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The Axiom Mission 3 debris find in Ituna, Saskatchewan - Canadian Armed Forces lessons learned on re-entry processing

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Abstract

A mysterious space object crash-lands in a rural farm field… While this sounds like the opening lines of *Superman*, this paper describes the story of a derelict piece of space debris from the Axiom-3 (Ax-3) commercial crewed space mission which re-entered over western Canada in winter 2024. Ax-3 launched a four-person commercial astronaut crew to the International Space Station in January that year. Prior to the astronauts' return to Earth, the Ax-3 capsule released a "trunk" cargo and service module in orbit. The trunk remained on orbit until it eventually decayed in late February. The trunk re-entered Earth's atmosphere and traversed at high altitude above southern Alberta and Saskatchewan. Large fragments of the trunk were found by a grain farmer near Ituna, Saskatchewan in spring that year. This paper examines what was known about the trunk just prior to re-entry, observations of its re-entry, and discusses the lessons-learned from the Canadian re-entry assessment evaluation process. Footage from meteor cameras in southern Alberta observed the trunk at ~75 km altitude above Keho Lake, AB. Using this very short track some insights about the trunk's trajectory was inferred. The trunk appears to have re-entered slightly earlier than predicted by the 18th Space Defense Squadron (18 SDS) and did not appear to fragment until it reached altitudes near 40 km. The trunk's survival through re-entry also prompted some adjusted consideration of the Canadian Space Operations Centre (CANSpOC) processing. After the trunk decayed from orbit, the event was reported within CANSpOC's normal daily SDA brief, but did not raise concern about the trunk surviving re-entry. After debris from the trunk was recovered in Ituna, CANSpOC adjusted their re-entry assessment process reflecting the changed nature of space objects in orbit. While the risk to the public is generally considered low from re-entering space objects the relatively large mass and size of recovered fragments in Ituna arguably raises questions about the risk to the Canadian public on the ground or in flight. Key parameters for casualty risk assessment considering the trunk's re-entry were evaluated. A risk was clearly present given the size, mass and impact kinetic energy of the recovered fragments. Fortunately, the low spatial density of the population and the local time of the re-entry (~4:17 AM local time where most persons were indoors) reduced the likelihood of injury to unprotected persons.

Keywords: Re-entry, orbital decay, commercial space, space safety, casualty risk

Nomenclature

$\ddot{\vec{r}}$	Acceleration vector of a space object
$\vec{v}_{atmos}$	Atmospheric velocity vector (co-rotational)
$\vec{v}_{rel}$	Relative velocity of headwind on a re-entering space object
$\vec{h}$	Orbital angular momentum vector
A_h	Cross sectional area of average human (~0.36 m^2)
A_c	Collision cross sectional area (m^2)
A_i	Cross sectional area of debris fragment (m^2)
$\frac{A}{m}$	Area to mass ratio (m^2/kg)
C_d	Coefficient of drag (unitless)
$D_{\frac{A}{M}}$	NASA breakup model distribution function
$D_{\Delta v}$	Normal distribution of velocity of rocket body explosions
E_c	Casualty expectation (#/unit time)
H_0	Scale height (km)
L_c	Characteristic length (m) of a debris fragment

P_d	Population density (#/km^2)
$\vec{R}$	Position vector of Earth ground station
$\hat{l}$	Look angle vector (unit vector)
$\vec{r}$	Position vector of a space object
x_o	Initial state vector of a space object
Dv	Delta-v (velocity change)
λ_c	$\log_{10}(Lc)$
μ_1, μ_2	Bimodal distribution means
ρ_0	Atmospheric density
ρ_d	Atmospheric density
σ_1, σ_2	Bimodal distribution standard deviation
h	Altitude (km)
$N(\,)$	Normal distribution function
k	Number of impact events
r	Position of a space object (scalar)
x	Random number
α	Bimodal distribution weighting parameter
μ	Gravitational parameter (3.986 x 10^5 km^3/s^2)
ρ	Range to a space object (scalar)
$\rho(h)$	Atmospheric density as a function of altitude

Acronyms/Abbreviations

18 SDS	18th Space Defence Squadron
Ax-3	Axiom-3 commercial crew mission
CANSpOC	Canadian Space Operations Centre
DEC	Declination
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NOTAM	Notice to Airmen
RA	Right Ascension
SDA	Space Domain Awareness
TIP	Trajectory Impact Predication
TLE	Two Line Orbital Elements
UTC	Universal Coordinated Time

1. Introduction

On 18 January 2024 a commercial crewed astronaut mission, named Axiom-3 (Ax-3), operated by Axiom Space was launched to the International Space Station from Canaveral, Florida [1]. The crew was safely recovered on 9 February 2024 off the Florida coast. Just prior to the astronauts' recovery, a cylindrical cargo module, a SpaceX Crew Dragon "trunk" (see Figure 1) was jettisoned from the inhabited Dragon capsule. This object was left in orbit to naturally decay.

The trunk, referred to in the Space-Track satellite catalogue as 2024-014B (Axiom 3 Deb) [2] eventually decayed from orbit and re-entered over western Canada on 26 Feb 2024. Fragments of the trunk were recovered by a grain farmer south of Ituna, Saskatchewan in spring of 2024. A media release [3] broadcast in May 2024 yielded significant public attention to the survival of the fragmented trunk parts through atmospheric re-entry, and the larger problem of space debris in general. As the recovered trunk fragments did not cause personal injury or property damage, nor did they appear to contain hazardous materials, there was little action for the Government of Canada to undertake with exception of liaising with the US Department of State to arrange for the recovery of the fragments and provide compensation to implicated landowners by SpaceX.

Re-entry warning for Canada is typically initiated by allied information exchange beginning with the United States Space Force 18th Space Defence Squadron (18 SDS). The alert message, called a TIP (Tracking and Impact Prediction), is generally provided large objects which are historically known to be survivable or are known to be carrying toxic chemicals (such as rocket propellant). In the case of the Ax-3 trunk re-entry, both US and Canadian militaries were aware of the trunk's re-entry and overflight of Canada, but did not expect the trunk to survive re-entry.

While this re-entry was harmless, the recovered fragments' intact state, and their large mass and size does give rise to a legitimate concern about space object survivability that could pose risk to Canadians on the ground, in flight, or in Canada's territorial waters. This paper describes some findings regarding the Ax-3 trunk re-entry fragments, assesses the observations of the re-entering object over Canada, and describes the change in practice performed by the CANSpOC when assessing debris re-entry. An examination of casualty risk is also examined considering the known debris impacts in Ituna.

2. Crew Dragon and timeline

The SpaceX Crew Dragon is an inhabited spacecraft flown to the ISS and is offered for commercial astronaut missions by Axiom Space [1]. The Crew Dragon consists of an inhabited, pressurized module where the astronauts reside (figure 1 left). The uninhabited trunk provides solar power and additional cargo space to ferry supplies to the ISS or to deploy subsatellites [4] is attached below the Dragon capsule. SpaceX controls the Crew Dragon from their headquarters in California. The inhabited portion of the Dragon capsule from the Ax-3 mission was identified in the satellite catalogue as 2024-014A (58815). The trunk, once jettisoned from the capsule, was identified as 2024-014B (58953). The trunk is a hollow cylinder of ~3.7 m diameter with a volume of ~37 m^3 [4]. The trunk is approximately 3.6 meters in length and is approximately ~2.9 t mass. Assuming edge-on motion, the area-to-mass ratio of this thin shelled object would be approximately ~0.01 m^2/kg.

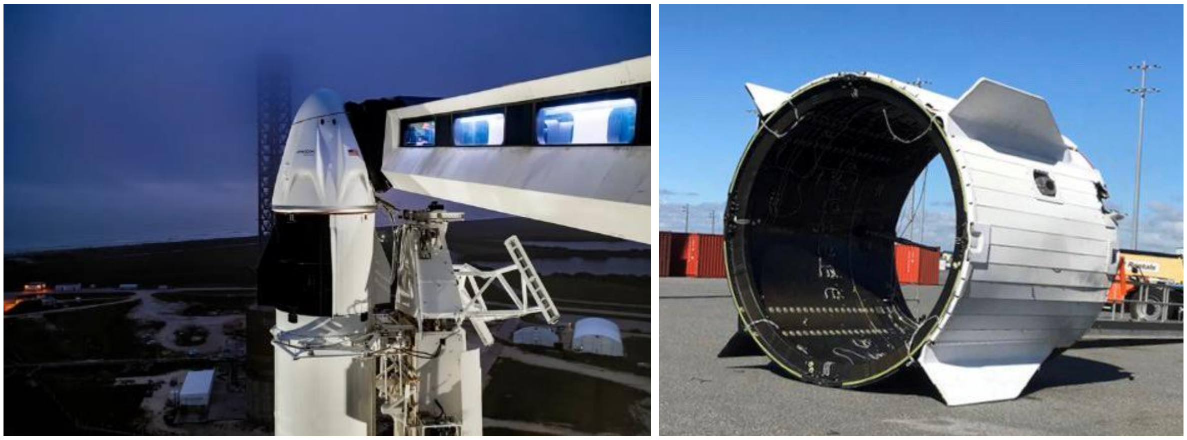


Fig.1. (*Left*): SpaceX Crew dragon (white capsule) and trunk (black and white cylindrical portion just below capsule) (*Right*): Trunk section after a flight abort test. Image credit: SpaceX non-commercial use license

The crew dragon docked with the International Space Station (ISS) on 20 Jan 2024. The altitude profile of the mission for both the Crewed capsule and the trunk is shown in Figure 2.

The trunk separated from the crew dragon and began its orbital decay with an initially eccentric orbit of 394 x 233 km. The two-line elements (TLE) orbital record for the trunk was regularly updated after separation following 7 Feb 2024. However, the TLE tracking data updates paused after 15 Feb 2024. The trunk did not appear to have TLEs published for a 10-day interval until they resumed on 25 Feb 2024, the day before its re-entry. It is unknown if this gap in the TLE record had an influence on the re-entry prediction process or if other means to update the trunk's orbit were being used (such as Special Perturbation vectors) during this gap in orbital custody. The object was large enough to be readily detected by ground-based radar so it is possible that the object was being detected, but published TLE data was not being produced.

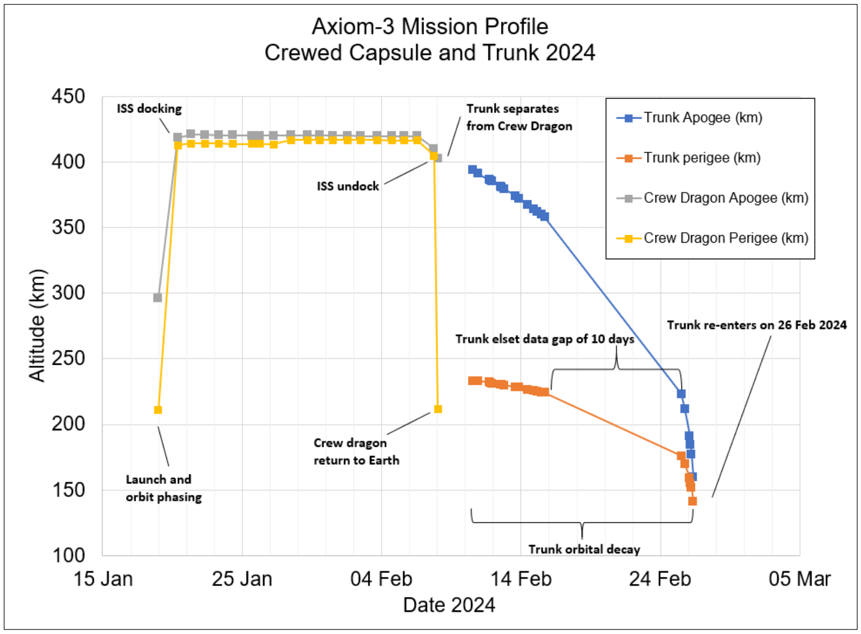
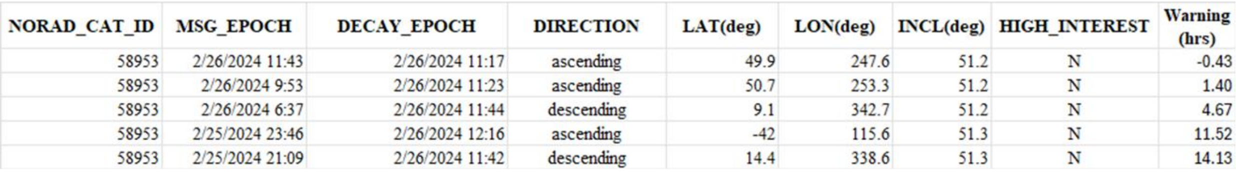


Fig.2. Orbital profile of the Axiom-3 mission showing the crewed mission portion (left side of plot) and trunk orbital decay (right side). Each point represents mean orbital data from TLEs produced by the 18th SDS. The trunk's had a 10-day period where TLE orbital data was not updated or published. TLE data for the trunk did not resume publication until the day before the trunk re-entry.

3. Warning history of object re-entry

The Canadian Space Operations Centre (CANSpOC) Space Domain Awareness section performs daily warning and monitoring of re-entries over Canada. If an object is of high interest, meaning a re-entering object poses a risk to the population of Canada or other environmental, security risk, CANSpOC will relay the information to the Canadian Government Operations Center (GOC). The GOC coordinates interaction with Public Safety, Global Affairs Canada, Canadian Space Agency, Fisheries and Oceans, NavCanada and provincial emergency coordination centres as required. The primary data source of data for re-entry assessment is the 18th Space Defence Squadron (18 SDS) who produces TIP messages [5] to forecast the predicted footprint of a re-entry. This product is available to authorized accounts via SpaceTrack.org [2] or is emailed directly to government users. The TIP message contains the predicted time, latitude and longitude of a space object's atmospheric entry. Generally, a TIP message is produced for objects with a radar cross section (RCS) larger than 1 m^2 within 4 days of the predicted re-entry interface. Table 1 shows the summarized TIP data for the Axiom 3 trunk re-entry. The TIP messages appear to have only begun being issued on 25 Feb 2024, the same day when the TLE updates reappeared for the trunk.

Table 1. Tracking Impact Prediction messages (TIP) messages for the Axiom-3 trunk prior to re-entry [2]



NORAD_CAT_ID	MSG_EPOCH	DECAY_EPOCH	DIRECTION	LAT(deg)	LON(deg)	INCL(deg)	HIGH_INTEREST	Warning (hrs)
58953	2/26/2024 11:43	2/26/2024 11:17	ascending	49.9	247.6	51.2	N	-0.43
58953	2/26/2024 9:53	2/26/2024 11:23	ascending	50.7	253.3	51.2	N	1.40
58953	2/26/2024 6:37	2/26/2024 11:44	descending	9.1	342.7	51.2	N	4.67
58953	2/25/2024 23:46	2/26/2024 12:16	ascending	-42	115.6	51.3	N	11.52
58953	2/25/2024 21:09	2/26/2024 11:42	descending	14.4	338.6	51.3	N	14.13

Table 1 shows that in less than 14 hours before re-entry there was ~1 hour of variation in the predicted time of the decay. While this predicted time of re-entry was relatively concise, the high orbital velocity of space objects in low Earth orbit can cover nearly 2/3 of the Earth in that time. It is therefore highly uncertain where the actual re-entry event would take place and regular tracking of decaying objects is required. The decay message, corresponding to the last message after re-entry (warning time of -0.43 hours) predicted that the object re-entered at 11:17 UT.

The criteria used for assessing the interest and concern level for Canada due to a re-entering space object is shown in Table 2. The CANSpOC was notified and aware of the predicted re-entry of the trunk and posted the upcoming event on their internal government daily Space Situational Awareness email [15]. Despite the trunk's predicted trajectory overflying Canada, the concern to Canada for the trunk's re-entry was assessed as "low" as its RCS did not exceed the ~10 m^2 threshold applied to higher concern re-entries. Re-entering space objects with an RCS greater than 10 m^2 are considered strong candidates to survive re-entry and may pose an impact risk on the ground. CANSpOC re-entry processing followed the standard processes where a TIP and decay message were noted, advised and assigned low interest as it was viewed to be less likely to survive re-entry.

Table 2. Re-entry assessment criteria used by the Canadian Space Operations Centre

Criteria	Threshold	Notes/Comments
Orbital inclination	Inclination > 41 degrees*	Determines if space object overflies Canadian territory or territorial waters
Radar Cross Section	RCS > 10 m^2	Typical threshold to estimate if a space object is likely to survive re-entry
Commander's directive	Commander's directive or judgment on security, safety and manned flight considerations for Canada	Applies to hazardous materials, national security concerns, significant media interest, human remains or respecting international treaty obligations
*denotes lowest geographic latitude of Canadian territory for consideration (41.68 deg)		

4. Ground based measurements of the trunk re-entry

After the trunk descended below its lowest sustainable altitude (approximately 120 km for a re-entering object) serendipitous measurements of the trunk's re-entry were made by a private meteor camera from the Global Meteor Network [14] operating south of Calgary, Alberta. Figure 3 shows composite images of the trunk's re-entry observed through heavy cloud. A short 2-second animation of the re-entry (captioned in Figure 3c) shows a single object with a visible ablation tail and possibly surface fragments separating from it. At the time of observation, the object did not appear to have fragmented (exploded) into larger pieces as of 11:17:38 UTC. The video possibly indicates smaller objects separating from its surface but a larger explosive event, which would have fragmented the object into dozens of larger pieces, does not appear to have occurred.

(a) (b) (c)

Fig.3. Trunk re-entry measurements from the CA001G meteor camera. (a): Initial detection of the trunk at 11:17:26 UTC marked by the arrow. (b): Stack of object detections until 11:17:38 UTC), (c): Single still taken from the 2-second animation of the trunk re-entry where a possible ablation tail appears. Image credits: Royal Astronomical Society of Canada - Calgary Centre.

3. Estimated Trajectory of the Trunk

The video of the object suggests that it was largely intact and did not appear to fragment into larger pieces. The timing of the video (11:17 UTC) suggests that the object, believed to be the trunk, began its re-entry descent earlier than the TIP prediction. Tracking data from the meteor camera included time and J2000 right ascension and declination angles measurements. This was more than enough to attempt measuring the object trajectory to verify that the detected object was indeed the trunk.

A single sensor optical sensor measuring "angles-only" positions cannot provide a full three-dimensional positioning of an object without a long, sweeping track on its orbital arc. Therefore, a-priori information about the trunk's motion was used to infer its position when measured by the meteor camera. An assumption is made that the trunk's orbital angular momentum $\vec{h} = \vec{r} \times \vec{v}$ forms a "plane" which the meteor camera angles measurements can be 'projected' onto. This constrains the measured position of the object and resolves the range ambiguity inherent in angles measurements. This is achieved by taking the slant range equation

$$\vec{r} = \rho\hat{l} + \vec{R} \qquad (1)$$

where ρ is the slant range, $\vec{R}$ is the J2000 position of the sensor position at the time of measurement and $\hat{l}$ is the look angle vector $\hat{l} = [\cos(\delta)\cos(\alpha) \quad \cos(\delta)sin(\alpha) \quad \sin(\delta)]^T$. Taking the dot product of (1) with the orbital angular momentum vector constrains the observations onto the virtual "plane" of the object's motion using the assumption that the orbital angular momentum vector is perpendicular to the orbital position vector of the object, e.g. $\vec{r} \cdot \vec{h} = 0$, such that

$$\vec{r} \cdot \vec{h} = \left(\rho\hat{l} + \vec{R}\right) \cdot \vec{h} = 0 \qquad (2)$$

Splitting the look angle vector $\hat{l}$ and orbital angular momentum vector $\vec{h} = [h_x \quad h_y \quad h_z]^T$ into components yields the following expression for the object position vector with indices *i* added to represent the observation time t_i

$$\vec{r}_i = -\frac{\vec{R}_i \cdot \vec{h}}{\hat{l}_i \cdot \vec{h}}\hat{l}_i + \vec{R}_i \qquad (3)$$

Using (3), the position and velocity of the object, as detected by the meteor camera, was approximately 74.9 km with a velocity of approximately 6.9 km/sec above Keho Lake, AB about 30 km northwest of Lethbridge, AB. Clearly the object was not a commercial aircraft. The short tracklet of angles measurements is shown in Figure 4 and the trajectory of the trunk, using the angles data for the 2 second track period, is shown in Figure 5.

The object's J2000 state vector at detection, corresponding to the start of the 2 second tracklet, and its epoch time is estimated to be:

$$x_o = \begin{bmatrix} -3528.417 \\ -2193.150 \\ 4921.362 \\ 4.6915 \\ -4.9656 \\ 1.0471 \end{bmatrix} (km), \left(\frac{km}{s}\right) \ with\ t_0 = \text{26 Feb 2024 11:17:38.124}$$

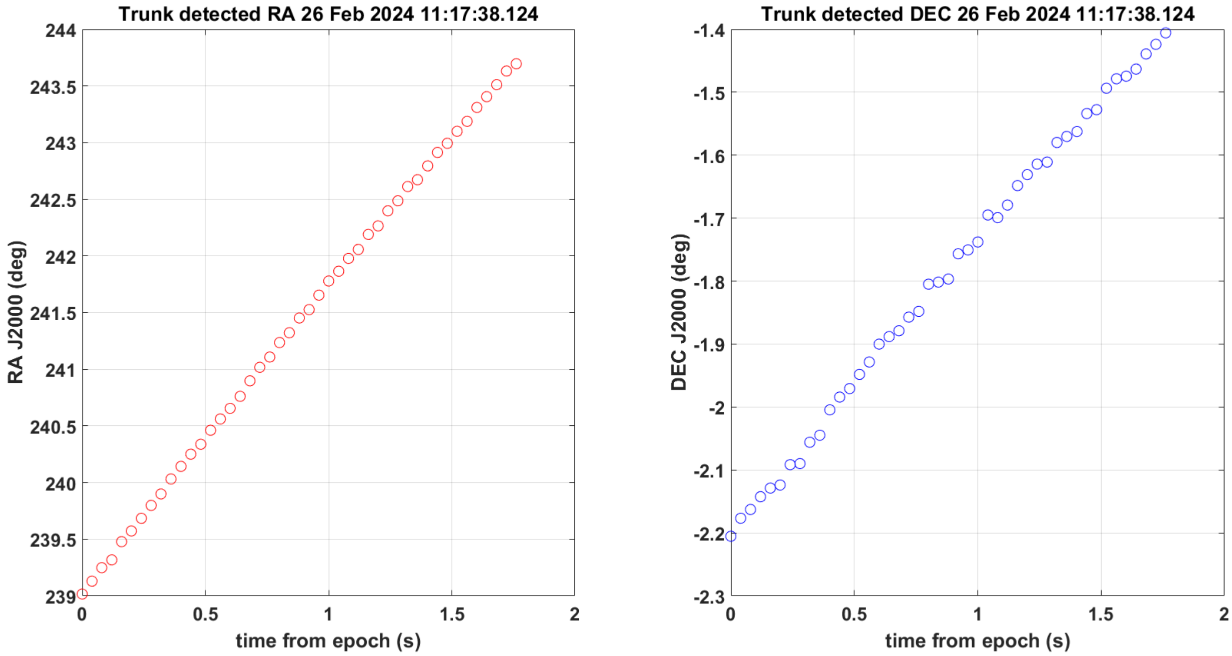


Fig.4. Measured trajectory of the trunk from the CA001G meteor camera

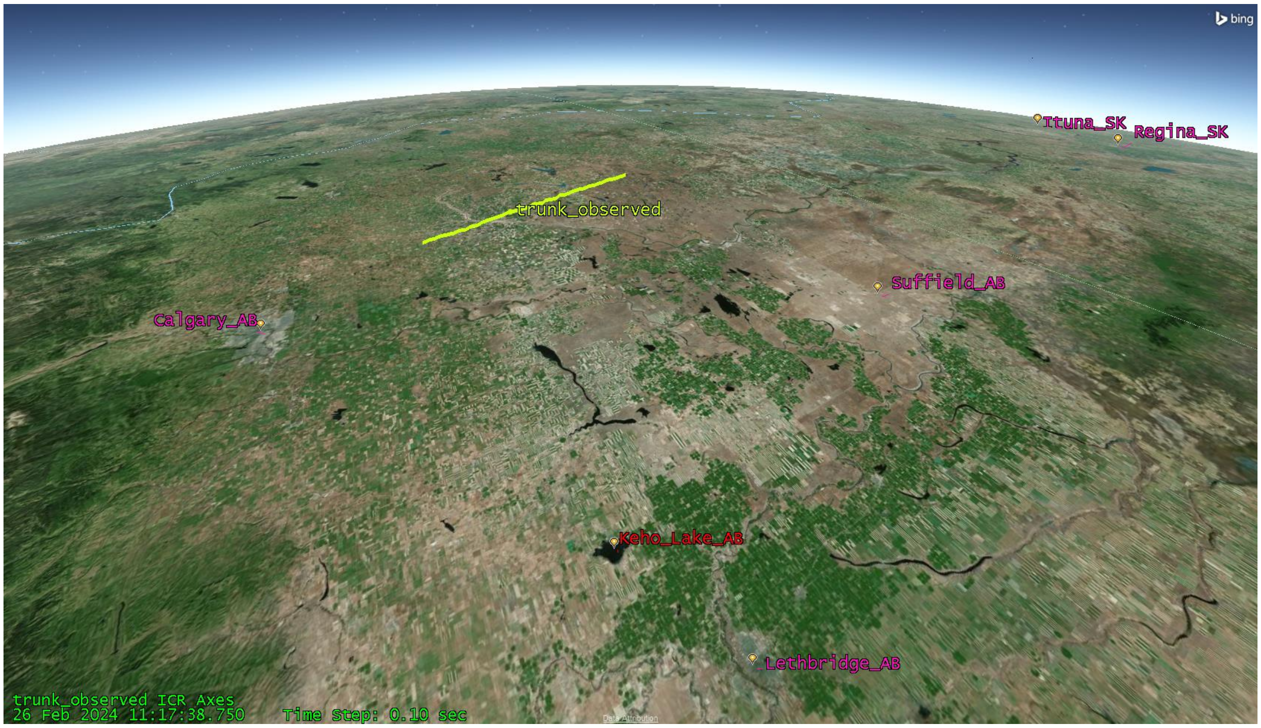


Fig.5. Measured track of the trunk (yellow segment) measured by the C001G ground-based meteor camera. The oscillation of the track is due to measurement noise from the camera. Object position was 74.9 km above Keho Lake, AB with an eastward velocity (toward top right) at ~6.9 km/sec.

3.1 Trajectory of the trunk

A model for the trunk's motion can be made using 2-body central body gravity acceleration and atmospheric drag acceleration (assuming no lifting force) as

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r} - \frac{1}{2}\rho_d\left(C_d\frac{A}{m}\right)|\vec{v}_{rel}|^2 \qquad (4)$$

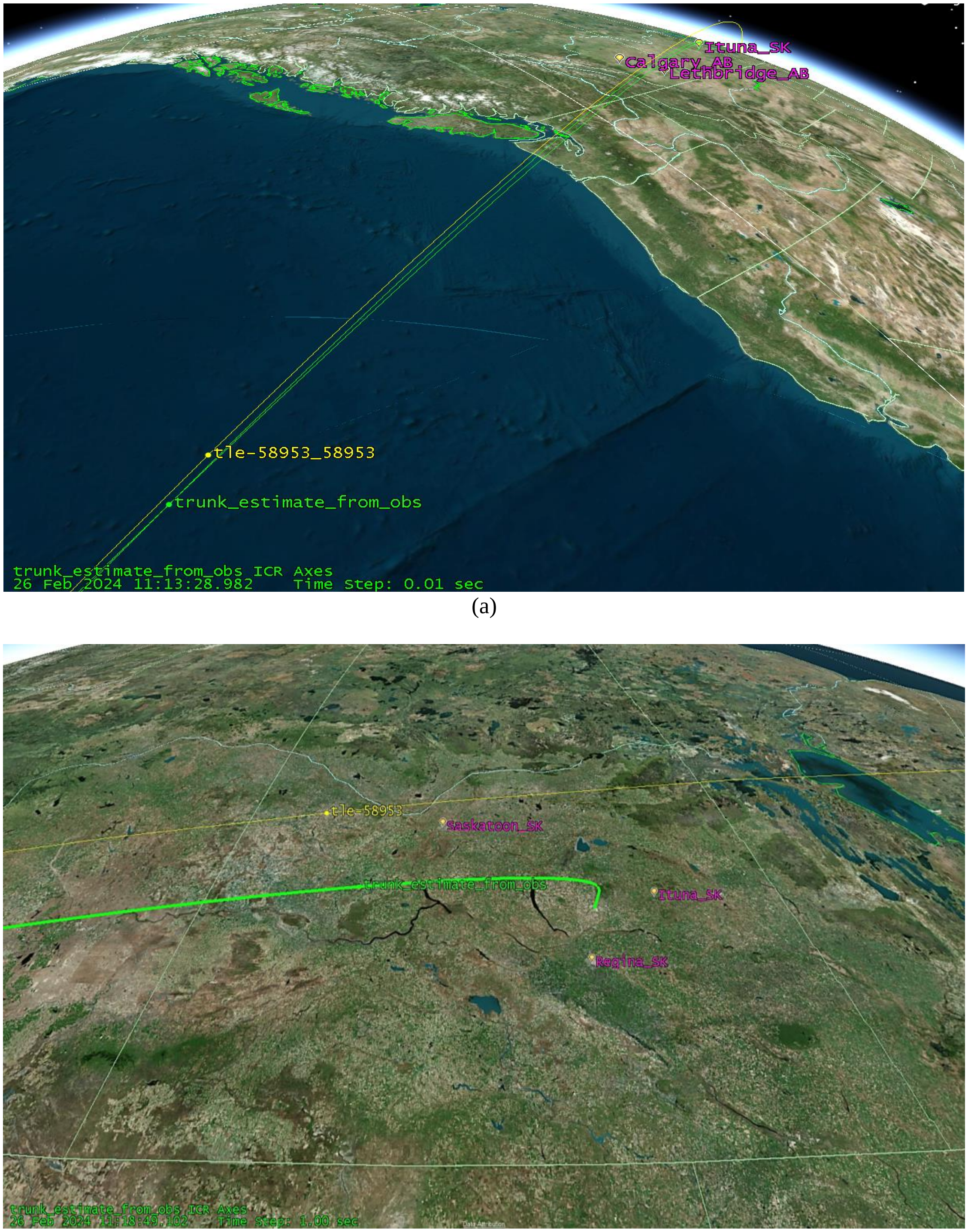
where $\vec{r}$ is the position vector of the trunk, C_d is the drag coefficient of the object, ρ is the atmospheric density at the altitude of the object's motion, A is the object cross sectional area (m^2), m is the mass of the object and $\vec{v}_{rel} = \vec{v}_{trunk} - \vec{v}_{atmos}$ is the object velocity relative to the corotating Earth atmosphere where $\vec{v}_{atmos} = \vec{\omega}_{\oplus} \times \vec{r}$. The bracketed product $\left(C_d\frac{A}{m}\right)$ is the ballistic parameter of a trunk fragment which will be modelled as a random variable in the next section. Atmospheric density ρ is modelled over lower altitudes by taking data from the CIRA-2012 model [7] for altitudes less than 150 km and fitting an exponential

$$\rho(h) = \rho_0 e^{-h/H_0} \ \text{[kg/m}^3\text{]} \qquad (5)$$

where h is the altitude of the object in km, ρ_0 is the base atmospheric density at mean sea level (1.225 kg/m^3) and H_0 is the fitted scale height of the atmosphere below 150 km where H_0 = 6.94 km.

Based on the measured initial state of the object measured by the Calgary meteor camera, a reverse propagation was performed using an order-of-magnitude estimated ballistic parameter of 0.01 kg/m^2. The reverse propagation agrees with the position of the trunk based on its last TLE from 42-155 kilometres. It appears that the trunk descended below 120 km altitude at 11:13:29 UTC near 42.0 °N, 137.2°W just west of the US and Canadian coastlines. Figure 6 (a) shows the reverse-propagated position of the trunk relative to the last two-line element orbital set. Comparing the time the trunk descended below 120 km to the second to last TIP message from Table 1 it appears that the trunk re-entered about 10 minutes early relative to the TIP prediction issued about 1.4 hours prior. The final (latest) TIP message in Table 2, known as the decay message, indicates that the trunk decayed at 11:17 UTC, about 3.5 minutes after the measured time of decay based on the short track of meteor camera data.

Forward propagating the same object detected above Keho Lake with the same ballistic parameter, it would have impacted ~66 km west of Ituna, Saskatchewan (see Figure 6 (b)). This gives good confidence that the object detected above Alberta was indeed the trunk given the consistency of its in-track motion relative to its last TLE, apparent altitude at the time of observation and approximate impact location. The next section examines the strewn field (debris field) by assuming two different rocket body breakup models to attempt to infer the altitude that the trunk primarily fragmented.



(a)

(b)

Fig.6. (***a***) Trajectory of the trunk (back-propagated) relative to the position of the trunk's last TLE. The trunk appears to have descended below 120 km altitude at 11:13:29 UTC whereas the second to last TIP message before re-entry predicted re-entry about 10 minutes later. (***b***) Forward propagation of the position of the trunk (green) assuming a ballistic coefficient of 0.01 m^2/kg. The consistency of the impact location 66 km west of Ituna, Saskatchewan and the approximate matching of the position of the object with the last trunk orbital TLE gives good confidence that it was indeed the trunk detected above Keho Lake, AB.

3. NASA Breakup model

The breakup of a re-entering space object does not have closed-form mathematical model due to the complex assembly of parts in most launch vehicles and satellites. We approximate the fragmentation of the Ax-3 trunk using the NASA breakup model [8] assuming the trunk fragments are like those of an upper stage rocket body. Rocket bodies, like the trunk, support large axial loads during launch and is modelled as a thin-walled cylindrical structure.

The ballistic parameter of fragments separated from the trunk are key to predict the down-range motion of the fragments in the atmosphere. For this analysis, the area-to-mass (*A/m*) ratios in the NASA breakup model for rocket bodies is used. There are some deviations prevalent in this assumption which we identify:

1) The trunk does not have a large, pressurized fuel tank as do upper stages from launch vehicles.
2) The trunk appears to have been constructed from a mix of aluminium and carbon fibre. This composite construction was not heavily used on upper stages used to form the NASA breakup model in the early 2000s. The NASA breakup model may underrepresent the *A/m* ratios due to the different material densities.
3) The trunk does not include dense mechanical parts present in the propulsion section from a launch vehicle, such as pump housings, valves, bell nozzles, combustion chambers and pressurant tanks.

The NASA breakup model generates two parameters for each simulated breakup fragment, its area-to-mass ratio and its delta velocity (Dv). The model described in Appendix A provides estimates of the *A/m* ratios for each fragment as a function of the characteristic size Lc of the fragment. We model Lc as a uniform distribution from ~11 cm to the largest dimension of the trunk (~3.7 m). A Matlab code was written to implement the model and estimates the total mass of the fragments generated to ensure mass conservation. The total surviving mass which was unablated was presumed to be 50% of the initial 2.9 t trunk re-entry mass. The area of a fragment is estimated [8] as

$$A_i = 0.556945 L_c^{\ 2} \quad \text{(for objects larger than 0.167 cm)} \qquad (6)$$

and the mass of each fragment is calculated using the above equation and the randomly drawn area-to-mass ratio $({}^{A}/_{m})_i$

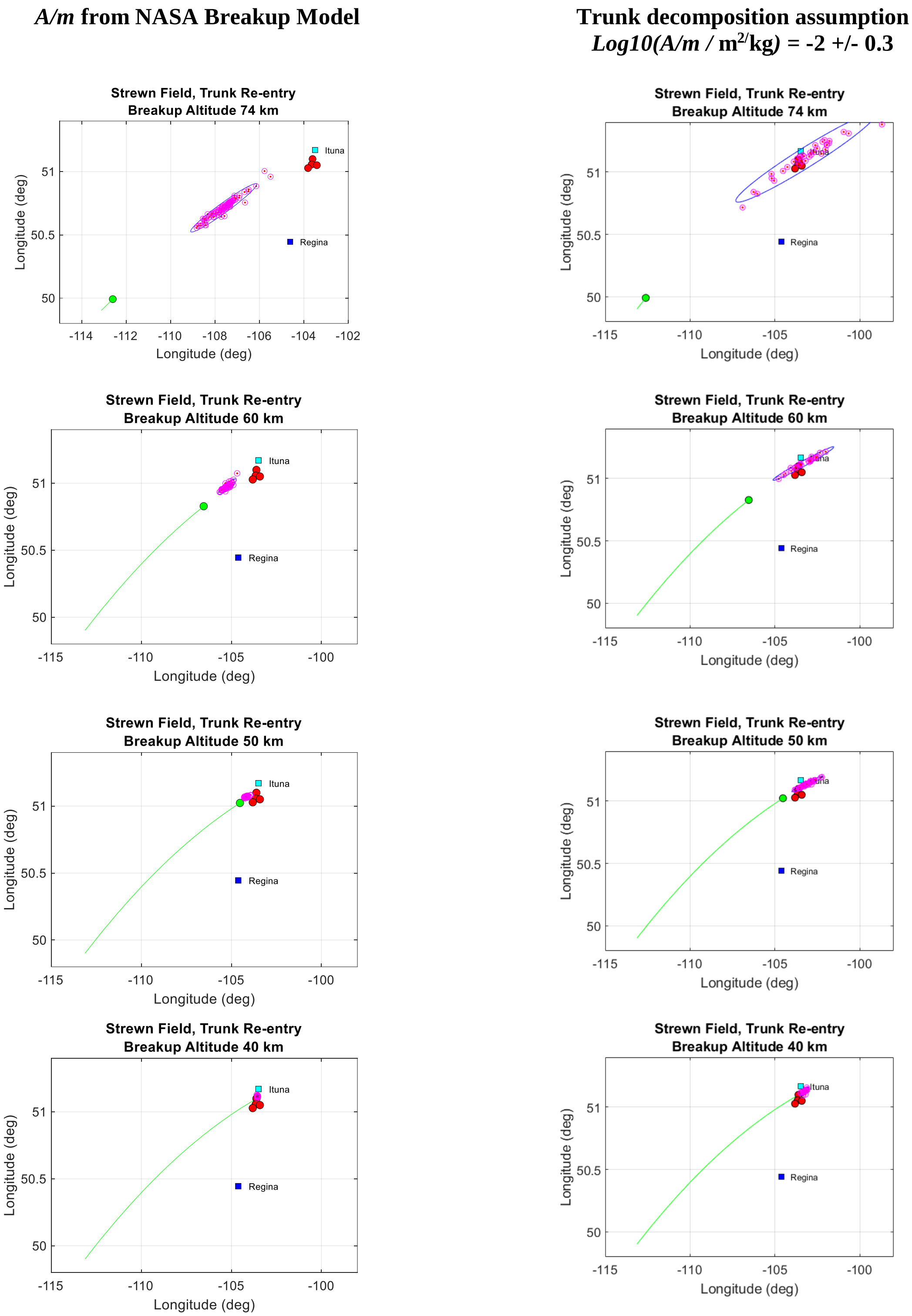
$$M_i = \frac{A_i}{({}^{A}/_{m})_i} \qquad (7)$$

3.1 Breakup altitude

Using the NASA breakup model and the dynamics model from section 3.1 a dispersion of ground impacted fragments (a strewn field) can be estimated. Breakup altitudes spanning 74 km (just after meteor camera observation) to 40 km are modelled and are shown in Figure 7 (left). The fragments (magenta points) illustrate where they were predicted to impact relative to the primary breakup location (green point) which is varied in altitude from 74 km to 40 km. The cities of Ituna and Regina, Saskatchewan are also shown for reference. The red points illustrate the locations of the known recovery of debris in 2024.

Figure 7 reveals that the dynamics model for the NASA generated debris fragments do closely match the location of the recovered debris and tend to “fall short” of the actual debris field location, excepting the lowest fragmentation altitude of 40 km. The strewn field is also somewhat dispersed northward of the actual recovered debris locations. This is likely due to errors in either the initial state derived from the meteor camera observations or stratospheric and tropospheric wind modelling which was neglected in our model affected the fragments’ motion. It is also notable that the strewn field footprint for the NASA model fragments, from toe to heel of the strewn field, compresses significantly as the breakup altitude decreases. This appears tied to the NASA breakup model which predominantly models the *A/m* ratios near ~0.12 m^2/kg. Such objects are strongly affected by atmospheric drag and are an order of magnitude larger in area-to-mass than the original parent trunk object was believed to be (~0.01 m^2/kg).

Recognizing that the locations of the impact fragments from the NASA model are not consistent with the locations of recovered debris near Ituna, a simplified “decomposition model” was tested. This model fractures the hollow cylindrical trunk uniformly around its periphery with fragments spanning 11 cm to 3.7 m in size. Each piece has an *A/m* ratio consistent with the original trunk’s mean of 0.01 m^2/kg but with a standard deviation which was varied logarithmically by 0.3.



***A/m* from NASA Breakup Model**

Trunk decomposition assumption
***Log10(A/m /* $m^{2/}$*kg)* = -2 +/- 0.3**

Fig.7. Estimated spatial distribution of debris fragments (magenta points) assuming uniform breakup from 70 km to 40 km altitude. Left column is results from the NASA breakup model and right column from the simplified decomposition model. The green track and green point indicate the path and location of the trunk at fragmentation for each test altitude. Red points indicate locations where trunk fragments were recovered. Green and blue squares are the cities of Ituna and Regina.

The decomposition model more consistently matches the debris field's centroid location in all test altitude cases (see Figure 8 left). Also, the fragment debris field size for the decomposition model (Figure 8 right) shows better consistency when comparing the field elongation of the simulated field compared to the extent of recovered fragments. This comparison was computed by taking

$$\text{Field Elongation Consistency} = \left| log_{10}\left(\frac{\sigma_{simulated}}{\sigma_{recovered}}\right)\right| \qquad (8)$$

Where $\sigma_{simulated}$ is the 1-sigma elongation size of the simulated fragment dispersion and $\sigma_{recovered}$ is the recovered fragment 1-sigma size field elongation size. A value of zero is a perfect match for the size of the strewn field elongation. As only 5 pieces were reported recovered it is difficult to know if the measured field elongation is a true representation of the actual debris field size as some objects may not have been discovered and reported. However, this metric is useful additional information to help infer the breakup altitude.

Taking both models into consideration it appears that the trunk primarily fragmented near 40 km altitude. This is based on the better agreement of the decomposition model across all breakup altitudes and the minima in the field elongation consistency. The NASA model suggests the field elongation consistency agrees with a breakup at 60 km, however the centroid of that field falls considerably short of the actual recovered debris locations (see Figure 7 NASA model at 60 km altitude). If the trunk did primarily fragment at 40 km altitude, it is considerably lower than the 80 km expectation for a re-entering space object [9]. While it cannot be confirmed with this data, it is possible that the composite construction of the trunk may have maintained structural integrity longer throughout the re-entry phase in comparison to typical satellites and rocket bodies. A 2019 study on re-entry material survivability performed on CFRP and other composite parts found that CFRP tends to be more survivable, and more tolerant to re-entry heating levels with less mass loss than what re-entry models predict [10].

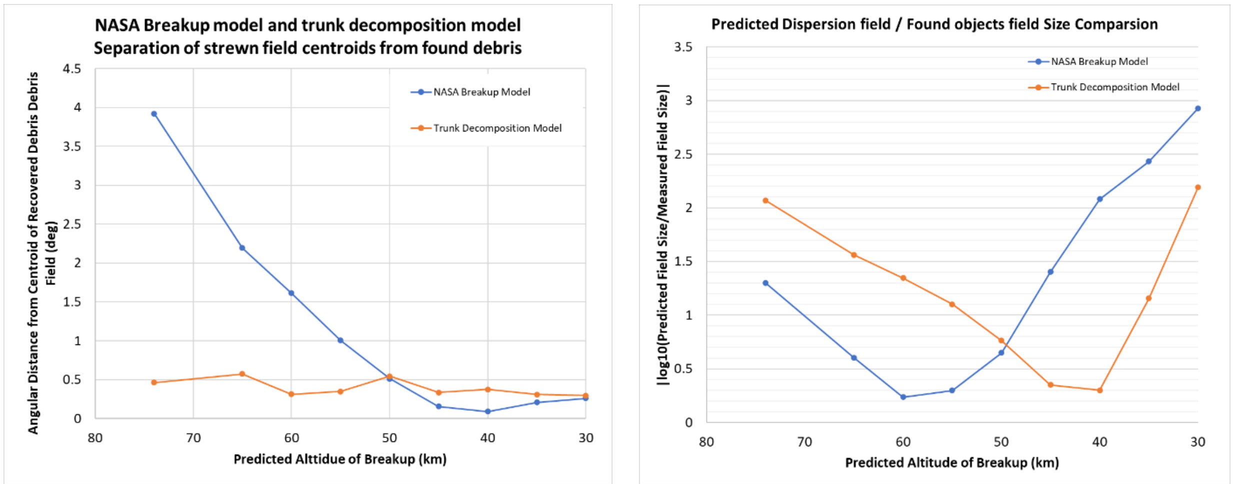


Fig.8. (*Left*): Predicted impact debris field centroids for the NASA breakup model and decomposition model. The trunk decomposition model is more consistent with the found debris for nearly all the altitude test cases. (*Right*): Field elongation consistency of the strewn field size to the size of the recovered objects using equation 8. It is believed that the trunk fragmented near 40 km altitude after the centroid location and strewn field size is compared to the locations of recovered debris near Ituna.

4. On the ground casualty assessment

Casualty assessment is based on the size of a fragmentary object impacting an unprotected human. A_h is the average cross-sectional area of an unprotected human (~0.36 m^2) [12] and A_i is the fragment cross sectional area used in the modelling for this paper. The total collision cross-section for a breakup is expressed as the sum of the individual collision radii added to the cross-sectional area of a human

$$A_c = \sum_j^N \left(\sqrt{A_h} + \sqrt{A_i}\right)^2 \qquad (8)$$

The expected casualty E_c is found taking the total collision cross section multiplied by the on-ground population density P_d

$$E_c = A_c P_d \qquad (9)$$

Canada's 2021 census [11] provides an estimate of the spatial distribution of persons per square kilometre (#/km^2) along the trunk's ground track in western Canada. This spatial density varies from 0.4 - 1 persons/km^2 depending on the rural and urban makeup of townships and cities in that region. A coarse estimate of the likelihood of 1 or more casualties from the trunk re-entry event can be made[*]. Assuming the object broke apart near 40 km altitude, the total casualty cross section is ~290 m^2. This corresponds to a computed casualty expectation between 1.1 x 10^{-4} casualties (0.4 persons/km^2) to 2.9 x 10^{-4} casualties (1.0 persons/km^2). This exceeds the casualty expectation for re-entering objects set in the NASA debris mitigation standard [12] and is high relative to the number of persons under the foot of the track of the trunk during its re-entry (~100,000 persons or more).

The fatality expectation is associated to the kinetic energy of the freefalling fragment. Objects with impact kinetic energies exceeding 15 J are injurious [12] and those exceeding ~103 J are considered fatal 50% of the time [6]. Figure 8 left shows the impact velocity and mass of fragments from a single run of the decomposition model. Figure 9 shows that nearly all simulated objects that hit the ground near Ituna would have had impact kinetic energies exceeding the 10^2 J 50% fatality threshold for an unprotected person. While clearly concerning, no injuries or fatalities were reported from the trunk's re-entry. The relatively low population spatial density, coupled with the fact that the re-entry occurred around 4 am local time reduced the likelihood of injury.

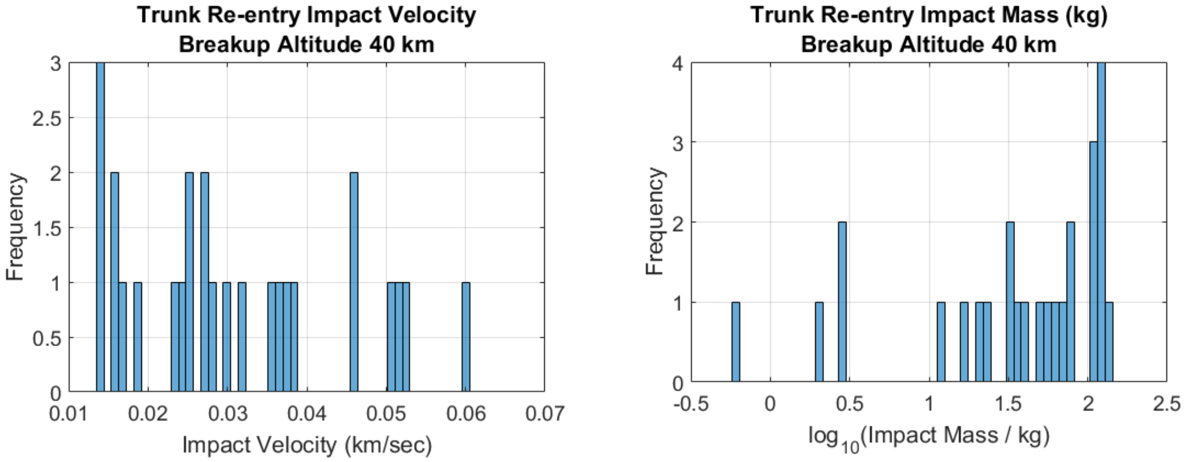


Fig.8. (Left): Speed of impact of fragments at impact. (Right): Mass of fragments

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[*] The Probability of k casualties can be estimated using Poisson statistics where $P(k) = \frac{{E_c}^k e^{-E_c}}{k!}$. Therefore, the probability of 1 or more casualties can be estimated as $P(k \geq 1) = 1 - P(0) \approx E_c$

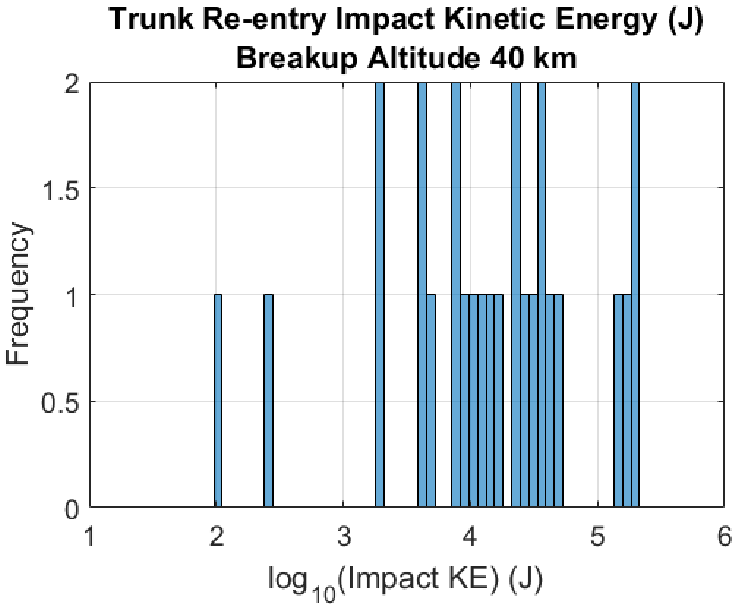

Fig.9. Kinetic energy of fragments.

Risk to Aircraft

Based on the decomposition model, we estimate that debris fragmenting from the trunk at 40 km altitude would have entered flight-controlled airspace (18.3 km altitude) within ~300 seconds (see Figure 10) depending on the fragment area-to-mass ratio. An estimate of mass of objects which could cause catastrophic damage to aircraft in flight can be estimated by using Figure 8 (right) where the average mass of a fragment would be ~60 kg. Again, there was no known damage to aircraft attributed to the trunk's re-entry. Further analysis will consider the track of modelled debris trajectories relative to aircraft known to have been operating near the trunk's descent.

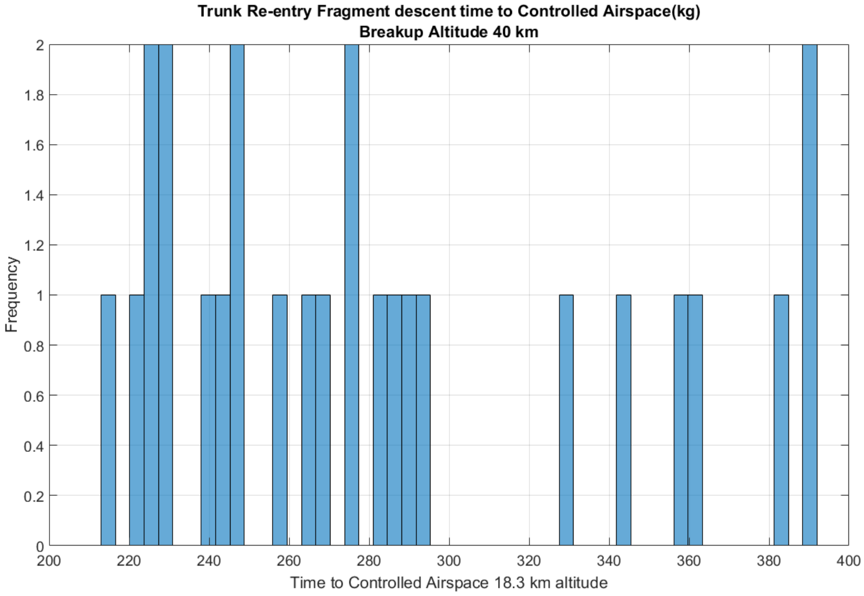

Fig.10. Time from breakup at 40 km altitude that debris would descend into controlled airspace (seconds)

5. Recovered debris

Mr Barry Sawchuk, a grain farmer south of Ituna, Saskatchewan noticed objects in his field during springtime preparations for the 2024 growing season. Figure 11 show photographs of the recovered objects taken by the University of Regina researcher Dr Sam Lawler. The fragments appear to be a mixture of both aluminium and carbon fibre weaves. Five fragments are known to have been recovered in the Ituna region and their approximate locations of recovery are shown in Figure 12. Figure 13 shows all recovered fragments returned to SpaceX. The largest of which is approximately 2.5 meters long. It is clear that a risk was present given the size of the recovered fragments.

Fig.11. Debris recovered from the Ituna area by Mr. Sawchuk, Image credit: Dr Samantha Lawler, University of Regina.

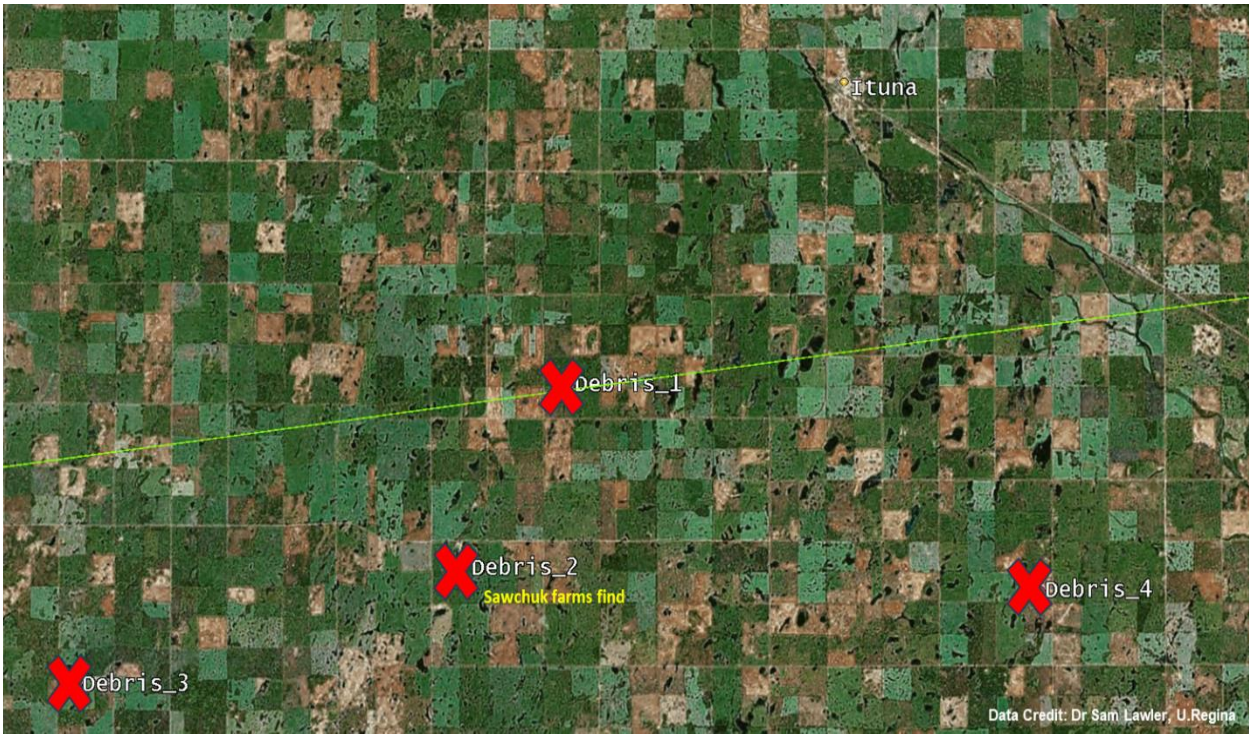

Fig.12. Locations of reported trunk fragment finds. Debris_2 is the location of the Sawchuk Farms find where two fragments were recovered. The yellow line is the round track of the trunk's last orbital revolution. Data credit: Dr Sam Lawler [13].

Fig.13. Fragments from the trunk recovered near Ituna and later returned to SpaceX. The tallest object on the left is approximately 2.5 meters in length. Image credit Dr Sam Lawler [13].

5. Discussion and Recommendations

The recovery of space debris in western Canada is a reminder of the significant changes occurring in low Earth orbit and the risks involved. Some discussion and recommendations based on this analysis are as follows:

a) The apparent loss of track of the trunk for nearly 10 days before the first TIP messages were received is notable. It is not known at this time if other orbital data was available to perform the re-entry assessment process. However, given that the usual processing for orbital decays normally has a 5-day look ahead, it is possible that the trunk was not actively tracked. Follow-up on this is recommended to determine the cause of the “gap” in orbital data and to determine if orbital custody was maintained by other data.

b) The assessment process used by the Canadian Armed Forces when examining this re-entry was consistent with prior established practice. The radar cross section of the trunk did not rise above the 10 m^2 threshold considered to be a high risk for re-entry survival. It is suspected that the material composition of the trunk made it tolerant to re-entry heating and increased its likelihood of survival. The Canadian Armed Forces are examining how to adjust the threshold of warning and whether material composition should play a role in this assessment process. It is known that other trunk fragments were recovered in Australia and the US from separate missions [16]. As the Crew Dragon trunk is known for its re-entry survivability, the Canadian Armed Forces should consider this in future assessments.

c) The use of serendipitous meteor camera data to track the trunk during its atmospheric flight worked relatively well to reconstruct insight about the trunk’s motion. Constraining the camera angles data onto the orbital angular momentum plane resulted in a state vector consistent with both the impact area near Ituna and the last orbital TLE of the trunk with simple assumptions for the ballistic behaviour. It was fortunate that the re-entry occurred at nighttime and within view of one of the meteor cameras from the Global Meteor Network [14]. If the re-entry occurred during the day there would not have been tracking data to perform this analysis. Remarkably, despite heavy clouds the camera was able to detect the re-entering trunk with sufficient data accuracy to estimate the trunk trajectory. An expanded analysis would attempt to obtain radar tracking data, if available, to determine if fragment trajectories were observed by another tracking source.

d) The NASA breakup model for rocket bodies was a reasonable first approximation for the breakup of the trunk providing fragment area-to-mass ratios and fragment delta-Vs relative to the parent at the time of breakup. However, the relatively high area to mass ratios from the NASA model were less consistent with the location of fragment finds compared to the simplified decomposition model. The decomposition model assumed that most of the trunk's mass was concentrated around its perimeter wall with an average area-to-mass ratio of ~0.01 m^2/kg consistent with the trunk's overall area-to-mass ratio. More investigation is required on the applicability of the NASA breakup model for composite and low-density aerospace parts given their higher heat resistance compared to aluminium and other common metals used in satellite construction. As the meteor camera did not reveal multiple independent tracks during the two second observation track we believe the trunk's primary break up occurred closer to 40 km altitude which provided a fragmentation area consistent with both the location and spread of the recovered debris fragments. The measured positions of recovered debris only have 5 datapoints to determine the elongation of the fragment field. This may bias our estimate as more fragment impact locations would help refine this analysis.

e) As the re-entry model used in this analysis did not include upper and lower atmospheric winds the locations of the debris may be biased northward. Surface fragments would have been ejected from the trunk at any time during the re-entry, and some surface fragments appear to have been observed by the meteor camera, however this analysis is of the view that these smaller surface fragments were more likely to have demised, or were simply too small to be noticed by local landowners if they impacted the ground.

f) The casualty expectation for this event, summed over the objects formed during the breakup was ~1×10^{-4}. No casualties were reported for this re-entry and is attributed to the lower general population density under the track of the trunk and that the re-entry occurred when most persons were indoors asleep. The breakup model suggests that all fragments would have contained enough impact kinetic energy to cause serious injury or fatality to an unprotected human.

g) Our modelling of the breakup suggests that fragments from the trunk entered controlled airspace (18.3 km altitude) within 300 seconds. If a re-entry and breakup over Canada were confirmed, there would be little time to issue a Notice to Airmen (NOTAM) in order for aircraft to avoid the ground track of a re-entering object. Further examination of the navigation warning processes is recommended to help ensure that the maximum warning time can be offered to assist air safety. Also, this analysis did not consider which aircraft transited below the trunk during its re-entry. Future analysis will consider this detail.

6. Conclusions

The Axiom-3 trunk re-entry over Western Canada was a wake-up call for Canadian space safety operations. This analysis finds that there appears to have been a period of tine where the trunk did not appear to be tracked (from the general perturbation TLE catalogue at least) for ~10 days leading up to the day before re-entry. The RCS thresholds to consider a re-entering object to be likely to survive are now being reconsidered given the new aerospace materials, and known object history, of space objects now in use in the expanding commercial space enterprise. The NASA Standard breakup model for debris fragments was less consistent with debris fragment behaviour in comparison to a simplified decomposition model of the trunk. The decomposition model had higher consistency with the recovered debris locations and the debris field size. We estimate that the trunk largely fragmented near 40 km altitude given the simulated location and debris field size compared to the positions of fragments that were recovered. While our modelling lacks radar tracking data of trunk fragment motion in the atmosphere it is clear a risk of injury and damage was present.

Acknowledgements

It is a pleasure to acknowledge the insight and experiences from Mr Barry Sawchuk who took the time to gather the trunk's debris and inform others of the significant find on his property. We thank Mr Sawchuk for taking the time to have a telephone conversation with one of the authors describing his experience. We also commend his community skating rink aspiration and hope that this project comes to fruition. We would also like to thank David Brown of the Royal Astronomical Society of Canada's Calgary Centre for the meteor camera tracking data which observed the trunk re-entry, and the University of Western Global Meteor Network team (Denis Vida, Peter Brown) who extracted the archival data and footage from their servers. We also wish to acknowledge Dr Samantha Lawler from the University of Regina for her field work, data collection, images and advocacy pertaining to this re-entry and the space debris problem in general.

Appendix A: NASA Standard Breakup model for Rocket Bodies

To generate the *A/m* ratio for each breakup fragment, the model in [8] uses a combination of two normal distributions shown below. A MATLAB algorithm was written using a pseudorandom number generator with the two means and two standard deviations that are dependent on a randomly chosen characteristic length L_c (in meters). A characteristic length of 11 cm and larger was used in this simulation

$$D_{\frac{A}{M}}(\lambda_c, x) = \alpha(\lambda_c)N(\mu_1(\lambda_c), \sigma_1(\lambda_c), x) + (1 - \alpha(\lambda_c))N(\mu_2(\lambda_c), \sigma_2(\lambda_c), x) \qquad \text{(A.1)}$$

Where $\lambda_c = \log_{10}(L_c)$, $x = \log_{10}(\frac{A}{M})$, the variable (area to mass ratio) in the normal distribution $N(\mu(\lambda_c), \sigma(\lambda_c), x)$, the Gaussian Normal Distribution with mean μ and standard deviation σ, both of which may depend on λ_c.

$$\alpha = \begin{cases} 1 & \lambda_c \leq -1.4 \\ 1 - 0.3571(\lambda_c + 1.4) & -1.4 < \lambda_c < 0 \\ 0.5 & \lambda_c \geq 0 \end{cases} \qquad \text{(A.2)}$$

$$\mu_1 = \begin{cases} -0.45 & \lambda_c \leq -0.5 \\ -0.45 - 0.9(\lambda_c + 0.5) & -0.5 < \lambda_c < 0 \\ -0.9 & \lambda_c \geq 0 \end{cases} \qquad \text{(A.3)}$$

$$\sigma_1 = 0.55 \quad , \quad \mu_2 = -0.9 \qquad \text{(A.4)}$$

$$\sigma_2 = \begin{cases} 0.28 & \lambda_c \leq -1.0 \\ 0.28 - 0.1636(\lambda_c + 1) & -1.0 < \lambda_c < 0.1 \\ 0.1 & \lambda_c \geq 0.1 \end{cases} \qquad \text{(A.5)}$$

To generate the velocity increment of each breakup fragment, a pseudorandom probability was drawn and a single normal distribution describing the separation velocities was used. Like the area-to-mass ratio distribution, this also makes use of a pseudorandom number generator in MATLAB, using a mean and standard deviation that is dependent on the area- to-mass ratio

$$D_{\Delta v}(x, v) = N(\mu(x), \sigma(x), v) \qquad \text{(A.6)}$$

where $x = \log_{10}(\frac{A}{M})$, $v = \log_{10}(\Delta v)$, the variable (delta v increment) in the normal distribution $\mu_v = 0.2x + 1.85$ and $\sigma_v = 0.4$. As this distribution is a single Gaussian distribution the velocity increment is directly solvable from

$$\Delta v = 10^{\mu_v + \sqrt{2}\sigma_v erf^{-1}(2P_i - 1)}$$

References

[1] Axiom Space, Axiom Mission 3, 27 February 2024, https://www.axiomspace.com/missions/ax3, (accessed 5.03.25).

[2] Space-track website, Satellite Catalog, 5 Mar 2025, https://www.space-track.org/#catalog, (accessed 5.03.25).

[3] A.Stewart, Sask. Farmers baffled after finding strange object in prairie field, 9 May 2024, https://www.ctvnews.ca/regina/article/sask-farmers-baffled-after-finding-strange-object-in-prairie-field/, (accessed 5.03.25).

[4] SpaceX, Dragon, https://www.spacex.com/vehicles/dragon/, (accessed 5.03.25).

[5] Z.Slatton, D.McKissock,P.Adams, 19 SPCS Methods of Processing Re-entries of Space Objects, https://conference.sdo.esoc.esa.int/proceedings/isdrw04/paper/14/ISDRW04-paper14.pdf, (accessed 5.03.25).

[6] H. Klinkrad, Space Debris Models and Risk Analysis, 2006 ed., Springer, Chichester, UK, 2006.

[7] COSPAR, COSPAR International Reference Atmosphere CIRA 2012, Version 1.0, 31 July 2012.

[8] N. Johnson, P.H. Krisko, J.-C. Liou, P.D. Anz-Meador, NASA's new breakup model of EVOLVE 4, Advances in Space Research, Vol. 28, Issue 9, (2001), 1377-1384.

[9] Federal Aviation Administration, Risk Associated with Re-entry Disposal of satellites from Proposed Large Constellations in Low Earth Orbit, https://www.faa.gov/sites/faa.gov/files/Report_to_Congress_Reentry_Disposal_of_Satellites.pdf, (accessed 27.03.25).

[10] B.R. Greene, C.M. Sanchez, Demisability of GFRP and CFRP Components of Re-entering Orbital Debris: Phase 1 Test Results, IAASS Conference *Making Safety Happen*, El Segundo, CA, 15 May 2019.

[11] Statistics Canada, Population Distribution as of July 1, 2022, by census division, https://www150.statcan.gc.ca/n1/pub/91-214-x/2023001/section01-eng.htm, (accessed 11.03.25).

[12] National Aeronautics and Space Administration, Process for Limiting Space Debris, /https://explorers.larc.nasa.gov/HPSMEX/MO/pdf_files/step-2/nasa-std-8719.14__A.pdf, (accessed 11.03.25).

[13] Dr Sam Lawler, personal communication, dated 12 June 2025.

[14] Global Meteor Network, https://globalmeteornetwork.org/ (accessed 11.03.25).

[15] Cochrane, S., Fuller, M., SDA Daily Update Report, Daily email report from CANSpOC., 26 Feb 2024 15:30:52Z.

[16] B.Tingley, Space.com, https://www.space.com/nasa-confirms-debris-spacex-crew-dragon, (accessed 11.03.25).