DFN Team report

Analysis of Soyuz re-entry over Tasman Sea in Aug 2023

29 Feb 2024

Table of Contents

Executive Summary

On 7th August 2023 a fireball and sonic boom from re-entering space debris was reported by multiple witnesses in Melbourne and Tasmania. It was later established that the fireball was from the re-entry of a 2.5 ton Russian Soyuz 2.1b upper stage, delivering a Glonass positioning satellite into orbit. It was headed for the Southern Ocean to be discarded. Spacecraft re-entries happen all the time but are rarely witnessed. The majority are planned to occur over uninhabited areas of the Pacific, rather than populated areas, but even controlled events can have unintended consequences. In July 2022, a SpaceX spacecraft failed to break up as predicted, dropping large pieces across rural NSW and a 6km^2 area of dust over the Canberra water catchment. **Unplanned and uncontrolled re-entry of spacecraft or debris is becoming more common**, and the rate will increase as low Earth orbit becomes more congested and changes begin to occur around the forecasted solar maximum in 2025. **Some of these events can have devastating consequences.** On Jan. 24, 1978, a Soviet nuclear satellite re-entered the Earth's atmosphere and exploded over northern Canada, scattering radioactive debris across an area of 100s km^2. Aircraft are also at risk, with near-misses being reported by pilots.

Australia currently has no dedicated debris tracking facility, so the observation of any ad-hoc event of this nature must coincide with observations taken by existing facilities and instruments. Fortuitously for this event, it was captured by autonomous observatories of the Desert Fireball Network – a Curtin University project to track fireballs from asteroidal material. This report reviews how the Desert Fireball Network capability was used to estimate the trajectory and predict the impact site for this spacecraft. The DFN team were able to determine an accurate track for the fireball to within 1km, with it passing over Melbourne at a height of 65 km before heading southeast over the Bass Strait. The last observed point was at a height of 64 km, still travelling at 6.3 km/s. When the fireball was beyond the range of the observatories, we used our sophisticated modelling tools, which incorporates extremely high weather modelling using multiple nested domains to generate a 4D data product. The allowed us to determine the final fall position of the Soyuz upper stage with high confidence.

Australia does have sovereign capability and expertise to monitor the re-entering debris issue, if we look to scientific instrumentation designed and funded for other uses. The DFN is built to observe fireballs in the interior of Australia. The observations of the 7th August Soyuz event close to the coast were fortuitous. A system that would routinely capture this sort of data, covering areas occupied by 90% of the Australian population, enabling rapid response in the case of debris events, is entirely feasible. The hardware is already designed. The software pipeline is built. A team of researchers with >10 years experience are ready to implement it.

Figure 1 - Image captured by DFN camera at Invergordon, VIC (top); calculated re-entry trajectory (bottom).

1. Introduction

Notification was given to Airservices Australia of a planned re-entry of a Russian missile between 1300h – 1600h UTC on the 7th of August, with debris planned to fall in the Pacific Ocean southeast of Tasmania. It was later traced to a planned re-entry of a Soyuz 2.1b upper stage – a rocket launch from Plesetsk Cosmodrome, Russia delivering a Glonass positioning satellite into orbit. Although standard practice to discard rocket debris through planned re-entry events, they typically take place over uninhabited areas and not usually witnessed. This event was widely observed and reported by the public in Victoria and Tasmania. The fireball and sonic boom were reported by multiple witnesses in Melbourne and surrounds, but the only accurate record of its trajectory was from two observatories from the Desert Fireball Network (DFN). The DFN is able to re-create the segment of the trajectory it observed, and predict a fall location for the main mass.

Understanding these re-entry events is crucial to assessing the risk to the public when such an event occurs over a populated area. This report details an analysis and discussion of the re-entry by non-dedicated observation networks just before local midnight on the 7th of August 2023, by the Curtin University DFN team.

1.1 Background

Curtin University's Desert Fireball Network (DFN) supports a blue-sky research project aimed at observing fireballs from incoming space rocks, calculating orbital origins, predicting fall positions of meteorites and recovering them. The team have 10+ years of expertise in observation and modelling of objects entering the Earth's atmosphere and recovery of meteorites. For the DFN project, specialist camera systems and purpose-built high-precision wind modelling software are used within trajectory models to predict constrained fall areas. For landed object recovery (with a scientific focus on meteorites), surveying using drones and apply machine learning techniques can automatically detect anomalies in images. This network was deployed in 2015 with 51 sites across the south of the country, from the WA wheatbelt to South Australia, observing 5 million km2 of skies. It was designed with a 5-year lifetime, and although it has far exceeded this, the network is reaching end of life; operating at less than half capacity. Two refurbished cameras were recently installed in Victoria alongside cameras of the Global Meteor Network (GMN) to compliment and support meteor and fireball observations of natural meteor shower events. We were very fortunate that these two cameras near Stanhope and Invergordan were operational and directly observed the fireball over Victoria on the 7th/8th of August.

Re-entry cases are similar to natural events, travelling at hypersonic speeds through the atmosphere. Although the fireball went beyond the field of view of these cameras, the team have made an analysis of the trajectory over mainland Australia and have lent their expertise to reviewing and collecting data from other sources to predict a more constrained fall region for debris.

1.2 Report Overview

The available data and the re-entry sequence is reviewed, followed by details of methodologies for atmospheric and dark flight modelling. The final section provides discussion and conclusion from the analyses, and discusses implications and recommendations for future re-entry events.

3. Re-entry Review of Data

Just before local midnight on the 7th Aug (23:56 07/08/23 UTC), a fireball from re-entering debris was observed by two recently installed DFN cameras in Victoria, as well as by eyewitnesses in Victoria and Tasmania. Felt reports of the sonic boom were also reported to Geoscience Australia around the Melbourne area. Table 1 summarises the potential data sources for observing re-entering debris events given the lack of any dedicated network within Australia. These have all been used successfully for natural meteoroid events in the past, and could feed into re-entry observations for this and other events.

3.1 Observational data – DFN and GMN cameras

Two newly-installed Desert Fireball Network (DFN) camera sites in Victoria captured this event (see Figure 2). Points along the fireball path are recorded, with their corresponding time. A calibration image allows conversion of these points from pixel coordinates to astrometric right ascension and declination (see deliverables). The two observation sites provided an approximate trajectory for a 450 km section over southern Victoria before going beyond the field of view of these cameras. See section 4 for more detail.

The Global Meteor Network (GMN) is a citizen science program with volunteer/amateur run cameras around the world. It is configured to detect and triangulate faint meteors, and uses a video system with narrow field of view lenses. Due to this, it has a low observational area, requiring a dense network for effective coverage. The GMN/DFN pipelines are fully compatible, and have been used in conjunction with one another in the past. Although one GMN camera in Melbourne caught a segment of this fireball, the operator was on holiday, and was not able to save high resolution data before it was overwritten. The GMN could be considered for future observations of re-entering debris, though significant area coverage would not be cost effective[1].

3.2 Atmospheric data

After sufficient deceleration, re-entering objects lose enough energy that the fireball phenomena ceases. During the following ‘dark-flight’ descent through the stratosphere and troposphere, the atmosphere is highly variable. Upper atmosphere winds and density variations can significantly affect the fall of surviving space debris to the ground; impact positions can be shifted by several kilometres. In particular, upper atmosphere phenomena such as jet streams are the major drivers of how the fall line is shifted relative to an analysis without considering winds.

Modelling the fall of space debris through the dark-flight, or non-luminous phase requires high precision wind modelling. The DFN team uses a custom version of the NCAR atmospheric modelling system Weather Research and Forecasting software (WRF), incorporating real-world data (such as balloon flights), to model atmosphere dynamics. It extracts data relevant for the dark-flight scenario, producing a 3D data matrix for the suite of fall times.

3.3 Seismic and infrasound data

Seismic and acoustic measurements are valuable tools for identifying and locating natural meteoroids entering the Earth's atmosphere. The propagation of the shockwave can be recorded. Unlike optical, seismoacoustic techniques allow over-the-horizon measurements to be made, as well as provide energy estimates that can be directly converted to body mass, where velocity is known. While the body remains supersonic, seismoacoustic can continue to detect objects during the dark-flight phase.

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[1] Note: the UK has full coverage by the GMN, with 275 cameras which can be compared to the 6 DFN cameras needed to cover the same area across the Nullarbor. DFN systems are also designed to survive the harsh outback environment.

Table 1 - *Observation techniques and their limitations for detecting re-entering debris.*

Observation method	**Comment and limitations**	**Soyuz event detected?**
Optical	Optical sensors have a wide range of capabilities depending on the sensor, time resolution and access to calibration data. They are limited to bright flight trajectory (fireball) and by weather. Different levels of optical systems include: **Dedicated camera network** such as the Desert Fireball Network can provide high precision position and timing, all sky so can cover large areas, currently limited to night-time and cloud-free observing. **Fixed casual video/images** such as a from a security camera, are lower resolution and usually struggle with precision timing of frame capture. Calibration can be difficult if resolution limits ability to see stars at night. **Non-fixed casual video/images** such as dashcam or smartphones are very imprecise as calibration cannot easily be done. They are serendipitous recordings, usually as a response to an event and so rarely detect the beginning of an event.	2 DFN sites See 3.1 Smartphone video footage
Doppler weather radar	Can see small things falling, but is too infrequent to guarantee capture of larger objects. 24 hr coverage, but over a very limited area (up to 150 km from a station and up to ~8km altitude). Limited number of sites over Australia, mostly over population centres. Poor weather introduces noise.	None visible, though expected to be out of range
Other radar (military)	Issues with access to data	Unknown
Passive Radar	Requires a radio source in the correct direction, but can detect the high altitude ionisation trail of hypersonic trajectories. Example would be the Murchison Widefield Array in WA.	MWA out of range, but private/ industry arrays could have captured it.
Seismic/ Infrasound	Are able to capture the sonic boom from the trajectory shock wave. It has 24 hour coverage, and can detect events within ~250 km (potentially further for infrasound, but no test cases to check). Very limited spatial resolution and at most can confirm an event occurred (and order of magnitude distance). Generally hard to detect events in the large noisy datasets in real time, but they can be found in the data afterwards.	multiple seismic sites / felt reports See 3.3
Earth observation satellites	Can have multispectral sensors, potentially identifying material properties of debris. For example, JAXA's Himawari. They are low spatial resolution, and mostly limited by infrequent observations.	Not found
AMOS	Dedicated scientific instrumentation to observe the spectra of a fireball. It provides details of the observed chemistry involved in an event, but only a few observatories exist.	Out of range
CNEOS[2]	Detections posted from the US DoD ballistic warning system. Limited to events greater than 0.7kT TNT equivalent energy (insensitive to low velocity/energy events). High time sensitivity, but low spatial sensitivity.	Below threshold
Drone surveying	Detailed surveying and searching of a strewn field after landing/impact	No impact over land expected

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[2] https://cneos.jpl.nasa.gov/fireballs/

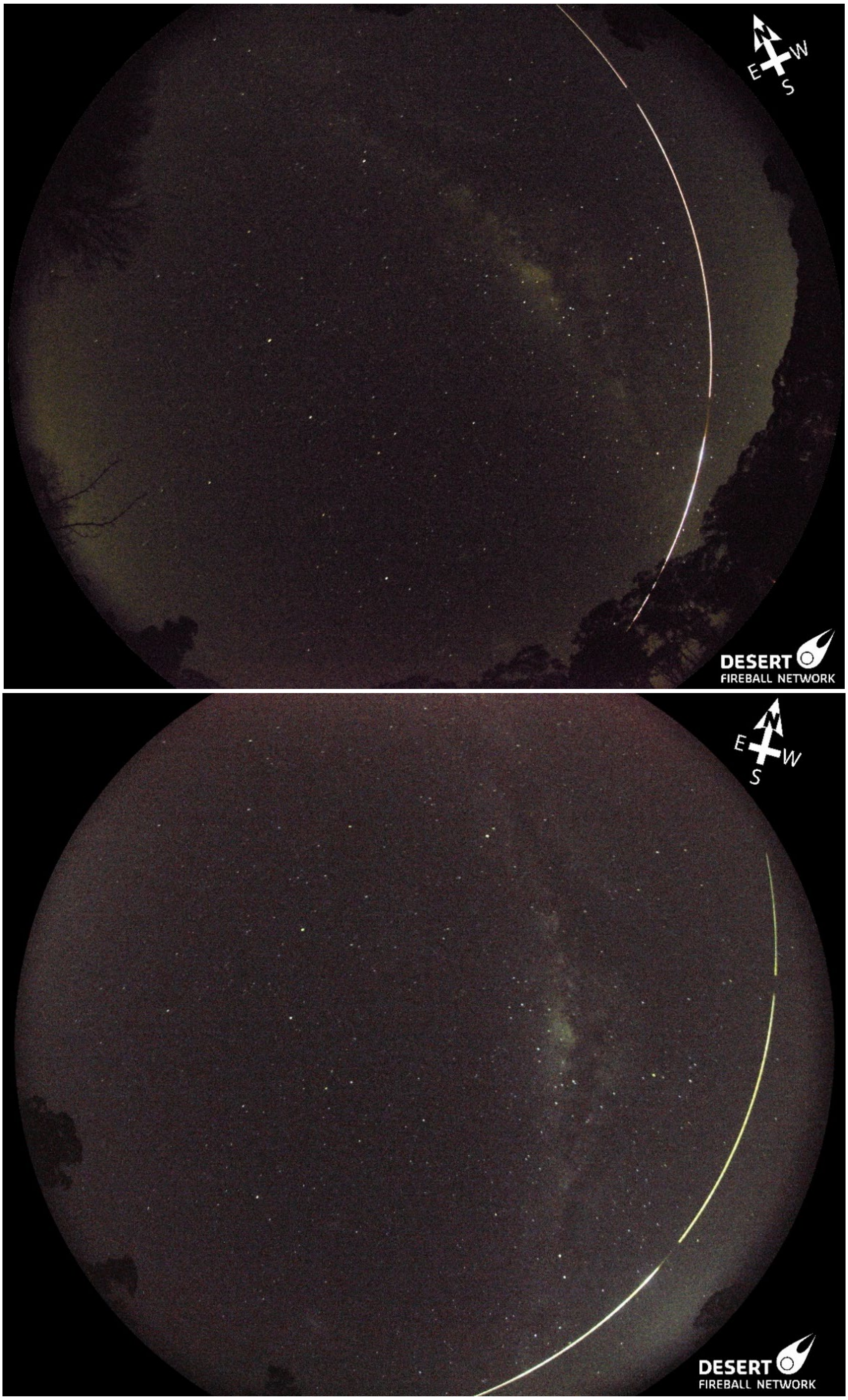

Figure 2: Fireball of the Soyuz module as captured by the DFN from Invergordon (above) and Stanhope (below). These are stacks of three 27 second, long-exposure images on 07/08/2023 between 13:56:00 and 13:57:30 UTC. Gaps are caused by a 3 second closure of the shutters between frames.

4. DFN DATA

4.1 DFN hardware and software pipeline

The main imaging system of the DFN fireball observatories is a 36 MPixel sensor: Nikon D810, combined with a Samyang lens 8 mm F/3.5. Long-exposure images, with a 27 second exposure, are taken every 30 s. Exposures are triggered roughly simultaneously across the network; however, the absolute and relative timing (from which the fireball velocity is derived) is embedded into the luminous trail itself by use of a liquid crystal (LC) shutter. This LC shutter is installed between the lens and image sensor in each observatory and is used to modulate the incoming light (by alternating between opaque and translucent states). Light is modulated according to a de-Brujin sequence (Howie et al. 2017) and is tightly regulated by a microcontroller synced with a Global Navigation Satellite System (GNSS) module. This ensures absolute timing accurate to 0.4 ms. For further details on DFN observatory specifications, see Howie et al. (2017).

Due to the light loss the LC shutter introduces, a calibration image is captured every half hour. The background stars are then used to provide an astrometric calibration to allow a conversion from x,y pixel coordinates in an image to spherical coordinates (right ascension/declination). Minute of arc astrometric precision is achieved with the method of Devillepoix (2018), allowing reliable astrometric measurements of observed fireballs down to $\sim 5^{\circ}$ elevations for clear horizon, and $\sim 10^{\circ}$ in the case of more light polluted and/or partly obstructed skies.

Decoding the de-Brujin sequence in the fireball trail is typically done on the green channel of an RGB image (see example in Figure 3), and provides a series of x, y points that are then converted to RA/DEC. Natural objects coming from beyond Earth's orbit enter at speeds above 11 km/s and can achieve speeds above 70 km/s. The 15 Hz frequency of the de-Brujin is optimised for these faster speeds, and lower angular velocities can produce highly condensed points that become difficult to decode. Re-entering debris will be travelling slower than 11 km/s and may be challenging with the current software configurations. In this case, as the object got further away from the observatories (>250 km) its angular velocity became too low to resolve timing further.

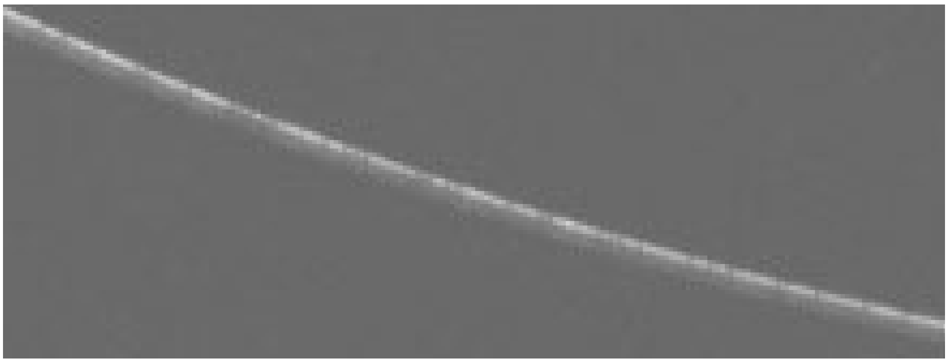

Figure 3 - A crop of the DFN image from Invergordon, where the green channel only from the RGB image is extracted to resolve LC shutter breaks.

Triangulation of an event requires two or more DFN observatories to have captured the fireball. The typical method follows an assumption of a straight line trajectory over a spherical Earth. The astrometric observations are converted to a plane, and the intersection of these planes provides the trajectory solution. For natural objects, this is usually sufficient as a typical fireball is ~6 seconds long; the effect of gravity can be disregarded compared to the ~100 m uncertainties. For longer events, the effect of gravity and other forces need to be accounted for. The Monte Carlo fitting techniques we use in these cases can account for gravity, but any lift forces or lateral spreading effects due to fragmentation, are still mostly unaccounted for and may need to be investigated further for re-entering debris events.

As the re-entry fireball continued beyond the field of view of the DFN cameras, we modified our darkflight integrator to predict the continuation of the object’s flight. A number of virtual particles of varying mass, density, and shape are generated within the modelled uncertainty surrounding the final triangulated position and velocity along the observed trajectory.

4.2 Triangulated trajectory

Three exposures from each of the Invergordon and Stanhope observatory sites captured the event. Data were acquired for 68.5 seconds of the fireball (~400 data points), spanning some 450 km. Triangulation of this event using our existing models posed challenging. We found the long, shallow, trajectory of a continuously fragmenting, non-spherical object, did not behave in quite the same way as incoming space rocks. The MonteCarlo fit was initially showing fit residuals of over 6 km at the trajectory ends (Figure 4). To improve this fit to our observations, we were required to run it in short segments. This has allowed us to estimate the trajectory, its height and speed, with fit residuals less than 1 km. This is still far off the ~100m we typically work with and reveals further investigation is needed into these re-entering debris events. Other considerations are likely needed, such as lift and shape factors to provide a higher fidelity result. Of interest is the variation to fits for the different segments. The higher altitude segment has lower residuals and could represent less atmospheric interaction with the object. This could also be an artifact of the majority of points being from a single viewpoint. Further investigation is needed.

From our triangulation, the object was first observed by the DFN cameras at a height of 73 km, going at a speed of 7.3 km/s. It passed over Melbourne at a height of 65km, before heading southeast over the Bass Strait. The last observed point was at a height of 64 km, still travelling at 6.1 km/s. By back-calculating the “entry” orbit of the object, we get an inclination of 65.3 degrees, consistent with that of a GLONASS satellite (64.8 degrees (Kumar et al. 2021)).

Table 2 - Observation summary for the two DFN cameras in Victoria.

	Invergordon	Stanhope
First obs time	13:56:14.0	13:56:25.2
Last obs time	13:57:22.5	13:57:09.8
Camera lat	-36.19844	-36.44022
Camera long	145.62069	144.99912

Table 3 - Triangulated trajectory summary

First observed position (Lat/Long/Height)	34.957389 °S, 141.973145 °W, 72.52 km
First velocity (in ECEF)	7324 m/s
Last observed position (Lat/Long/Height)	38.553424 °S, 144.842308 °E, 64.13 km
Last velocity (in ECEF)	6061 m/s
Slope of trajectory from local horizontal	~2°
Orbital inclination of incoming object	65.3 °

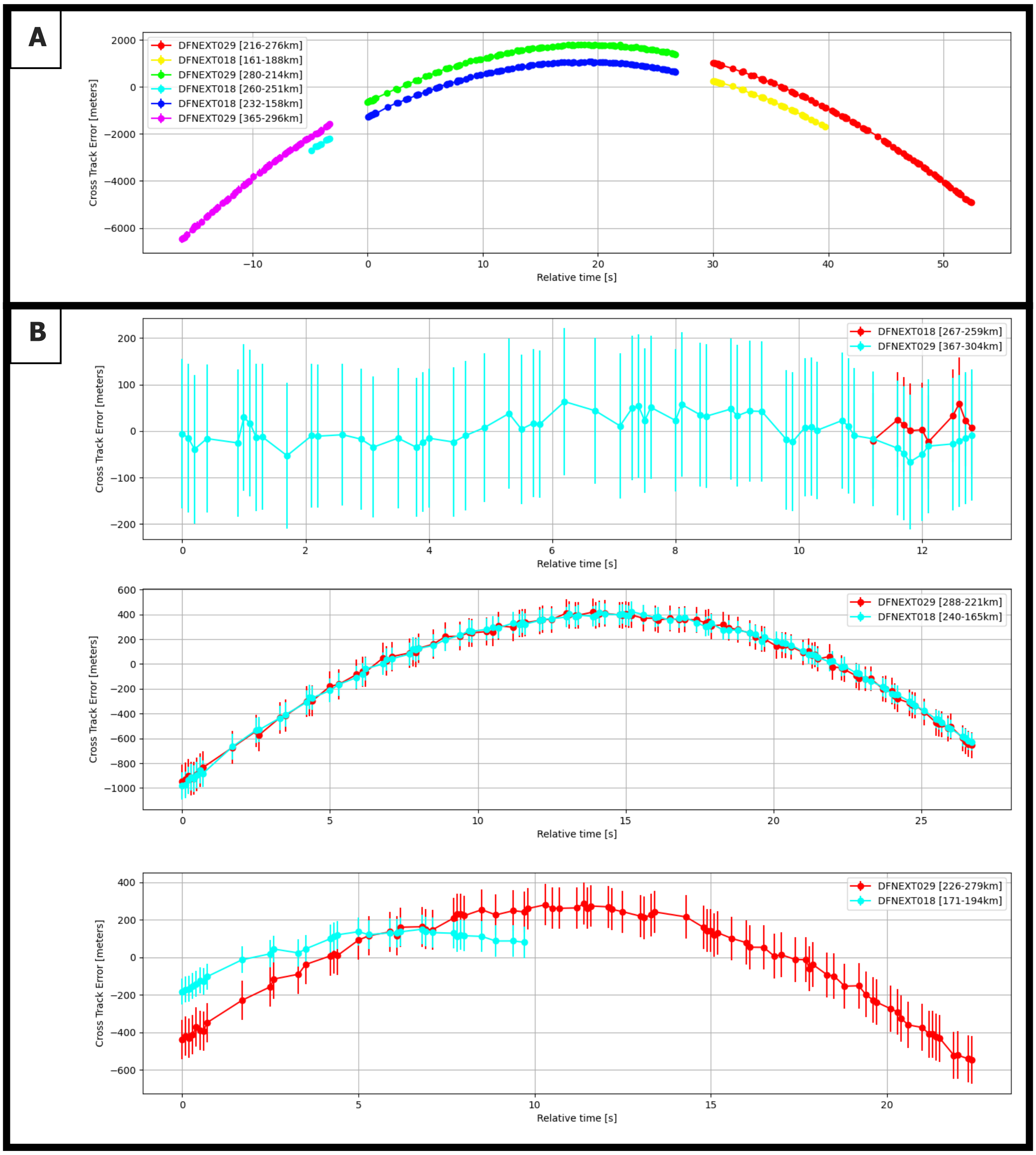

*Figure 4 -Cross-track residual plots from two different base model triangulation solutions. **A**: Best fit trajectory to all observations (method used for natural meteoroid events). This poor fit shows re-entry events will need additional considerations added to understand trajectory dynamics. **B**: Observations are split into three segments and triangulation run on separately. Upper plot represents observations above 73 km; middle 73 – 70 km altitude; lower below 70 km. Label shows observing camera name and distance range to fireball.*

5. Atmospheric Modelling

To predict the atmospheric properties, the DFN uses the NCAR atmospheric modelling system WRF version 4, with ARW dynamic core (Skamarock et al. 2019; https://doi.org/10.5065/D68S4MVH), initiated with NCEP FNL (Final) Global Tropospheric Analysis dataset (https://rda.ucar.edu/datasets/ds083.2/). The WRF is a forecast model that incorporates real-world data to model atmosphere dynamics, capable of being initialised from a global data set to generate mesoscale results at high spatial resolutions suitable for inputs into a dark-flight calculation. The WRF software generates a weather simulation product as a three-dimensional data matrix in a latitude/ longitude/height cuboid around the bright-flight endpoint. From the model, grid values are extracted for the atmospheric properties of relevance to trajectory modelling. This includes the pressure, density, temperature, relative humidity, and horizontal wind speeds as a function of height, latitude, and longitude (in u, v coordinates)

The WRF data cuboid is not necessarily north–south oriented and wind values must be extracted. Local verticals may also need to be corrected. For darkflight modelling of trajectories, this is incorporated into the calculation.

For convention in our analyses, we define wind directions in degrees, with north = 0, east positive, with a positive wind magnitude in the direction of wind travel, not the wind's origin.

As we are interpolating the past state of weather rather than forecasting, we can extract a physical model of the atmosphere based on observations both before and after the event, using the archived data from the NCEP FNL Operational Model Global Tropospheric Analysis online data sets. These contain snapshots of global weather conditions every 6 hours.

The modelling case uses 4 nested domains, from level 1 (4860x4860 km, 180x180 cells with 27km resolution) down to level 4 nested domain with resolution 1km of size 337 x 337 cells. Due to the stochastic nature of the WRF numerical modelling software, slightly different results are produced each time it is run, even with the same input data, but the model outputs do not provide any error analysis. To resolve this lack of defined error bars, we initiated several models using different archived global snapshots up to 24 hours before the time of the re-entry (7 August 2023, 14:00 UTC; Table 4).

Four runs were performed for an area south of Victoria and for Tasmania, where each run varied the simulation start time. These four models are compared in order to find out the stability of the weather (Towner et al., 2022).

5.1 4D Data Product Description

The provided 4D data is level 4, with 1 km resolution for an area of 337x337 kilometres around the two central points of coordinates: LAT=-38.552258, LON=144.83473 (south of Victoria) and LAT=-41.8900, LON=147.5500 (Tasmania).

The weather model product includes a number of parameters, of which wind speed components, pressure, temperature, and relative humidity at heights ranging up to 30 km are applicable for the re-entry trajectory modelling.

The WRF model output files are in NetCDF format V4 and contain 4D matrix of weather data for the duration of the simulation (weather parameters at latitude, longitude, height and time). More details on the NetCDF format can be find in the user guide (https://docs.unidata.ucar.edu/nug/current/)

Table 4: WRF model product files

File	Modelling start time UTC	Modelling end time UTC
wrfout_d04_2023-08-06_18:00:00	6 Aug 2023, 18:00:00	7 Aug 2023, 14:30:00
wrfout_d04_2023-08-07_00:00:00	7 Aug 2023, 0:00:00	7 Aug 2023, 14:30:00
wrfout_d04_2023-08-07_06:00:00	7 Aug 2023, 06:00:00	7 Aug 2023, 14:30:00
wrfout_d04_2023-08-07_12:00:00	7 Aug 2023, 12:00:00	7 Aug 2023, 14:30:00

5.2 Vertical Weather Profiles

Three vertical profiles have been extracted from the 4D data matrices in an easily accessible csv format and include primary and derived parameters. The profiles were extracted for coodinates corresponding to major points of interest; Melbourne, Launceston, and Hobart (Table 5). These are shown in Figures 5 - 7. Table 6 describes the meaning of the parameters essential for dark flight ballistic modelling.

Table 5: WRF profile locations

File	Latitude	Longitude
Melbourne	-38.2000	144.5734
Launceston	-41.4480	147.1441
Hobart	-42.7515	147.3015

Table 6: Parameters used for dark flight simulation

Parameter	Meaning	Units
height	Height (for pressure level used in the model internally)	[m]
temperature	Air temperature at height	[K]
pressure	Air pressure at height	[Pa]
relative_humidity	Relative humidity at height	[%]
wind_horizontal	Wind speed (scalar horizontal component of the wind) at height	[m/s]
wind_direction	Wind direction at height (easterly = 90° = blowing from East)	[deg]
wind_east	East-West component of the wind at height	[m/s]
wind_north	North-South component of the wind at height	[m/s]
wind_up	Vertical component of the wind at height	[m/s]
density	Atmospheric air density at height (calculated from pressure, temperature and relative humidity)	[kg/m^3]

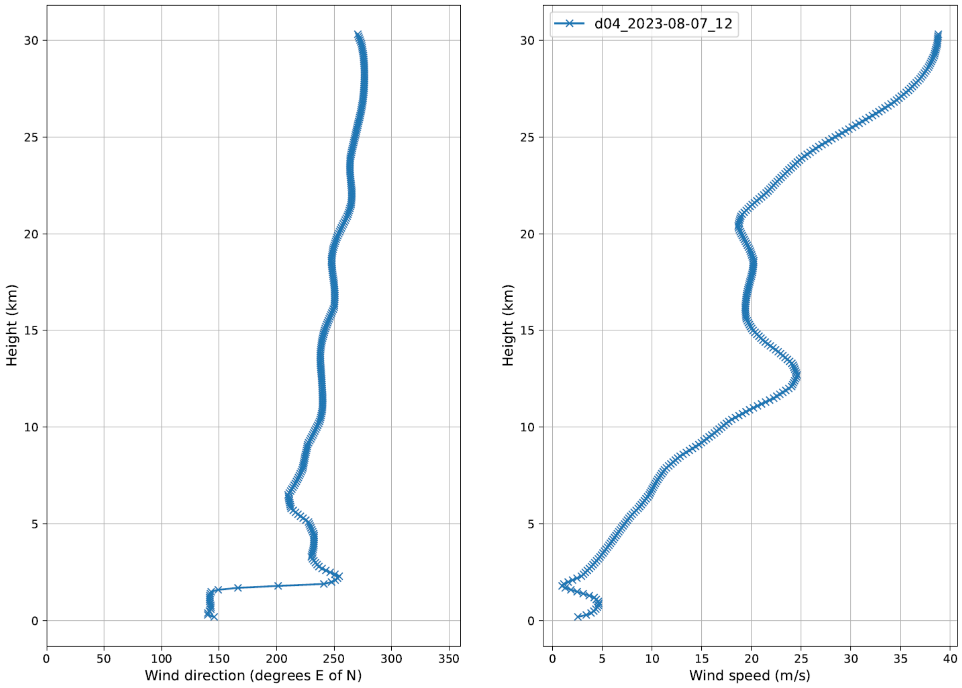

Figure 5 - Comparative plot of wind profiles for Melbourne, showing direction and speed as a function of height

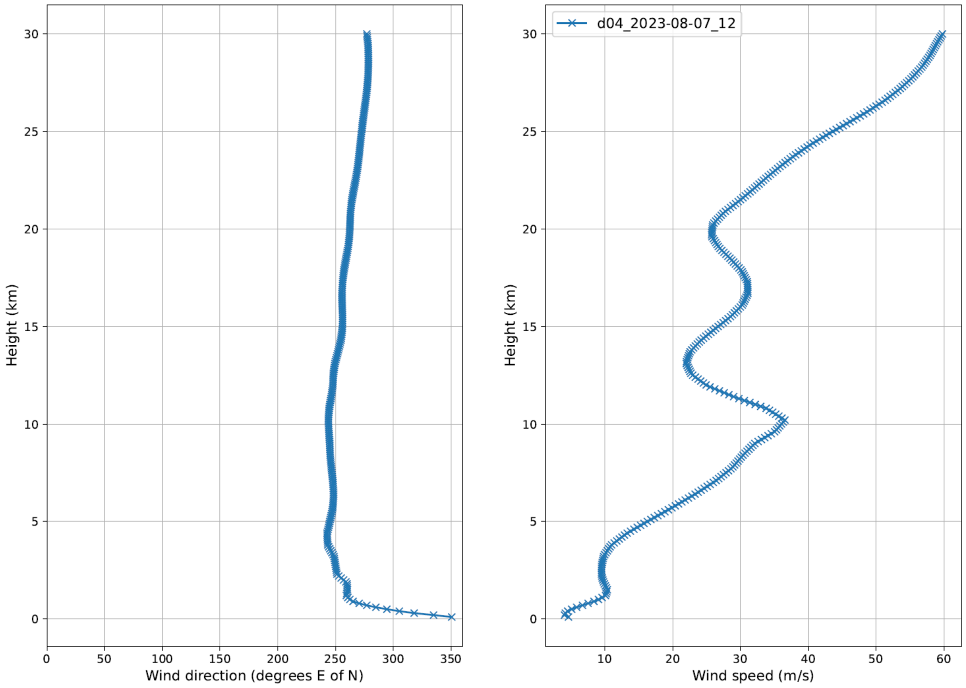

Figure 6 - Comparative plot of wind profiles for Hobart, showing direction and speed as a function of height

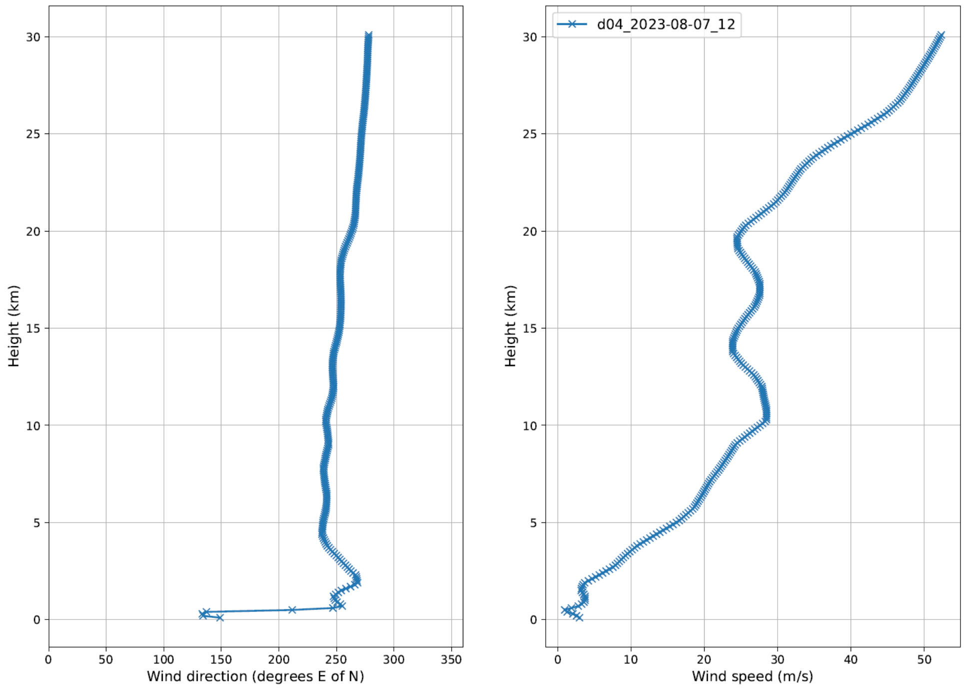

Figure 7 - Comparative plot of wind profiles for Launceston, showing direction and speed as a function of height

6. Re-entry Predictions

From direct observation of the fireball with two DFN cameras, we are able to recreate a segment of the debris' trajectory. As the DFN cameras do not capture the end of the fireball, we cannot perform a high fidelity darkflight model that will represent the most likely fall position/scenario. Additionally, DFN darkflight software is optimised for analysis of meteors falling through the lower atmosphere, and for a case of starting at ~60 km altitude, this is well above typical atmosphere encounters. We have instead assumed a remaining mass of 2500kg for the object at the last observed point, to predict the final trajectory path, as well as shape and density estimates from published data for the Soyuz 2.1b upper stage, "Blok-1/RD-1024" used in this launch (Figure 8).

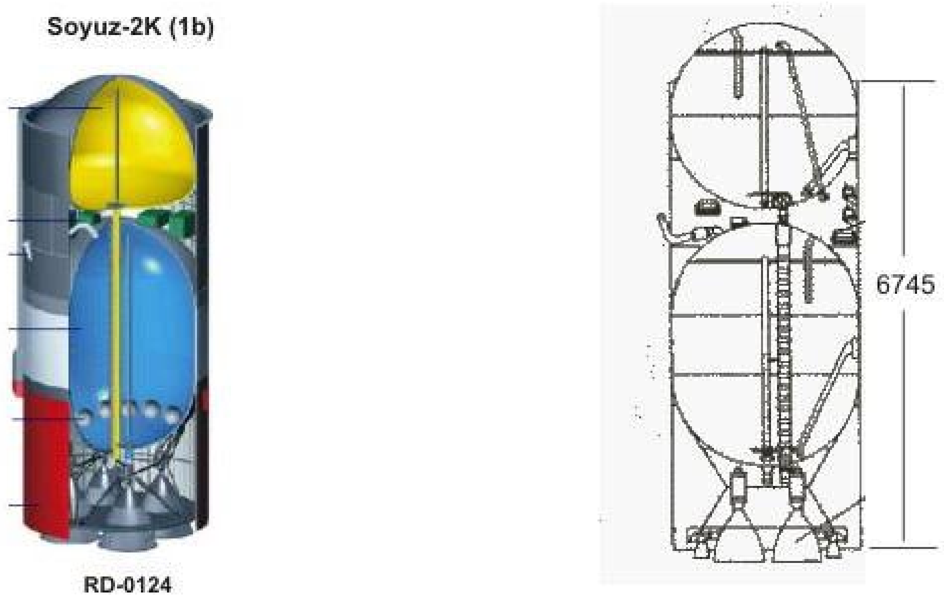

Figure 8 – estimated form factor of the Soyuz 2.1b upper stage, "Blok-1/RD-1024" used in this launch

This passes over the northeast of Tasmania (Figure 9). We have also carried out a Monte Carlo analysis of this main mass, assuming a 10% variation in mass as pieces are shed, shown by the yellow impact locations in the following figures. In all cases, the main mass passes over Tasmania to fall in the ocean. We also performed a series of darkflight models to investigate the potential for debris to fall from an altitude of 65 km (near Melbourne) and 55-45 km (over Tasmania). The height of debris above mainland Australia, in particular over the population centre of Melbourne, gives a negligible risk of material surviving to impact due to the altitude and velocity. In the case of natural objects, fireball heights below 35 km are highly likely to have dropped a meteorite on the ground. For manmade objects, very little is known about the fall scenarios, and whether small pieces may survive from higher up. We have therefore modelled a 5kg object falling over Tasmania (see attached kmz) to show the effect of wind and drag on a smaller sized body toward the end of flight. There is a possibility that small fragments would have made it to the ground in NE Tasmania, with material falling several km to the east of the main mass trajectory (Figure 10).

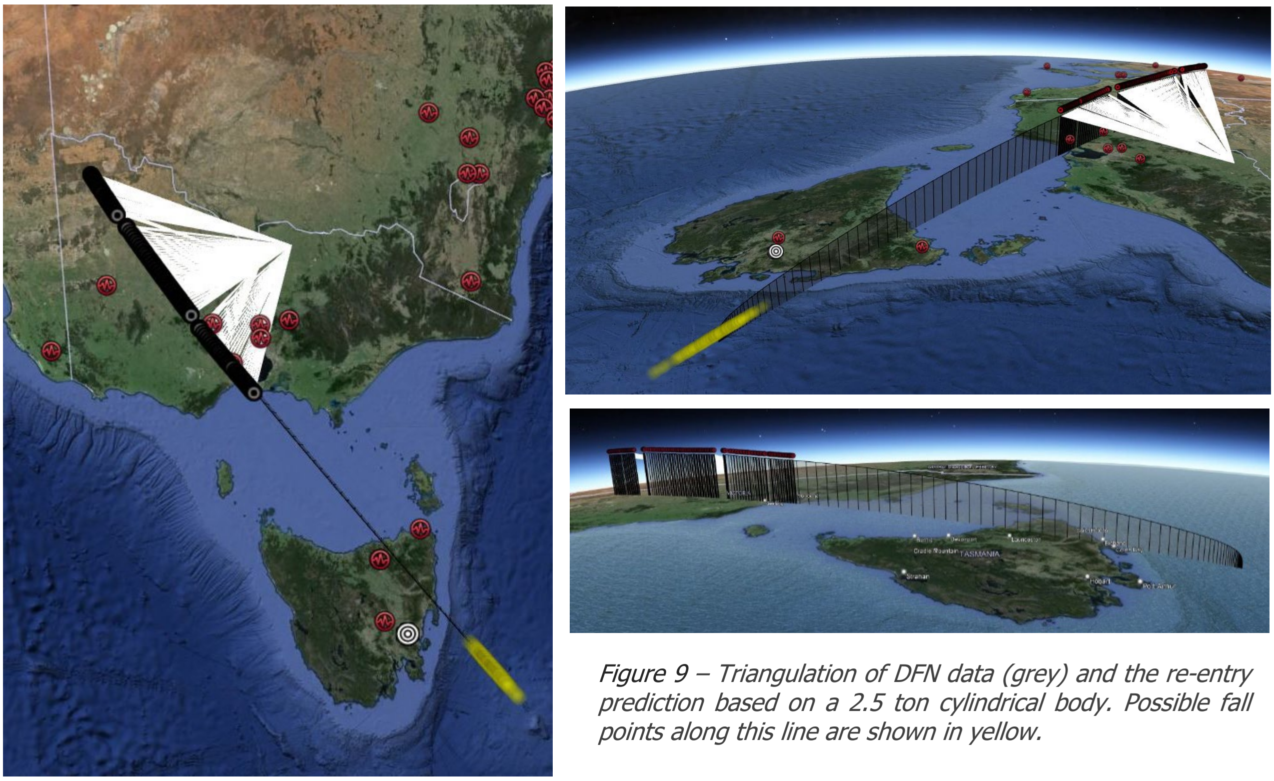

Figure 9 – Triangulation of DFN data (grey) and the re-entry prediction based on a 2.5 ton cylindrical body. Possible fall points along this line are shown in yellow.

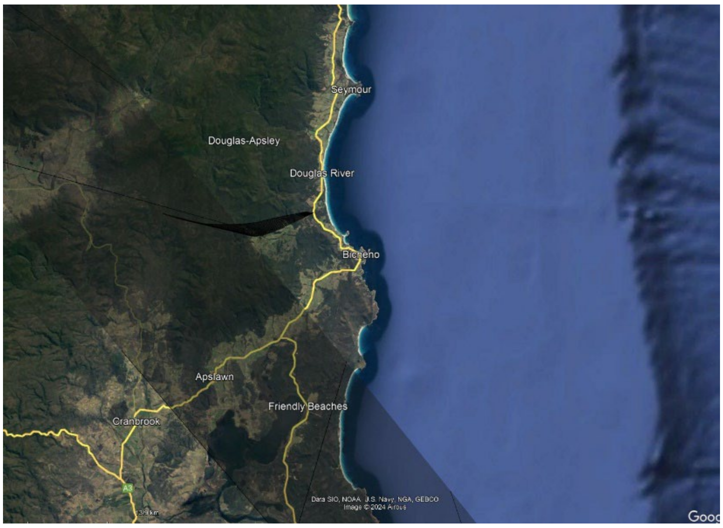

Figure 10 - Close up of hypothetical 5kg debris breaking from main mass, showing possible fall location offset from main trajectory. (There is no indication of such a breakup event, but the scenario indicates that if one was searching for fragments, one should looking about 10km NE of the main trajectory)

7. Seismoacoustic

As there were witness reports of a sonic boom, seismic sensors from the Australian National Seismograph Network were checked for signals. A significant spike is noticeable in all the nearby stations, with some examples show in in Figure 11.

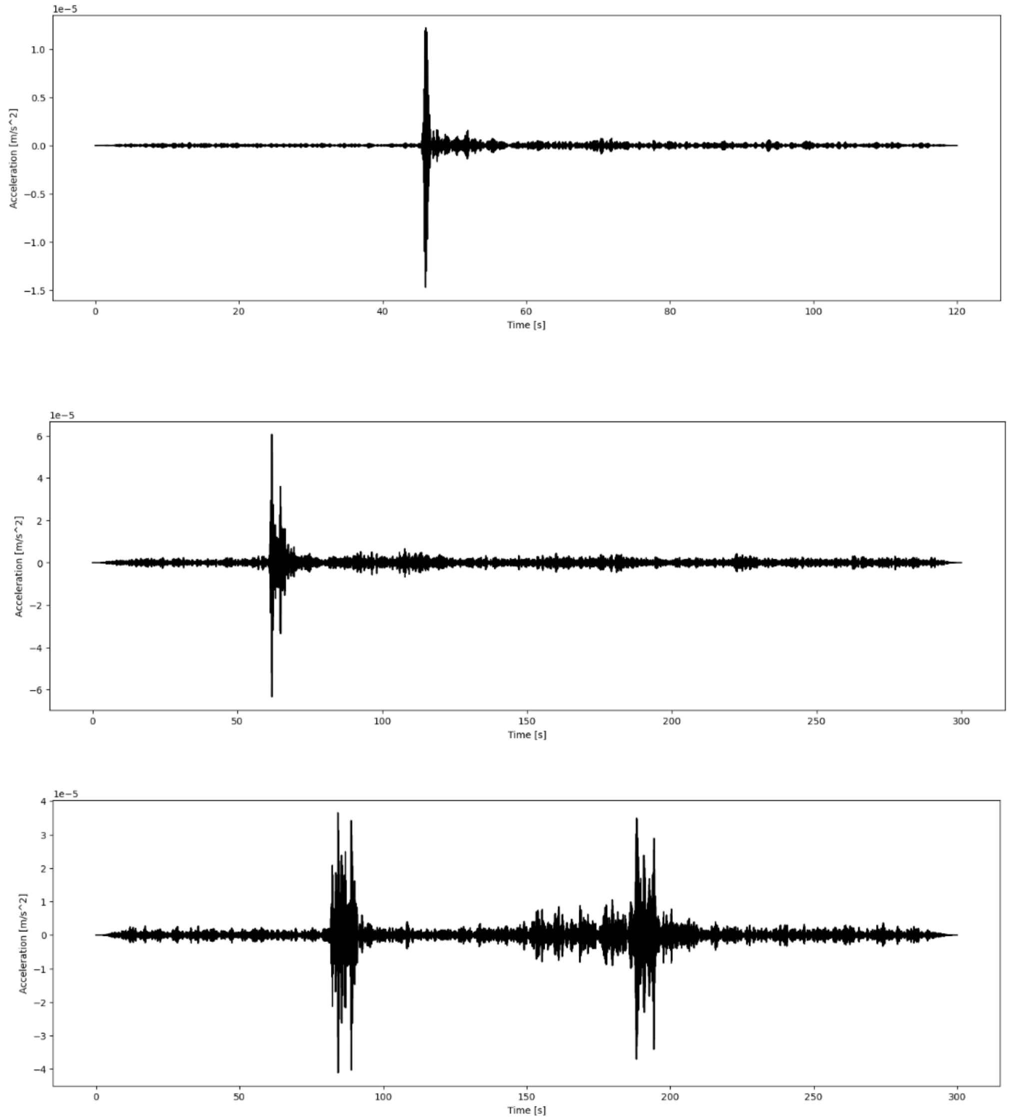

Figure 11 – Example seismic signals from Ballarat (top), Geelong (Middle) and Coronation Park in Launceston (Bottom). Times are not aligned, but the change in form of the signal, including the double 'boom' seen over Tasmania could indicate object fragmentation.

Infrasound signals from the Hobart Infrasonic Array as shared by ASA are able to confirm the supersonic nature of the trajectory continued beyond Tasmania. Assuming an altitude from the DFN predictions of ~45km altitude, this puts it at 80-100km NE of the IS05 array, passing over the north east corner of Tasmania from Scottsdale to Bicheno (see kmz). As seen in Figure 12, these arrivals are an extremely good match to the predicted trajectory. The slight eastward offset of later arrivals could be due to wind, or the curvature of the trajectory due to Earth rotation.

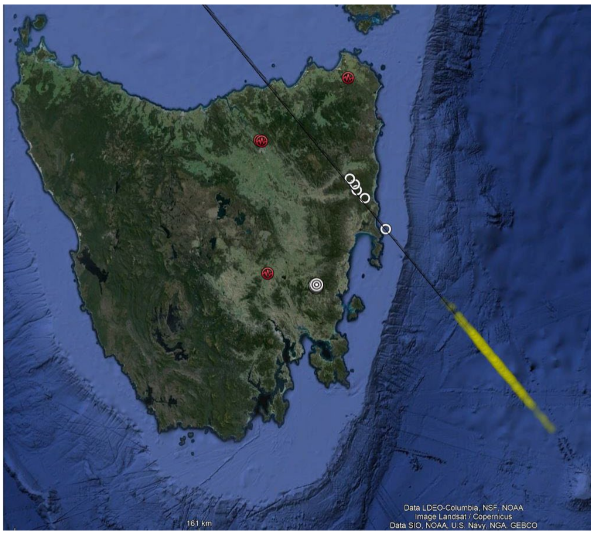

Figure 12 - IS05 infrasound array located at the white bullseye, with corresponding source locations as white circles. The predicted re-entry path from DFN is also shown.

Infrasound has a huge potential for detection and verification/validation of re-entering debris events. The expertise in analysing these data for the purpose of atmospheric shock waves from re-entering objects is not currently available in Australia. The DFN team currently consult with global experts in Japan and France, and are looking to expand their capabilities in this area over the coming year.

8. Alternative Sources of Data

The DFN team investigated the following alternative data sources that may have captured data from this event.

Doppler weather radars operated by the Bureau of Meteorology (C or S-band) are designed to reflect off precipitation but can also ping off falling material such as meteorites and space debris. This capability has led to the successful recovery of meteorites in the past, and most recently by the DFN team in 2022 (Devillepoix et al., 2022, Anderson et al., 2023). The SpaceX event in July 2022 produced distinctive signatures in doppler weather radar data. The most likely station to have caught this event would have been Hobart, and no signatures were detected around the time of the event.

The **Himari weather satellite** captures visual/near infrared global observations of the Earth over Australia/Japan every 10 min. In the past, it has observed transient dust clouds from very large meteor entries. Data taken around this event show no features of interest. This is disappointing, but not unexpected, as the global images is relatively low resolution, and only captured every 10 minutes.

The **CNEOS database** displays US NASA/DoD observations of atmospheric fireballs/explosions. The system is designed primarily to detect missile launches and nuclear explosions greater than 0.07kT of TNT equivalent, and only detects the largest atmospheric impact events. It is therefore relatively insensitive to re-entries (in particular, ones that do not end in a single catastrophic airburst), and unfortunately nothing is reported that correlates with this re-entry.

Other military monitoring systems may have observed the entry and may be of interest to defence.

9. Implications/recommendations

Australia currently has no dedicated debris tracking facility. The tracking of known re-entries over Australia is currently limited, relying on satellite operators and Tracking and Impact Prediction (TIP) messaging, with no way of verifying a fall if not reported by a casual observer. Re-entries due to launches, such as the Soyuz event, are not tracked at all.

The record and observations of any ad-hoc event of this nature must coincide with observations taken by existing facilities and instruments. The event must also have occurred within the operational parameters of those instruments, such as field of view. Even if these requirements are met, the re-purposed or re-processed data may not be suitable for analysis, as data pulled from an instrument that is not designed for the tracking of spacecraft will inherently have limited utility in the tracking of spacecraft. In this case, it was extremely fortunate the re-entry was observed by recently installed cameras of the DFN, considering this facility is approaching end of life and is not a dedicated debris tracking facility.

Due to Australia's size, objects re-entering the Earth's atmosphere over sparsely populated remote regions go relatively undetected. This could threaten protected natural environments by contamination, as well as cultural heritage areas and areas of indigenous significance (as famously occurred with the uncontrolled re-entry of Skylab over WA in 1979).

An increase in unplanned and uncontrolled re-entries are expected over the next few years around the solar maximum. This increase in solar activity will increase atmospheric drag and cause satellites to re-enter prematurely. To monitor these issues with confidence, observing capability is needed, be it with optical sensors or other sources such as in Table 1. Observing re-entry events in order to validate a prediction also improves our understanding and confidence in models for planned re-entry events. This could take the form **of temporary, multi-sensor stations** along the ground track of a planned re-entry event in order to better understand the nature of breakup and quantify the risks.

The ideal method of monitoring space debris re-entry for the future is a dedicated network that can provide a trajectory solution and assess the point at which the debris transitions from burn-up to free-fall. The height and speed of the debris at this point is critical to assessing the full impact. It would also have the capability to identify fragmentation points. There is value in collaborating with Defence in this area, particularly where they have existing radar and existing sensors, or looking to develop them. Data fusion across sensors, and developing a common data format for sharing of data could be considered.

Increasing capabilities in seismic and infrasound detection and processing is also needed to exploit this additional rich dataset.

An augmented DFN-like multi-sensor solution, covering areas occupied by 90% of the Australian population is entirely feasible and would enable a rapid response in the case of debris events. The base hardware and software pipelines are already designed, with a team of researchers with >10 years experience ready to implement it.

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APPENDIX A - Accompanying Deliverables

- Weather model simulation products (“wind_models”)
  - 4 dimensional model (space + time) of atmospheric conditions, up to 30 km altitude (temperature, pressure, density, relative humidity, wind strength, wind direction) over Melbourne area the time of debris re-entry.
    File format: WRFOUT NetCDF. 4 files, 37 GB total

  - 4 dimensional model (space + time) of atmospheric conditions, up to 30 km altitude (temperature, pressure, density, relative humidity, wind strength, wind direction) over Tasmania at the time of debris re-entry.
    File format: WRFOUT NetCDF. 4 files, 37 GB total

  - Vertical weather profiles at Melbourne location and time
    File format: csv, 50kb total

  - Vertical weather profiles at Launceston location and time
    File format: csv, 50kb total

  - Vertical weather profiles at Hobart location and time
    File format: csv, 50kb total

- Raw observation files (“raw_observations”)
  - ECSV text files of raw (Right Ascension, Declination) observations. There are three observation windows (trajectory segments) from each of the two DFN cameras. *File format: text, 10kb total*

- ECSV text file of triangulated trajectory
  - “DN230807_02_triangulation_combined_trajectory_observations.ecsv”
    File format: text, 154 kb total

- Google Earth KMZ file that includes astrometric observations from two DFN cameras, our best estimated trajectory and dark flight with fall area predictions.
  - “DN230807_02_Soyuz_deliverable.kmz”
    File format: kmz. 1 File, 1MB total