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REVIEW

A review of airborne observations for space debris re-entry break-up and dispersion measurements

Fabian Zander[1] · **Stefan Löhle**[2]

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Abstract
Airborne observations provide opportunities to collect rare and unique data from space debris re-entries. To date, six different observations of space debris have been undertaken, collecting spectral and spatial data to help understand debris break-up and dispersion. The data is important to help validate computational space debris break-up models. A particular focus to date has been on the spectral data collection, and results have helped understand the sequence of debris break-up by identifying individual elements as they are released in time. Due to the resourcing required, a limited amount of work has been undertaken on trajectory analysis for dispersion measurements. A noted downside of the observations to date is that all the resourcing has gone into the observations and data collection, and then relied on self-motivated researchers to undertake detailed analysis. The ever-increasing amount of space debris drives the need for a better understanding of space debris break-up and dispersion and there is a clear need for invaluable flight data for further model validation.

Keywords Space debris · Airborne observation · Optical diagnostics

1 Introduction

Space debris is defined by the Inter-Agency Space Debris Coordination Committee (IADC) as "Space debris are all human made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional" [1], and by NASA as a general term for unused spacecraft, spacecraft fragments or meteoroids in orbit [2]. Since the advent of commercial satellites in orbit, space debris is often related only to unused spacecraft which are to re-enter into the Earth's atmosphere. The number of unused satellite structures is rising extremely fast [3], particularly since the advent of satellite mega constellations [4]. The risk of on-orbit collisions has to be reduced to a minimum, because resulting fragment clouds are a severe risk for structures in space. The post-mission lifetime has only recently been reduced from 25 years to 5 years [5], requiring that satellites are to be manoeuvered to ensure re-entry into the Earth atmosphere to break-up and demise in the upper atmosphere. In 2022 the European Space Agency (ESA) started the Zero Debris Charter with the objective of demising the satellite entirely after the spacecraft end-of-life [5].

For spacecraft which enter the Earth's atmosphere, the risk must be assessed to determine whether the structure demises completely or whether surviving components will reach the Earth's surface. For larger satellite structures current calculations always predict a number of fragments surviving the atmospheric re-entry. Therefore, controlled re-entries are usually targeted at the *South Pacific Ocean Uninhabited Area* (SPOUA) to minimise the risk of harm or damage. Current research focuses on the mechanisms leading to break-up and its impact on the demisability of spacecraft structures during re-entry. Both numerical simulations, using either CFD tools [6] or re-entry break-up analysis programs [7–10], and experimental investigations are ongoing. Experiments for the aerodynamics of fragmentation are

Fabian Zander and Stefan Löhle contributed equally to this work.

✉ Fabian Zander
fabian.zander@unisq.edu.au

✉ Stefan Löhle
loehle@irs.uni-stuttgart.de

[1] Institute for Advanced Engineering and Space Sciences, University of Southern Queensland, West Street, Toowoomba, QLD 4350, Australia

[2] High Enthalpy Flow Diagnostics Group, Institute of Space Systems, University of Stuttgart, Pfaffenwaldring, 70569 Stuttgart, Germany

conducted in impulse facilities [11, 12], the aerothermodynamic analysis of the melting, evaporation and mechanical break-up are investigated in plasma wind tunnels [13].

Validation of the analysis techniques is an important aspect of both the simulations and experiments. While ground testing and code-to-code comparisons provide a good baseline [14], true validation is only possible through the measurements and analysis of real re-entry flights. Since 2008, there have been a small number of airborne observation of destructive re-entries undertaken. The data from these rare occasions, specifically visual and spectral observations of the events, allows conclusions to be drawn about the break-up phenomena. The primary value of the data collected is to help validate the computational models of the re-entry space debris break-up and dispersion. The complexity of the phenomena being modelled requires that simplified engineering models are used to ensure the simulations are computationally tractable. The observation data helps in the validation process of the models.

This paper presents a review of previous airborne observations of re-entering space debris and provides insight into the measurements and data extracted. The next section gives an overview of the main phenomena of re-entry space debris break-up, followed by a description of airborne re-entry observation campaigns in general and space debris-related observations in particular. The paper finishes with a discussion of the results, including some high-level recommendations for future work, and a conclusion.

1.1 Re-entry space debris break-up

The mechanisms by which re-entering space debris breaks up are multi-faceted and complex. During the high-speed re-entry the structure experiences ever-increased heating and aerodynamic loading. The combination of these results in structural failure due to, amongst others, melting, pressure forces resulting in bending moments, explosion of fuel remnants, etc. Which of these mechanisms are relevant for a given re-entry is dependent on the spacecraft structure, the contents of the spacecraft, the orbit and resulting re-entry trajectory, and the local atmospheric conditions.

An understanding of which mechanisms are occurring and the order of the re-entry space debris break-up can be gained through spectroscopic measurements of break-up events. Spectroscopic data reveals which atomic and molecular elements are present at a given point in time. This can be used to help infer the order in which the spacecraft break-up process occurs. For example, strong aluminium emission would be an indicator that the aluminium structure has been exposed to the hot flow field.

Obtaining the best possible data for understanding the break-up process requires prior knowledge of the object structure and materials. This allows instrumentation to be customised for the expected signatures, enabling the collection of high-quality data. Typically, the break-up of re-entries that are to be observed is modelled to predict a break-up scenario. The observation mission then provides real flight data which shows agreements and discrepancies to the predictions. Real flight data is the only method known so far to provide data models can be compared to. No ground testing approach is able to simulate a re-entry break-up with a level of detail sufficient to compare to a break-up scenario in flight. However, certain aspects can be studied separately in ground testing facilities, e.g. fragment separation in a shock tunnel or aerothermal break-up in a plasma wind tunnel facility [15].

Alternatively, spectroscopic measurements of an unknown object can help identify what the object might be based on the elemental signature. If an object of unknown origin has been detected, the observational data can help identify the object and consequently help determine where it originated from, see for example WT1190F described later in this paper [16].

1.2 Re-entry debris dispersion

Re-entry space debris dispersion is about understanding where the different pieces go during and after the re-entry break-up event(s). The re-entry debris' ground impact zone size is driven by the dispersion, hence a well established understanding of the dispersion has a direct impact on safety regulations. Spacecraft re-entry break-up can be caused by a variety of mechanisms including thermal loading during re-entry, which causes melting, or could directly induce an explosive event if there is residual fuel or other combustible substances on the vehicle. The different break-up mechanisms also result in very different dispersion of components.

Measuring the dispersion of space debris requires either two different viewing angles, or some assumptions about the re-entry trajectory. If only a single measurement is available, then the assumption must be made that the debris fragments remain in the orbital plane during the re-entry. Triangulation is especially challenging as each individual fragment must be uniquely identified across the two (or more) viewing angles for the analysis. As described in the following sections, both of these methods have previously been used with some success.

2 Airborne observations

Observations of aerospace phenomena are an invaluable tool for research. From early optical measurements of meteor showers and images of the first manned flights through to the high-resolution video of the Space Shuttle and SpaceX launches, the imagery has been, and continues to be, a vitally

important component of the data collection and analysis. Particularly over the last two decades, since the attempted observation of the Genesis capsule re-entry in 2004 [17, 18] there has been an increasing engineering and scientific interest in undertaking observations of different experiments and tests. Since the Genesis re-entry there has been a number of airborne observations of capsules and space debris including the Stardust capsule re-entry [19–29], the ATV-1 re-entry break-up [30–36], the Space Shuttle returns [37–40], the Hayabusa capsule return and spacecraft bus break-up [41–51], the WT1190F space debris object re-entry [16, 52], the Cygnus-OA6 destructive re-entry [52, 53], the Hayabusa2 capsule return [54–64], the OSIRIS-REx capsule return [65], the Cygnus-NG20 destructive re-entry, and most recently the Cluster2 Salsa destructive re-entry.

The scientific objectives of these observations varied from mission to mission depending on the target object and who was supporting the observation campaign. The objectives of the missions can however be broadly categorised into two types, firstly capsule and shuttle re-entries where the radiating flow-field and the thermal protection system performance are the primary targets of interest, and secondly, space debris observations where the re-entry break-up and dispersion of the debris are of primary interest.

An airborne observation is undertaken by flying in a small aircraft in the vicinity of a phenomena of interest. Imaging systems are then targeted at the object through the aircraft windows. Airborne observations are generally undertaken from a small aircraft at a range of 100–800 km away from the target object. Historically these observations have been undertaken from both dedicated scientific aircraft (e.g. NASA's DC-8, GV-III, GV-IV) or a commercial business jet chartered specifically for a particular observation. The scientific aircraft have significant advantages in terms of specialised windows for optical transmission, bespoke hardware mounting points, significant power availability etc. However, such aircraft are hard to come by and expensive to use, hence quite a few observations have also been undertaken from chartered aircraft. Chartered aircraft pose significant challenges with window types, fixed interiors, limited power, etc. however, they are accessible and comparatively cheap. For this reason, chartered aircraft have been used for the majority of space debris observations to date.

With the current increased interest in understanding re-entry space debris break-up and dispersion, and in increasing the fidelity of the modelling capability, there is demand for more and higher fidelity observation data. This requires more observations targeting specific measurements to provide the data required.

3 Space debris observations

3.1 ATV-1 (2008)

The observation of the ATV-1 re-entry on the 29th of September 2008 was the first observation specifically focused on capturing re-entry spacecraft demise and break-up data. This was a two-aircraft observation undertaken as a joint ESA and NASA mission with participants from a variety of research organisations, universities and industry partners. The mission was focused on the main explosive events, fragment triangulation data and identification of fragments through spectroscopy. ATV-1 entered the atmosphere at approximately 7.57 km/s with a relative flight path angle of − 1.45 deg [30] and a significant amount of data was collected from both aircraft [30–36]. A still image from the re-entry is shown in Fig. 1.

Utilising two aircraft for observations enables the triangulation, and hence the trajectory determination, of individual fragments. Lips [32] and Blasco [33] present the results of the trajectory reconstruction work. This was undertaken following the principles presented for astrophysical research by Wescott [66], utilising the star background for calibration

Fig. 1 ATV-1 re-entry as imaged by David Sliski of Dexter and Southfield Schools from the DC-8 aircraft (image from https://atv.seti.org/)

and then triangulating fragments that can be clearly identified from the two different viewing angles. Due to the imaging quality only a limited subset of fragments could be analysed. This was done and the trajectories propagated through to a debris footprint. Lips [32] presented the calculated footprints for both non-melting and melting fragments based on the observation results. Blasco [33] presented a variant on this analysis also including data from fragments that were only identified in a single camera but analysed using some reasonable assumptions about the flight plane. This resulted in a slightly larger footprint as could be expected given the larger number of fragments and higher uncertainty in the computed trajectories.

Spectroscopic data were collected and published by the teams of Snively [35] and Löhle [31, 36]. The NIRSPEC system, deployed by Snively, recorded spectral data from the zeroth order (nominally 0 nm) up to approximately 1000 nm. Of particular interest is the NIRSPEC data published by Blasco [33] showing three distinct spectra from different fragments. These have been analysed and conclusions drawn about the likely fragment identification. They concluded that the first fragment was the cargo bay from the barium sulfate paint signature, the second fragment was the external bay due to the copper signature, and the third fragment was the bottom propulsion bay identified from the titanium emission resulting from the titanium oxide paint.

3.2 Hayabusa (2010)

The observations of the Hayabusa re-entry (June 13th 2010) were focused primarily on the sample return capsule which landed in Woomera, South Australia. However, during this re-entry the spacecraft bus also re-entered directly behind the capsule and many of the instruments also captured the break-up and dispersion event. The data from the Hayabusa re-entry, the sample return capsule and the bus, has had the most analysis undertaken and published of all the re-entry observations. This includes data from the airborne observation as well as multiple ground stations. For completeness, we will include the ground station observations and analysis results here [45, 67–79], as these techniques and methods can equally be applied to airborne measurements (as has been demonstrated in earlier and later observations, e.g. ATV-1 and Zander's trajectory reconstruction of Hayabusa2 [64]).

From a re-entering space debris perspective the Hayabusa re-entry was very fast. As the spacecraft was returning on a heliocentric orbit the re-entry had a velocity of approximately 12.2 km/s and a entry angle of −12.3°. The velocity and entry angle have a significant impact on the breakup and dispersion of the spacecraft and must be considered when comparing the different measurement data sets.

As the breakup was not the scientific target of the observations (the sample return capsule was the main target), less analysis has been undertaken on the available data. Some spectral elements have been identified which could be used as a data set for model validation and some preliminary dispersion analysis has been undertaken. Figure 2 shows the Hayabusa bus break-up as imaged by the Clay Center Observatory team. The break-up event and the resulting dispersion is clearly visible. The small visible object in the bottom right is the sample return capsule.

Abe [45] captured spectroscopic data of the main break-up event and measured a range of atomic species including Fe, Mg, Na, Al, Cr, Mn, Ni, Ti, Li, Zn, Cu, Mo, Xe, Hg, O, and N, as well as molecular FeO. They make particular note of some of the more exotic species, including Mo (molybdenum), which is a component in a common lubricant, and Xe (xenon), which was used for the electric propulsion system aboard the spacecraft. Also noted is the very strong emission line of Li (lithium) during the 'last flash' (55 km altitude break-up event) of the spacecraft. This is a very strong indicator of the lithium-ion batteries demising in the break-up sequence.

Borovicka [70] showed that the intensity of the break-up event was significantly brighter than the capsule re-entry. By analysing the bus emission, they determined that there were two initial events causing a spike in intensity at altitudes of 85.1 km and 77.5 km, presumably these relate to the break-up of some external components on the bus. The emission intensity then continually increased to a peak at an altitude of 66.9 km after which it remained high but fluctuated substantially down to an altitude of 56.7 km. This period describes the main break-up event after which many small pieces were measured, however the emission of these decreased very rapidly.

Watanabe [71] undertook analysis on optical imaging to track the number of fragments and to estimate the size distribution of the fragments resulting from the bus break-up. They show two initial fragments break off from the

Fig. 2 Hayabusa break-up as imaged by the Clay Center Observatory team (image from https://hayabusa.seti.org/index-old1.html)

main body early in the re-entry, corresponding to the initial events described by Borovicka, followed by the two break-up events. The number of fragments increased greatly during the first break-up event, at an altitude of approximately 68 km, resulting in over 800 fragments in total. Approximately 7 s later there was what is considered the main break-up event at 56.7 km and this resulted in approximately 1800 fragments being measured. The size distributed analysis is rooted in astronomical analysis techniques for meteors and shows that there are significantly more smaller fragments than larger ones, following a power law relationship.

Ueda [74] calculated the trajectory of the Hayabusa spacecraft re-entry based on the video captured from four different ground stations. The trajectory calculation was undertaken using meteor astronomy techniques assuming that the flight is in a straight line. The analysis was undertaken up until the fragmentation events at which point the authors could not identify the fragments across the different cameras and hence no further analysis was possible. However, the technique used here would be feasible for debris calculations if there was clear fragment identification in each video stream.

Shoemaker [79] analysed the trajectories of approximately 80 different fragments from the Hayabusa spacecraft. This was done from a single camera using an Extended Kalman Filter (EKF) to model each fragment under the assumption of a known initial dynamics state. This was assumed to be the nominal Hayabusa spacecraft trajectory. Using the EKF, the aerodynamic characteristics (ballistic coefficient, lift, drag, etc.) of each fragment are computed. This data is then coupled with the assumption of spherical shape and used to compute fragment sizes and masses, which are of the order of centimetres and grams.

3.3 WT1190F (2015)

The observation of WT1190F was a unique event as this was the only airborne observation, to the authors knowledge, where the identity of the target object was unknown. The object entered the atmosphere on the 13th of November 2015 in the vicinity of Sri Lanka at 1120 local time, providing challenging daytime conditions for a re-entry observation. The observation mission was led by the SETI Institute and included participants from the International Astronomical Center, Dexter Southfield and Embry-Riddle Aeronautical University and the University of Stuttgart [16].

WT1190F entered the atmosphere on a steep orbit at a speed of approximately 10.6 km/s and an entry angle of 20.6 deg [16]. The observation was undertaken in a Gulfstream G450 organised by the International Astronomical Center and the United Arab Emirates Space Agency. A range of instruments were flown including high-resolution imaging, filtered imaging, transmission grating spectrographs and an Echelle spectrograph. The re-entry was measured in most of the instruments for approximately 12 s, which was the length of time that there was visible emission (Fig. 3).

The spectroscopic measurements showed the presence of titanium oxide (TiO) which provides evidence that the object was made from titanium. The light curve which was derived from one of the imaging cameras showed strong fluctuations in intensity, presumably due to tumbling of the object. The high-resolution imaging showed that the object broke up into at least eight clearly distinct fragments during the entry. It is interesting to note that three of the smaller fragments proceeded the main object by quite some distance. The other aspect worth noting is that the high-resolution imaging was in colour, and some of the fragments were very distinctly blue in colour which would be more indicative of aluminium.

Based on the orbital characteristics, coupled with the spectral measurements taken during the observation campaign, scientists have claimed that WT1190F is most likely a translunar injection module of Lunar Prospector [80].

3.4 Cygnus-OA6 (2016)

The Cygnus-OA6 re-entry coming from the International Space Station (ISS) was a planned destructive re-entry to dispose the transport vehicle and the rubbish on-board (from the ISS). The observation mission, occurring on June 22nd

Fig. 3 WT1190F as imaged by the Dexter Southfield team from the aircraft (image from https://impact.seti.org/)

2016, was planned by the SETI Institute and included mission participants from The Aerospace Corporation, Dexter Southfield, Embry-Riddle Aeronautical University, The University of Stuttgart, The University of Southern Queensland, The University of Queensland, and Curtin University. The interesting aspect of this re-entry was that it was a very shallow re-entry compared to previous observations. Coming from Low Earth Orbit (LEO) the spacecraft was de-orbited over a period of time resulting in a shallow re-entry angle when it finally entered the atmosphere and demised. Due to the low angle, the spacecraft was imaged for approximately six minutes by the observation team. Most of the data collected on this observation has not been published (with the exception of [52]), however, the authors as mission participants have access to some of the data collected. Most of the data summary discussed below is taken from an unpublished work by many authors but led by Peter Jenniskens [81, 82] (Fig. 4).

Data was measured with an array of imaging and spectrographic camera systems. The imaging data showed interesting features throughout the re-entry, initially, between 85 km and 80 km altitudes, there are oscillations in intensity which would indicate tumbling of the spacecraft. Following this, there is a main break-up event at an altitude of 79.7 km resulting in fifteen different fragments. Further along the trajectory, at altitudes between 72 km and 52 km, there are a series of visual flares indicating individual secondary break-up events.

The spectral data contained a number of interesting features identifying sodium (Na), potassium (K), lithium (Li), aluminium (Al), magnesium (Mg), diatomic carbon (C_2), methylidyne (CH), and aluminium oxide (AlO). Some of the species detected can give indications as to how the spacecraft broke up on re-entry. The potassium is likely to be from the paint which uses a binder containing potassium. Lithium is usually indicative of batteries, indicating that the battery bay had been breached. Although carbon and hydrogen can be found in many different components, the presence of diatomic carbon and methylidyne is considered most likely to result from fuel remnants. The aluminium and aluminium oxide result from a structural break-up as the main spacecraft ablates. Due to the extensive use of aluminium it is difficult to use this to pinpoint any specific break-up event.

3.5 Cygnus-NG20 (2024)

The Cygnus-NG20 spacecraft re-entered the Earth's atmosphere from Low Earth Orbit on the 13th July 2024. In two weeks a team from the University of Southern Queensland, the University of Kentucky and the University of Stuttgart planned and executed an observation of the re-entry over the South Pacific.

The observation was challenging as the re-entry occurred in the early hours of the morning and was encroaching on sunrise. Due to the location of the re-entry in the South Pacific, and basing the observation out of the Cook Islands, the observation flight path needed to be on the western side of the re-entry looking east, into the sunrise. Despite this, the team was able to get measurements over a significant time and the re-entry was imaged for approximately four minutes with a range of visual, near-infrared and spectroscopic camera systems.

Two particular outcomes of these measurements to date (as processed by the authors of this paper, not yet published elsewhere), are, firstly, the measurement of presumed tumbling of the vehicle during the early part of the trajectory, and secondly, the detection of what is being considered the main break-up event.

The tumbling was detected in one of the near-infrared imaging cameras as an intensity oscillation for a period of approximately 20 s early in the observation. The luminous variation was analysed by summing the pixel intensities of

Fig. 4 Cygnus-OA6 as imaged by the airborne observation team (image from https://atv5.seti.org/cygnus/)

the spacecraft for every frame captured and undertaking a Fast Fourier Transform on the resulting data. This corresponded to a very clear 2 Hz signal that is assumed to be the tumbling of the spacecraft as it enters the atmosphere. When compared to the expected re-entry trajectory this occurs at an altitude of approximately 85 km.

Later in the observation a bright 'flash' event was detected in multiple cameras. This event was imaged at a distance of approximately 800 km and was clearly visible in multiple cameras indicating that the event must have been very bright. The short wave infrared imaging is shown in Fig. 5. When comparing the time that this event occurred with the predicted re-entry trajectory it can be seen that this occurred at an altitude of 77.87 km. This is an important finding as re-entry break-up modelling analyses commonly use a 78 km altitude as a nominal break-up altitude.

3.6 Cluster2-Salsa (2024)

The Salsa satellite re-entry was observed on September 8th 2024 within the context of an ESA-funded project run by Astros Solutions. A team from the University of Southern Queensland, the University of Stuttgart, the Comenius University of Bratislava set up an airborne campaign. The mission was supported by re-entry debris modelling from Hyperschalltechnologie Göttingen (HTG). The observation mission was flown from Easter Island, Chile, and the actual re-entry took place west of Easter Island. This observation was particularly challenging, as it occurred during the day at 1148 local time.

In total twelve spectrally filtered and visual and infrared imaging cameras captured data of the demising re-entry. As this mission has only just occurred (at the time of writing), the data analysis of this observation has not been extensive, however, it is clear that multiple different atomic species have been measured. An initial image of the re-entry taken with a short wave infrared tracking camera is shown in Fig. 6. The results of this observation will be particularly interesting as the project includes a modelling prime, HTG, who will endeavour to rebuild the break-up and compare directly to the measured data. As this is spectroscopic data, the objective will be to understand how the satellite broke up during the re-entry process.

4 Discussion

To date, significant spectral and dispersion data has been collected from space debris re-entries. The measurements have demonstrated the types of data that can be collected, and the analyses have shown what can be extracted from the data sets. The main focus of the prior observations has been spectral data collection, and the outcomes of the research reflect this. The spectral data sets have been used to identify which materials are present in a given fragment, what the identity of an unknown object may be, and to help determine the order in which the object broke-up during the re-entry process. WT1190F is a good example of the identification of an unknown object, and ATV-1 is a good example of determining the order of break-up from spectral data. From the perspective of general scientific enquiry, this has been done quite successfully to date. Figure 7 shows some example data from the ATV-1 break-up just before (frame 152) and after (frame 153) the main explosive event. As well as increasing the overall emission intensity, the explosive event also vaporised additional metallic components as is demonstrated by the sudden appearance of iron (Fe), titanium (Ti), strontium (Sr) and chromium (Cr). A forensic analysis of the ATV-1 vehicle structure together with the spectra can help identify the order in which the break-up occurred.

Thus far, with the exception of the ATV-1 observation, triangulation and trajectory reconstruction efforts have been secondary to the spectral measurements. This is in part due to the cost (as triangulation requires a second aircraft), in part due to the analysis challenges of fragment identification, and in part due to the fact that the observations to date have been driven by scientific rather than engineering interest. Unlike the spectral measurements,

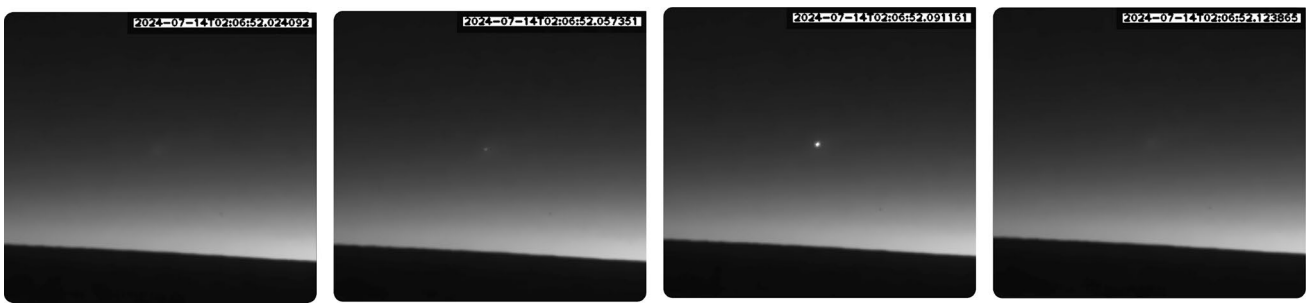

Fig. 5 Cygnus-NG20 main break-up event imaged with a SWIR camera at a distance of approximately 800 km. Four consecutive frames over 10 ms are shown

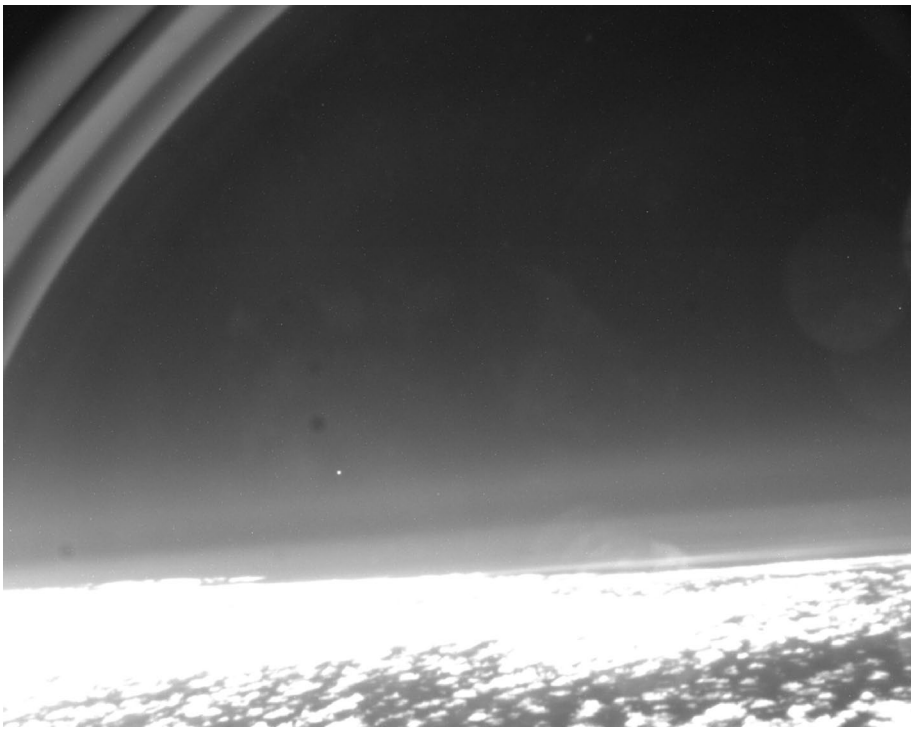

Fig. 6 Cluster2's Salsa satellite during re-entry as seen from the observation aircraft at approximately 900 km distance during the daytime with a SWIR camera. Image from https://www.esa.int/Science_Exploration/Space_Science/Cluster/Goodnight_Cluster_brilliant_end_to_trailblazing_mission

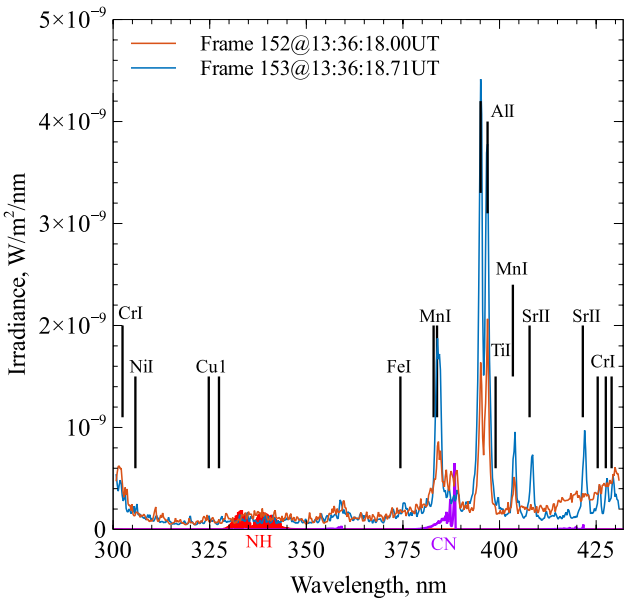

Fig. 7 ATV-1 spectral data from either side of the main explosive event

which have additional standalone scientific value, the greatest interest for the trajectory determination is the dispersion model validation and as most previous observations have been driven by researchers, the trajectory aspect has not been investigated as much. The most extensive trajectory reconstructions to date were undertaken for ATV-1 and for the Hayabusa (2010) spacecraft bus.

It is apparent that the previous observation opportunities have yielded valuable data sets. However, it is also apparent that there has not been enough emphasis on the analysis of the data. Projects, and corresponding funding, are established only for the actual observations and then it is up to the individual researchers to undertake the analysis out of scientific interest. This has yielded some very good results, however, it does open the question as to how much more information could be extracted from existing data sets. It is imperative that for future work more resourcing is allocated to the data processing and analysis.

The second aspect of the data collection and processing which requires more consideration is 'closing the loop' with the space debris re-entry break-up and dispersion modelling community. The main objective of space debris re-entry observations is to collect data for validation of re-entering space debris break-up and dispersion models. It is imperative that the break-up modelling of an event is undertaken to compare with the experimental data, and that the models can then be improved as required based on the data. This is a challenging process as the fidelity of the data desired by the modelling community is often higher than is practically measurable, however, by including the modelling community in the observation planning process the usage of the data can be maximised. This process has already begun in Europe with some progressive ESA projects, but more effort is required across the entire community.

5 Conclusion

A small set of airborne observations of re-entering space debris have been undertaken over the past 20 years. The observations of ATV-1, Hayabusa (2010), WT1190F, Cygnus-OA6, Cygnus-NG20 and Cluster2-Salsa have primarily been driven by the scientific community with ever-increasing support from industry and agencies. The data collected on previous observations focused primarily on spectral data for break-up measurements, with some additional attempts made to triangulate debris fragments for dispersion measurements.

The data collected to date has been very valuable in helping understand the re-entering space debris break-up and dispersion phenomena, however, there is still significant room for improvement in regard to utilising the data for improving re-entry space debris modelling tools. This will require a combined effort of observation experimentalists and space debris modellers to ensure the best possible outcomes of observation missions. This process has already commenced under various ESA projects.

There is great value in the observation data collected from the space debris re-entries. Given the ever-increasing number of objects being put into orbit, and subsequently coming back down into the atmosphere, it is imperative that the observation work is continued and supported by the international community. The ability to collect invaluable, high fidelity data has been demonstrated across the previous observations. More real flight data is required to increase understanding of both break-up and dispersion and help improve the state of the art modelling tools.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest

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