

COMPARISON OF REENTRY BREAKUP MEASUREMENTS FOR THREE ATMOSPHERIC REENTRIES

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ABSTRACT

Reentry breakup data were collected during atmospheric reentries of Japan's H-II Transfer Vehicles HTV2 and HTV3 and the European Space Agency's ATV-3 vehicle. The three vehicles were used to carry supplies to the International Space Station and were directed to reenter the atmosphere such that surviving debris would land in the South Pacific Ocean. They were also used as demonstration flights for the Reentry Breakup Recorder (REBR), a device designed to collect reentry breakup data, to survive reentry, and to transmit the data prior to earth impact. The collected data are unique for reentries of unprotected objects and include rotational rates and accelerations from the reentry point through breakup and release of the REBR, as well as information on REBR's internal pressure, heat shield temperatures, and component temperatures. Once released by breakup of the host vehicle, REBR also collected GPS data providing impact locations of each device. The REBR devices were released within an altitude range of 68-66 km for all three reentries. The paper compares REBR data for these three reentries and includes an overview of REBR and plans for its evolution.

1. INTRODUCTION

When unprotected, man-made objects reenter the Earth's atmosphere, debris of significant mass frequently survive to ground impact. Roughly 50 objects weighing over 900 kg reenter randomly each year, posing potential hazards to people and property. The inherent violence of the reentry process makes recording and broadcasting data during that phase difficult, and relatively little empirical data have been collected about the reentry process. Space agencies predict the survivability of these objects with theoretical heating and loads environment models and atmospheric predictions, but differences in model assumptions and analysis methodologies result in significantly different results. Model comparison efforts are on-going, and to continue improving and validating models, a growing need is developing for more information on the environment and response of unprotected reentering bodies.

2. REENTRY BREAKUP RECORDER

The Reentry Breakup Recorder [1] (REBR) is a device that collects data during the violent reentry and breakup of a host spacecraft. REBR 'hibernates' in a low-power mode until the early stages of reentry are detected, when the device begins recording data. The data are protected while the host vehicle disintegrates and are then transmitted over the Iridium satellite phone system before ground impact, thus eliminating any need for the hardware to survive impact and be retrieved. The device is small; including its housing and interface adapter it weighs roughly 8.6 kg, is 36 cm in diameter, and stands 28 cm high. An expanded view of the REBR assembly is shown in Fig. 1. The sensor suite includes accelerometers, gyros, internal pressure and temperature sensors, and heat shield temperature sensors. The Iridium modem has a built-in GPS receiver. Reference 2 presents specific details of the REBR physical design and configuration.

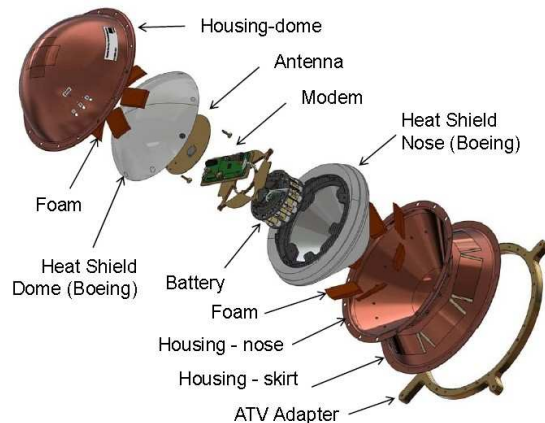


Figure 1: Expanded view of REBR assembly

3. REBR AND HOST VEHICLE DETAILS

All four REBR flights were aboard resupply spacecraft for the International Space Station (ISS). Two flights have been courtesy of the Japan Aerospace Exploration Agency's H-II Transfer Vehicles (HTV) and two flights have been courtesy of the European Space Agency's Automated Transfer Vehicles (ATV). Tab. 1 introduces this paper's numbering scheme for REBRs and provides

the flight path angle (γ) and velocity of the host vehicles at Entry Interface (EI, defined as 120 km in altitude) as well as REBR measured mass (without housing), the mounting style to the host vehicle, and whether or not the REBR was successful in transmitting data.

Table 1: REBR and Host Vehicle Specifics

	REBR1	REBR2	REBR3	REBR4
Host vehicle	HTV2	ATV-2	HTV3	ATV-3
Reentry date	30 Mar 2011	21 Jun 2011	14 Sep 2012	03 Oct 2012
Reentry attitude	controlled	tumbling	controlled	tumbling
γ (deg) at EI	-1.229	-1.655	-1.426	-1.663
Vel (km/s) at EI	7.591	7.580	7.605	7.593
REBR mass (kg)	4.44	3.95	4.17	4.09
REBR mount	soft	hard	soft	soft
REBR success?	yes	no	yes	yes

The HTV and ATV are approximately cylindrical in shape, with length of ~ 10 m and diameter of ~ 4.5 m. The HTV's solar arrays are conformal with the main body, while the ATV has four cantilevered solar array panels that span 22.3 m. The HTV flights carrying REBRs were controlled to reenter with their aft end (propulsion system) forward, while the ATVs carrying REBRs were commanded into a tumble before reaching EI. The flight path angles were steeper than the less-than-one degree that is common for most uncontrolled reentries, which ensured the EIs and impact footprints of these intentionally-reentered vehicles were over the South Pacific Ocean Uninhabited Area to reduce potential interaction with people and property.

4. DATA TRANSMISSIONS

REBR is not specifically designed for either survival or demise upon water impact because its operational concept is to transmit all recorded breakup data before surface impact. Even though survivability is not a requirement, both REBR1 and REBR3 continued to transmit after water impact. REBR4 is the only successful flight whose data transmission went completely dark after water impact.

The REBR modem requires roughly 30 seconds of no-contact with the Iridium satellites before hanging up and redialing. The REBR1 Iridium phone call was sustained throughout the water impact timeframe with only a 15 second gap in Iridium connection, based on GPS data which are streamed in real time directly by the Iridium modem. The REBR1 connection continued for 16.9 hours after water impact and the longest gap in connection during that time was six minutes. REBR1 was pre-programmed to stop recording from its sensor suite 256 seconds after REBR initialization,

emphasizing capture of data from the breakup phase, so the only information transmitted, besides the 256 seconds of REBR instrumentation data, was GPS data. Although battery voltage information was not available, it is believed the eventual loss of contact was due to battery depletion. REBR1's impact location was 51.77°S , 118.05°W , and it traversed 16 km of north-easterly ground track (distance does not account for vertical wave motion) to eventually go quiet at 51.73°S , 117.85°W . Fig. 2 shows the vertical wave and tidal motion experienced by REBR1 after water impact; the altitudes are not filtered, so some noise is present due to variations in GPS signal strength (GPS signal health statistics are collected but not shown).

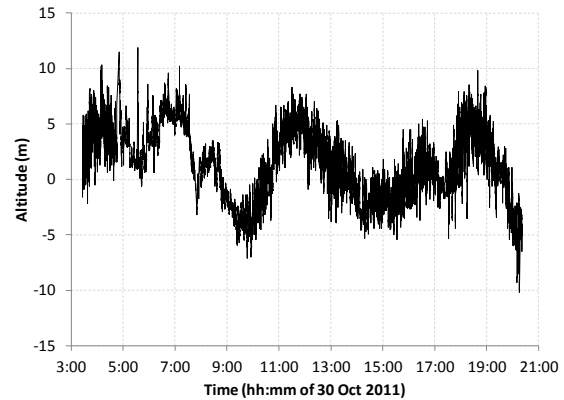


Figure 2: REBR1 tidal drift – GPS altitude

The 256 second limitation on data collection for the first generation of REBRs was relieved for the second generation, so once activated, data from REBR3 and REBR4 was continuously collected and transmitted “first in, first out” until loss of power. REBR3 transmitted 500 seconds of data from its sensor suite's recorded buffer in 362 real-time seconds before water impact. A six second connection gap exists when impact occurs, and then another 194 seconds of REBR data were transmitted in 139 real-time seconds after impact. The Iridium connection was then lost for 23.1 hours but then reconnected for 10.0 more hours of transmission before ultimately going silent. The REBR3 time stamp, reported voltage, and original data buffer storage were corrupted during the 23.1 hour transmission hiatus although GPS data, internal temperatures, pressure, accelerations and rotation rates were all with expected ranges for tidal drift. Bad weather existed in the South Pacific during REBR3's communications hiatus, and it is possible REBR3 was floating upside down during that time. REBR3's impact location was 51.76°S , 132.67°W , it reappeared at 51.61°S , 132.58°W and proceeded to traverse 17 km of north-easterly ground track to eventually go quiet at 51.57°S , 132.35°W . Fig. 3 shows the vertical wave and tidal motion experienced by REBR3 after water impact;

the spike at time 9:44 and other visible noise is due to intermittently poor GPS signal strength.

A summary of the data transmissions and water impact survival for all successful REBR flights is given as Tab. 2. The transmitted seconds of sensor suite data and the real-time transmission duration before and after water impact are provided.

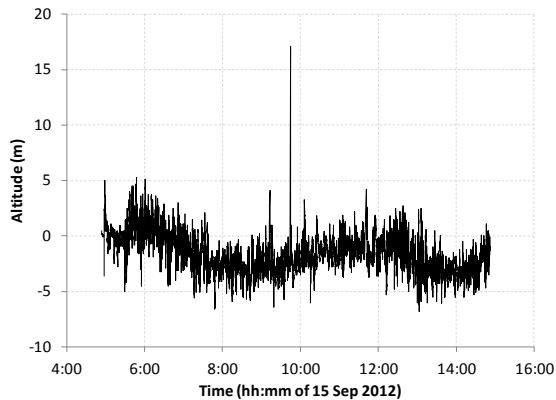


Figure 3: REBR3 tidal drift – GPS altitude

Table 2: Data Transmission and Impact Summary

Event	REBR1	REBR3	REBR4
Sensor suite data (sec) transmitted <i>before</i> splash	256	500	386
Real-time transmission duration (sec) <i>before</i> splash	372	362	263
Survived splash?	yes	yes	no
Sensor suite data (sec) transmitted <i>after</i> splash	0	194	0
Real-time transmission duration (hr) <i>after</i> splash	16.9	10.0	0

5. DATA COMPARISON

After each flight, the REBR flight data are fused together with pre-flight ballistic coefficient predictions, host vehicle telemetry, and daily atmospheric measurements to create a post-flight best-estimate trajectory (BET.) Reference 3 reports the data and results for REBR1 and examines the most likely reason why no data were received for REBR2. Reference 2 provides additional REBR1 results and documents the improvements made to the REBR platform after those first two flights. The flight profiles and initial data analyses of the second generation REBRs (REBR3 and REBR4) are presented in [4]. While select REBR results have been presented previously, this paper is focused on comparing the data of all three successful flights and how those comparisons affect the interpretation of events in the REBR flight data. The reconstructed REBR altitude and smoothed-accelerations are resolved against time-past-EI in Fig. 4.

Host vehicles with steeper flight path angle experience breakup and REBR acceleration peaks at times earlier than host vehicles with shallower flight path angle, although the acceleration peaks occur at relatively similar altitudes for all vehicles.

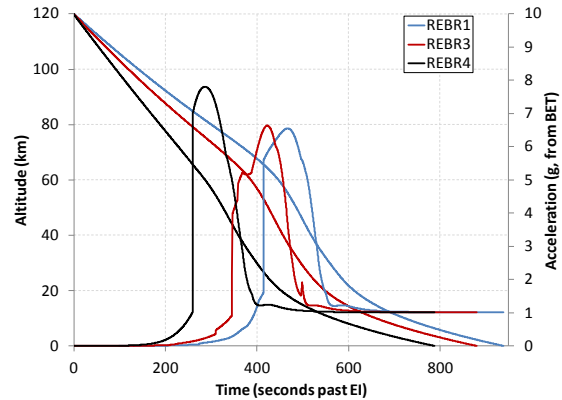


Figure 4: Altitude and smoothed acceleration versus time past Entry Interface (EI, 120 km)

5.1. Event Labeling

Fig. 5 illustrates that key REBR events occurred at roughly the same altitude for all three flights despite differences in the flight path angle. REBR data recording consistently began between 95 and 90 km. The first REBR pressure drop, which likely indicates a breaching of the host vehicle’s pressure containment, occurred between 84 and 78 km. Acceleration and gyro data indicate pronounced, sustained movement of the host vehicle between 74 and 70 km, which likely reflects the start of main structural breakup. REBR acceleration and gyro data consistently exhibit rapid damping between 65 and 64 km, indicating aerodynamic stabilization after REBR is clear of the major-breakup event.

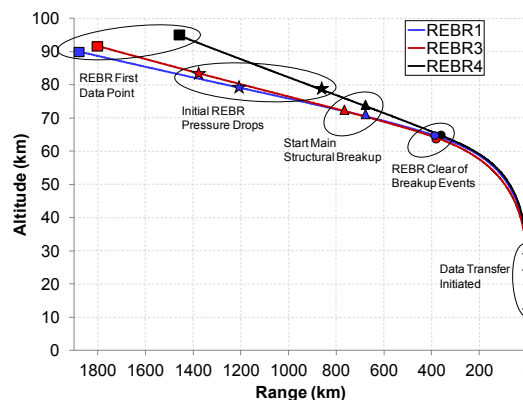


Figure 5: Altitude vs. range

More key events are displayed in Fig. 6. Initial pressure drop and data transfer initiation are labelled as in Fig. 5,

with the addition of a modem-on label and a shading of the duration between start of main breakup and REBR release, which is consistently between 33 and 35 seconds for all three flights. The REBR modem was programmed to turn on at either 256 seconds past the initialization of data recording or when the aerodynamic deceleration dropped below 1.75 g. The modem was turned on by the 256 second timer for all flights and the disparity in altitude of modem-turn-on is directly related to the flight path angle of the host vehicle. The starting time of data transfer is a result of the variable line-of-sight geometry between the REBR and the Iridium satellites. The data transfer began as soon as a consistent Iridium connection was made, which in seconds-past-modem-on was 87 for REBR1, 88 for REBR3, and 152 for REBR4.

5.2. Accelerations

The accelerations displayed in Fig. 6 are combinations of root-sum-squares (RSS) of REBR's low-g and high-g accelerometers. Each accelerometer has 3-axes and compliments each other's limitations; the high-g accelerometer is noisy at low accelerations and the low-g accelerometer (with a useful limit of 1.7 g) saturates at 2 g. The accelerations from all flights show small events prior to the main breakup region, likely due to small pieces of host vehicle's structure being released. The early jolts in acceleration are dampened because

there is padding between the REBR and the copper housing, and also between the copper housing and the host vehicle. After departing from the host vehicle and clearing the main breakup region, the REBR acceleration profiles stabilize and then increase. The accelerations for the HTV REBRs (REBR1 and REBR3) both increased to a maximum of 6.5 g and the REBR4 acceleration peaked at 7.5 g. REBR1 intentionally stopped recording sensor data once the modem turned on, although REBR3 and REBR4 continued to record and transmit data that shows the deceleration curve down to 1 g once their speed slows to terminal velocity at roughly 30 km altitude.

5.3. Pressures

Internal pressures for REBR are shown in Fig. 7. At the ISS, REBRs are mounted by astronauts inside the pressurized compartments of the ISS resupply vehicles. REBRs are not built to be air tight, and internal pressure will equilibrate with the surrounding environment at a slow, but otherwise unknown, rate. Initial REBR pressure is essentially that of the pressurized host vehicle. The first REBR pressure drop likely indicates the host vehicle's pressure containment has been breached. The specific rate of change of pressure is reflective of REBR's leak rate and not the leak rate of the host vehicle. The initial drop occurred at 84 km for REBR3 and reached the roughly stable value of 10 kPa

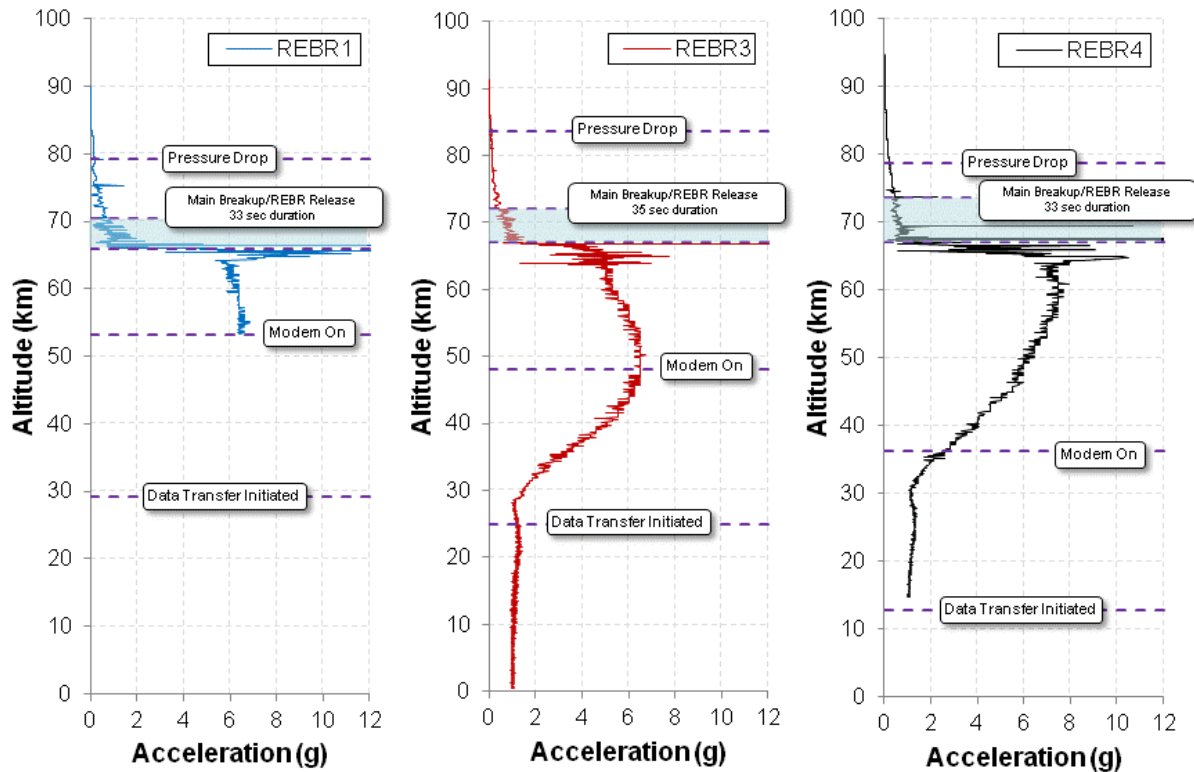


Figure 6: Altitude vs. acceleration

by the time the altitude was 70 km. At 14 km, the internal pressure of REBR3 began to increase toward standard atmosphere and followed reasonable trends for atmospheric pressure vs. altitude. The internal pressures for both REBR1 and REBR4 began to initially decline at roughly the same altitude (79 km) and at roughly the same rate. The increases to the leak rates around 65 km for REBR4 and 60 km for REBR1 are due to thermal effects. REBR4 eventually reached the same stable pressure as REBR3 before its data stream ended, and REBR1's data stream ended while the pressure was still dropping; no pressure increase was transmitted for either of those two devices.

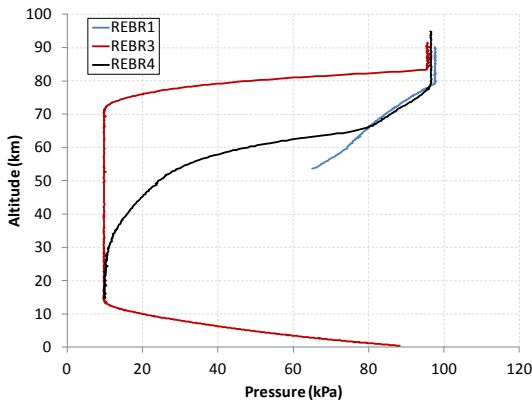


Figure 7: REBR internal pressure

5.4. Heat Shield Temperatures

The heat shield was designed and fabricated by The Boeing Company under contract to The Aerospace Corporation. Details on the heat shield performance are proprietary to The Boeing Company so Fig. 8 only shows normalized temperatures of the outermost thermistor in the heat shield. The two halves of the REBR copper housing are held together by low-melt-temperature retaining bolts. The initial rise in temperature shown between 67 and 65 km for all vehicles is evidence that REBR was free of its copper housing at approximately this time. REBR4's maximum shell temperature was roughly twice that of REBR3 and REBR3 reached its maximum temperature at 47 km, roughly 10 km lower than both REBR1 (56 km) and REBR4 (54 km).

5.5. Rotation Rates

The RSS of the three-axis rate gyros are shown in Fig. 9. The rotation rates increased in the high altitude region as aerodynamic moments increased and propelled the host vehicle into an uncontrollable tumble. Within the main breakup region the rotation rates became erratic. REBR is designed so its conical nose points forward into the airstream, stabilizing the two lateral axes that are normal to the longitudinal axis of

symmetry and allowing the Iridium and GPS antennas to point to zenith as the REBR nose points to nadir at terminal velocity. REBR is designed to have a subsonic trim limit of 7 degrees. The third rotational axis, which is the REBR axis of symmetry, has no natural damping, so REBR tends to spin like a top after stable flight is reached. The 400 deg/s gyro saturation in REBR3 and REBR4 data will be alleviated for future flights. In general, the large RSS values seen after release of REBR are due to spinning about the longitudinal axis that dominates the relatively low lateral rotation rates.

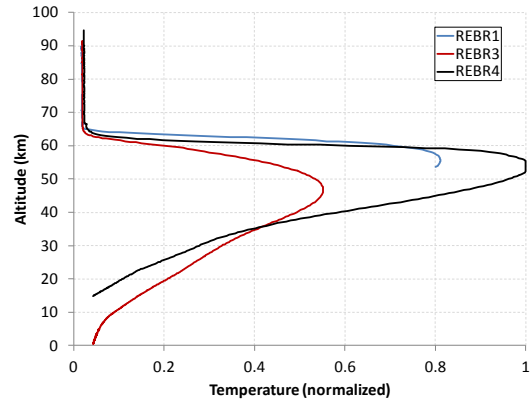


Figure 8: REBR heat shield temperature

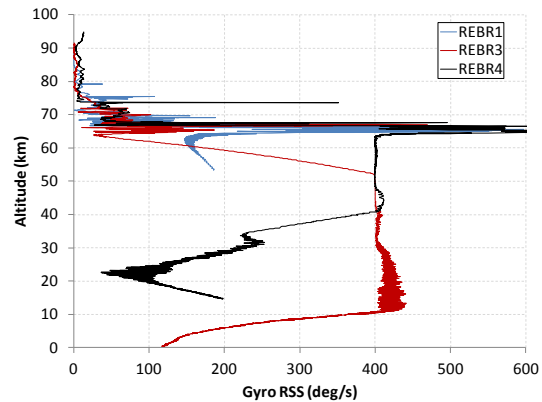


Figure 9: REBR gyro rates

5.6. Battery Voltages

The REBR battery voltages are shown in Fig. 10. REBR1 data recording stopped before any change in voltage, but the data for REBR3 and REBR4 show the first drops at 42 km and 25 km, respectively. The voltage drop happened 19 seconds after the modem is initiated for REBR3 and 48 seconds after the modem is initiated for REBR4. This is the timeframe that REBR is searching for a stable Iridium connection prior to data transmission. Power-draw specifics are given in [2].

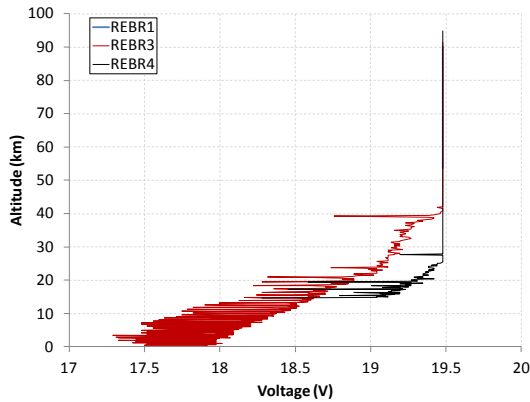


Figure 10: REBR battery voltage

6. DETAILED INITIAL REBR TIMELINES

The comparison of flight results from multiple REBRs has helped solidify the interpretation of flight data events and has increased confidence in the comprehensive timelines pieced together for each flight. Fig. 11 through Fig. 13 show the initial regions of select REBR flight data. The RSS of the low-g accelerometer is plotted as a blue line against the left vertical axis and the rotational rates of all three gyro axes are plotted as greyscale lines against the right vertical axis. Vertical dotted lines are placed at significant events in the REBR flight data and are numerically labelled at the top of the plot

The first 204 seconds of select REBR1 flight data are shown in Fig. 11. REBR1 began recording data when the reentry acceleration reached 0.0125 g, which corresponds to an altitude of 90.1 km. At 90 seconds (79.2 km), a jolt registered in the low-g accelerometer and gyro rates and the REBR internal pressure began to decrease, indicating that the pressure containment system of HTV2 had been breached. At 122 seconds (75.4 km), pronounced disruptions began in the acceleration and rotational data, which is interpreted as the beginning of significant debris shedding of HTV2. The high-g accelerometer (high-g data not shown in Fig. 11) registered a shock at 149.5 sec (72.1 km) which was followed by a change in the rotation rate trend. At 162 seconds (70.5 km), the rotation rates and accelerations began to be more pronounced, which is interpreted as the start of main structural breakup of HTV2. It is believed at this time that the REBR1 and its copper housing were released from their HTV2 straps and were bouncing around inside or in the wake of major debris of HTV2. At 187.5 seconds (67.1 km), both the recorded rotation rates and accelerations became erratic, clipping against their sensor's usable physical limits and over the 4 Hz REBR data sample rate. This erratic period of extremely dynamic motion is interpreted as when REBR1, inside its copper housing, was released into the airstream. At 198 seconds (65.5 km), the

outermost thermistor in the REBR1 heat shield began to register a temperature increase, indicating that REBR1 left its housing no more than 11.5 seconds after it hit the airstream. Erratic rotational rates and major acceleration events continue until 203 seconds (64.7 km) when it is evident that REBR1 was completely clear of all HTV2 debris and quickly reached aerodynamically stable flight.

The first 180 seconds of select REBR3 flight data are shown in Fig. 12. REBR3 began recording data when the reentry acceleration reached 0.0125 g, which corresponds to an altitude of 91.7 km. At 55 seconds (83.6 km), the REBR3 internal pressure began to decrease and very small disruptions were registered in the rotation and acceleration data for the following 20 seconds, likely as the pressurized atmosphere inside HTV3 rapidly dispersed. A single minor acceleration bump occurred at 96 seconds (77.9 km), which preceded an immediate change in the trend of rotations and accelerations; this region of motional growth is interpreted as the beginning of significant debris shedding of HTV3. At 138 seconds (72.1 km), an acceleration disruption occurred and was immediately succeeded by a drastic change in acceleration and rotational trends, which is believed to be the time when REBR and its copper housing were released from their HTV3 straps and bouncing around inside of or within a large debris wake of HTV3. At 173 seconds (67 km), the acceleration and rotational data became erratic, indicating that the REBR and its copper housing hit the airstream. By 176.5 seconds (66.5 km) the erratic motion (defined by clipping data) dampened, although large acceleration and rotation rate changes still existed. At 184 seconds (65.3 km), the outermost thermistor in the REBR3 heat shield registered a rise in temperature, indicating that REBR3 was free of its housing within 11 seconds of being released into the free stream. The rotational rates quickly dampened to display aerodynamically stable flight, although one last spike in acceleration occurred at 192 seconds (64 km) which was likely REBR3 impacting or being impacted by one last HTV3 debris.

The first 144 seconds of select REBR4 flight data are shown in Fig. 13. REBR4 sensed over 0.0125 g of centripetal acceleration during the intentional ATV-3 tumble that was commanded roughly 20 minutes after ATV-3's final de-orbit burn. A secondary requirement before permanent REBR recording begins, that the acceleration must continue to grow after reaching 0.0125 g, was enacted for REBR4 and the recording and transmission of roughly 15 minutes of ATV-3 tumble was avoided. At 79 seconds (78.7 km), the REBR4 internal pressure began to decrease, indicating that the pressure containment system of ATV-3 had been breached. No acceleration disturbance registered with the REBR4 accelerometers at the time of pressure

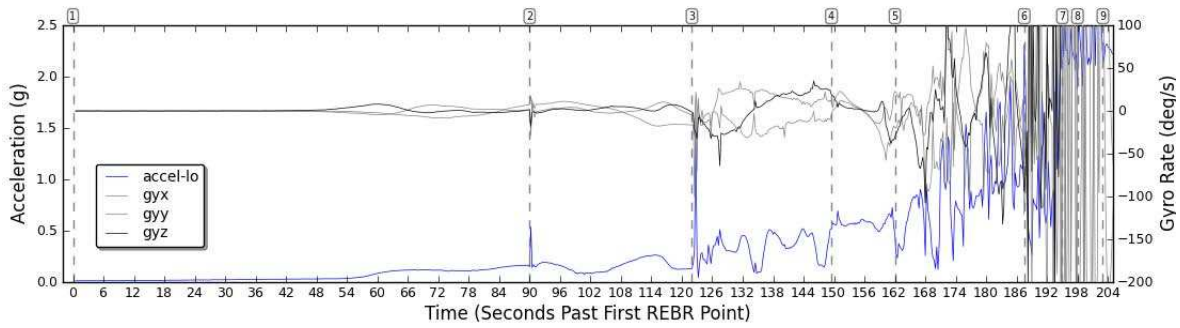


Figure 11: Initial region of select REBR1 data

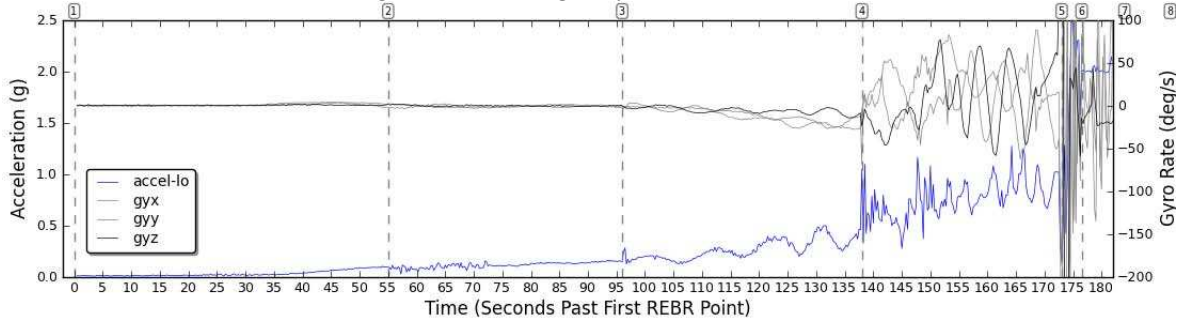


Figure 12: Initial region of select REBR3 data

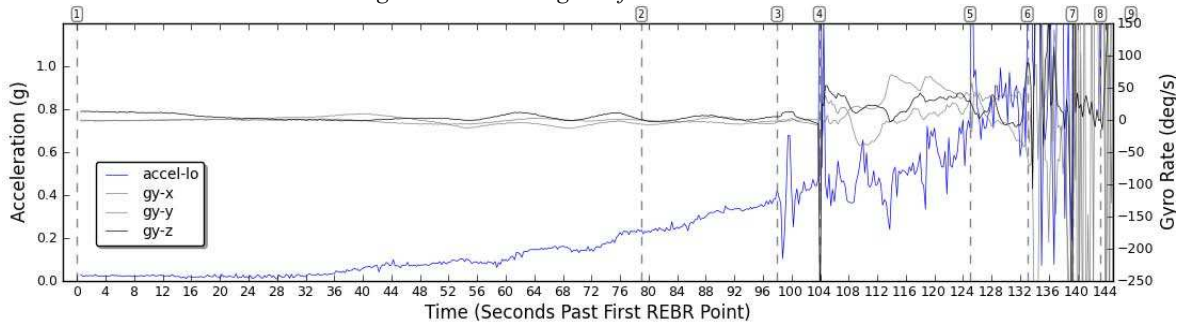


Figure 13: Initial region of select REBR4 data

decrease and it is suspected that short acceleration spikes may have been missed by REBR4's 4 Hz data sample rate. At 98 seconds (74.9 km), minor acceleration and rotational disruptions began, which are interpreted as the initial ATV-3 debris shedding. A major acceleration spike registered at 103.9 seconds (73.7 km) and was followed by an immediate, pronounced change in acceleration and rotation rate trends, which is interpreted as the region of ATV-3's major structural breakup. At 133 seconds (67.8 km), a drastic change in accelerations and rotation rates is interpreted to mean the REBR4 and its copper housing were released into the airstream. The acceleration and rotational rates became increasingly erratic until 139.25 seconds (66.5 km) when the temperature of REBR4's outermost heat shield thermistor first rose, indicating that the copper housing separated from REBR4 within 7 seconds of hitting the airstream. Erratic motion continued until 147.5 seconds (64.8 km), when the last major acceleration disturbance occurred and was followed by a quick dampening of motion to

aerodynamically stable flight; a noticeable increase in the rate of REBR4 internal pressure loss also occurred at this time.

7. FUTURE DEVELOPMENT

The success of both second-generation REBRs (REBR3 and REBR4) validated the adjustments, detailed in [2], that were made to the REBR platform after the first generation (REBR1 and REBR2) flights, and increased confidence that the REBR vehicle will return recorded data from reentry breakup.

Data from REBR internal sensors alone are insufficient for comparison with detailed breakup models, which is motivation for the third generation of REBRs. Dubbed REBR-Wireless (REBR-W), this new generation will utilize external sensors, placed strategically around the host vehicle which will communicate their data to the central REBR device for recording, storage, protection, and later Iridium transmission. The architecture and

data collection for REBR-W, have been successfully demonstrated in ground testing. Funding is currently being sought for the fabrication of flight systems to meet upcoming flight opportunities.

The REBR flight data collected to date are from host vehicles of similar design. It is desired to eventually fly REBR-like devices on a variety of host vehicles. The Aerospace Corporation has entered into an exclusive licensing agreement with Terminal Velocity Aerospace (TVA), LLC. TVA offers a variety of re-entry devices devoted to both reentry debris safety and commercial space applications.

8. SUMMARY

The data recorded by REBR during the reentry of three ISS supply vehicles indicate that these vehicles experience main structural breakup between an altitude range of 74 to 64 km. Major events determined from REBR flight data and best-estimate-trajectory analysis are tabulated by altitude in Tab. 3, and interpreted events not immediately reflective of REBR flight data appear in italics. It is evident that the REBR devices departed from the host vehicles within the range of 68 to 66 km for all three reentries, and that all REBRs were completely clear of the breakup events and in stable flight between 65 and 64 km.

Table 3: REBR events vs. reconstructed altitude

Event	REBR1	REBR3	REBR4
REBR start of data recording	90.1	91.7	94.9
REBR internal pressure drop	79.2	83.6	78.7
<i>Initial debris shedding</i>	75.4	77.9	74.9
<i>Start of main structural breakup</i>	70.5	72.1	73.7
REBR motion goes erratic, REBR housing exposed to freestream	67.1	67.0	67.8
First rise in REBR heat shield temperature, REBR released from housing	65.5	65.3	66.5
REBR in aerodynamically stable flight	64.7	64.0	64.8
Peak REBR heat shield temperature	55.9	46.9	53.6
REBR modem turns on	53.2	48.1	36.2
REBR reaches subsonic speed	31.0	29.2	31.6
Start of data transfer	29.3	25.0	12.7

9. ACKNOWLEDGEMENTS

We particularly want to thank the Japan Aerospace Exploration Agency (JAXA) for launching the REBRs to the International Space Station, the astronauts who installed and activated the REBRs, and the European

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