demonstrate the danger of relying on TLE-based solutions for analysis of very close events. The TLE-derived TCA and relative speed, however, are in good agreement with LeoLabs' results. Over the course of four years of the MCMA effort, it has been found that TLE-derived miss distances after the event have a median mismatch from the SP-derived closest approach of 150 m, however, about 20% of the time the mismatch exceeds 1 km [7].

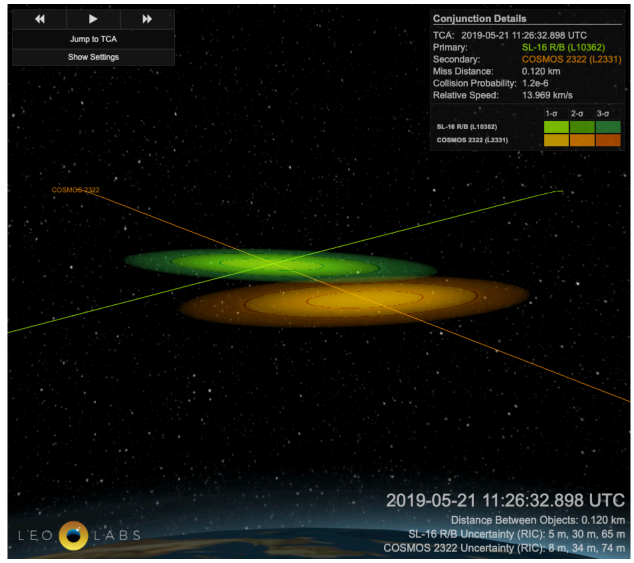

Fig. 4.4. LeoLabs' visualization of the conjunction highlighted in Section 4.2 in three-dimensions. The snapshot is at TCA.

Table 4.2. Comparison between LeoLabs and CSpOC solutions for the event described in Section 4.2.

Data Source	TCA (UTC)	Probability of Collision	Relative Speed (km/s)	Miss Distance (m)	Radial Miss (m)	In-Track Miss (m)	Cross-Track Miss (m)
LeoLabs	2019-05-21 11:26:32.898	~10^{-7}	13.969	94	45	29	78
CSpOC (TLE)	2019-05-21 11:26:32.985	N/A	13.969	189	147	44	110
CSpoC (Def)	Unknown	Unknown	13.968	87	75	16	42

4.3 Event 3: Satellite and rocket body encounter

The third and final event that we investigate is another close approach between a satellite and a rocket body, in this case not the payload's parent upper stage. The two objects are COSMOS 1459 (NORAD ID 14057) and the SL-8 rocket body with NORAD ID 28381, and the event took place on 24 June 2019. LeoLabs' Conjunction Analysis Report for this event is available at https://platform.leolabs.space/conjunctions/reports/9237784. These objects have a combined mass of over 2200 kg and each have an RCS of approximately 4 m^2 according to LeoLabs.

A summary of the data for this event is shown in Fig. 4.5. In this case, the LeoLabs-derived TCA, miss distance, and Pc evolved considerably in the days leading up to TCA. LeoLabs first identified the event approximately 3 days before TCA, and generated 16 unique CDMs for the event. The TCA evolved by over 0.1 seconds in those 3 days. In addition, despite the state solutions having low uncertainties, the miss distance evolved from about 850 meters 3 days out, to less than 100 meters in the retrospective analysis performed after TCA. This significant change resulted in the probability of collision evolving from a negligible value 3 days out to 10^{-3} to 10^{-4} on the day of the event. This is highlighted in the evolution of the error ellipses, which shifted in the horizontal plane but remained largely fixed in the vertical plane.

The final result for this event as reported by LeoLabs was a miss distance of approximately 97 meters at 12.635 km/s and a Pc close to 10^{-3}. The result derived from CSpOC TLEs showed a miss distance of approximately 60 meters at 12.635 km/s, in good agreement. This event appeared on the MCMA TLE list only the day before TCA, which is consistent with the significant evolution of the rocket body ephemeris. Data derived from CSpOC SP ephemeris were not available for this case. This event serves to demonstrate that frequent updates and continuous monitoring of events is needed in order to accurately predict collision risk. Events can evolve rapidly with time, and while the cause of that evolution is not always known, frequent updates and forecast revisions are required to accurately characterize risk.

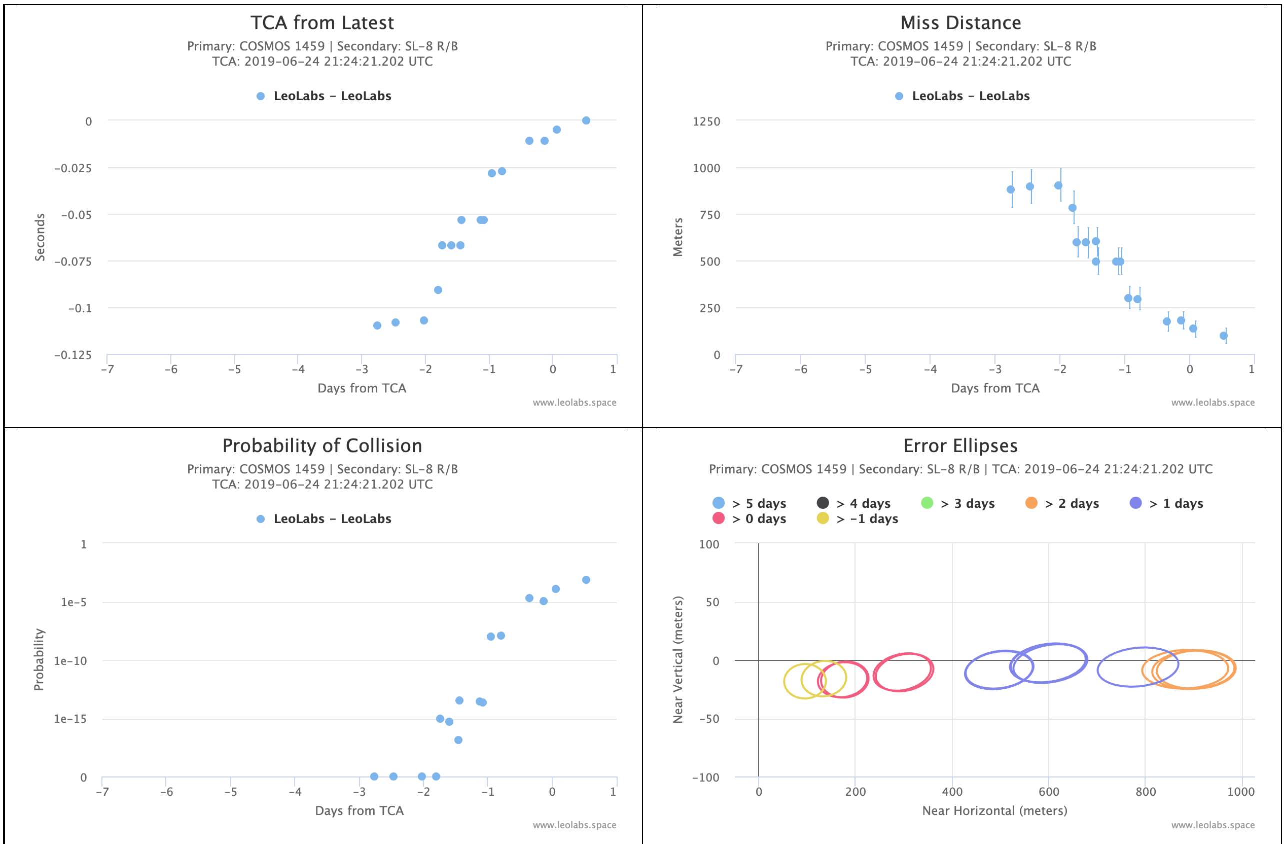

Fig. 4.5. LeoLabs' event analysis for a conjunction between COSMOS 1459 and an SL-8 rocket body on 24 May 2019. (Top left) TCA change as a function of time. (Top right) Miss distance with 1-sigma RMS uncertainty as a function of time. (Bottom left) Probability of collision as a function of time. (Bottom right) One-sigma error ellipses in the conjunction plane, color coded by days before TCA.

5 CONCLUSION

Debris-on-debris collisions currently go unmonitored today, yet they present the most likely scenario for large increases in the LEO space debris population. LeoLabs is now automatically analyzing and storing risky conjunctions for all objects in LEO, regardless of object type. LeoLabs high-precision ephemerides are able to provide the necessary data for full event analysis. Conversely, TLEs have limited accuracy [6] and should be used cautiously when applied to individual collision risk assessment and resulting collision avoidance maneuver planning. In addition, because TLEs do not encapsulate uncertainties, they cannot be used to produce metrics such as probability of collision or Mahalanobis distance, which are critical for assessing collision risk.

In this paper, we have focused on a particularly dangerous class of objects in LEO. In the 8-month study, we found 28 events involving massive objects (>775 kg in size) with probability of collision greater than 10^{-4}, which is the typical maneuver Pc for operational satellites (this number may be underestimated because of the hard-body radius of 5 meters used in the calculations). It is safe to say that the rocket bodies and defunct satellites involved in the majority of these conjunctions did not execute a collision avoidance maneuver.

The data represented in Figs. 4.1, 4.3, and 4.5 provide a concise yet complete depiction of the critical conjunction parameters that are not available from any other source. For example, depicting the sensitivity to HBR provides a unique perspective for the analyst. Further, plotting both the Pc and the covariances over time highlight critical environmental and measurement factors that provide context on the total event assessment. Lastly, the trending of the miss distance, TCA, Pc, and covariances permit a better understanding of whether final errors are due to environmental perturbations, too infrequent of measurements, or possible changing orientation of the object's being tracked; this last issue is much more important for the massive derelicts that drive potential debris-generating risk in LEO.

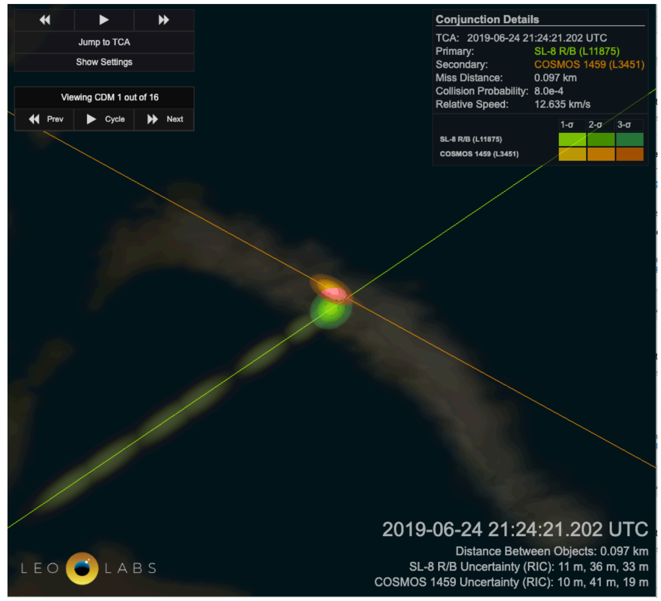

Fig. 4.6. LeoLabs' visualization of the evolution of the conjunction highlighted in Section 4.3 in three-dimensions, at TCA. In this case we show the evolution of the CDM as the shaded blobs evolving in time, especially evident for the SL-8 rocket body.

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