REENTRY BREAKUP RECORDER: SUMMARY OF DATA FOR HTV3 AND ATV-3 REENTRIES AND FUTURE DIRECTIONS

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ABSTRACT

In late 2012, Japan's H-II Transfer Vehicle, HTV3, and the European Automated Transfer Vehicle, ATV-3, both ended their International Space Station (ISS) resupply missions by reentering the atmosphere and breaking apart due to atmospheric heating and loads, with debris landing in the South Pacific Ocean. Both vehicles carried a Reentry Breakup Recorder (REBR) that recorded and transmitted acceleration, attitude rate, and other data during the reentry and breakup. This paper provides samples of the data collected for these two missions. REBR is collecting the first *in-situ* data on the breakup of unprotected space hardware during reentry, data that will increase our understanding of reentry breakup and lead to space hardware designs that pose less of a hazard to people and property when they reenter.

1 INTRODUCTION

In the early 1970s, six satellite reentry tests were conducted to determine experimentally the reentry survivability and condition of vehicle payload elements (see [1]). Four of the tests, referred to as Vehicle Atmospheric Survivability Tests (VAST), used one specific type of satellite vehicle; the final two tests, referred to as the Vehicle Atmospheric Survivability Project (VASP), involved the reentry of a second, larger satellite vehicle. All tests included the deorbit of satellites into the Pacific Ocean, with reentries and breakup of the first four vehicles observed by land and ship-borne radars, and optical tracking aircraft, with good coverage of the altitude range between 114 and 56 km (62 and 30 nmi). While tracking resources were reduced for the VASP tests, there was sufficient tracking available to verify that breakup was consistent with that observed for the previous VAST reentries. Limited telemetry from some of the reentering vehicles was available to help verify some events.

The VASP tests substantiated results from the VAST tests and found that "contrary to theory, breakup was essentially independent of attitude behavior and geometry [of the reentering satellites]. In addition, "onboard temperature data collected prior to breakup…indicated heating an order of magnitude less than obtained by traditional heating analysis." For the vehicles tested, initial fragmentation during reentry began at approximately 87 km altitude, and major breakup events occurred at approximately 78 km. The unexpected nature of these results has been verified by occasional observations of reentry events since that time. As an example, [2] reported that breakup of the Space Shuttle External Tank was observed to occur at altitude ranges between 74 and 71 km (40 and 38 nmi), altitudes significantly lower than predicted at the time, even accounting for the effects of the thermal insulation that covered the tank.

Two possibilities have been proposed as reasons for the discrepancies in breakup predictions: 1) the models of the response of the vehicle structure to reentry heating require modification, or 2) the heating environment between the free molecular and continuum flow regimes is over-predicted in current models.

While the VAST, VASP and other observational tests provide excellent evidence related to the macroscopic breakup characteristics of reentering space hardware, observational data cannot provide details on the actual environment experienced by the reentering body and the effects of that environment on critical elements leading to breakup. Observational data have been supplemented with analyses of debris that survived reentry and was subsequently recovered. Reference [3] provides analysis results for several recovered items, results that include maximum temperatures achieved during reentry. While these analyses also provide benchmarks as to what can actually survive, the data alone are not sufficient to provide details of the heating environment and the response of satellite and rocket stage materials.

In 2011, the Reentry Breakup Recorder (REBR), a device designed to collect detailed data on reentry breakup, flew its first reentry test. REBR reentered inside the Japanese HTV2 ISS supply vehicle, recorded data as HTV2 heated and broke apart, was released during breakup of the HTV2 host vehicle, and "phoned home" recorded data via the Iridium system prior to landing in the South Pacific Ocean. Data from this successful test was first published in 2011 [4], with additional data analysis in 2012 [5]. A second test was flown later in 2011, with a REBR inside the European ATV-2 vehicle. This test was not successful.

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The next two flight tests were flown in 2012, with REBRs aboard HTV3 and ATV-3. Both of these REBRs had been upgraded with modifications suggested by extensive evaluations of data from the HTV2 flight and possible causes of the failed ATV-2 flight, and both the HTV3 and ATV-3 flight tests were successful.

2 REBR OVERVIEW

REBR is a small (30 cm diameter, 23 cm high), lightweight (4 kg), low cost, autonomous device protected by a heat shield that records accelerations, attitude rates, internal temperatures, and internal pressure during the reentry and breakup of a host vehicle, separates as the host disintegrates during reentry, and "phones home" the recorded data prior to surface impact. Data are transmitted via the Iridium system, so data can be retrieved from reentries anywhere on earth. Except for the heat shield, aeroshell and some custom housing and internal chassis hardware, REBR components are commercially available off-the-shelf items.

The REBR device is shown in Fig.1 and Fig. 2 gives an exploded view of the complete assembly. Note that for the ATV and HTV flights, REBR was contained within a copper housing that provided some protection from early breakup events. REBR was released when reentry heating increased to the point where the sixteen low-melt-temperature bolts joining the two halves of the copper housing melted. In its copper housing, the REBR assembly has a mass of 8.6 kg and is 36 cm in diameter and 28 cm high.

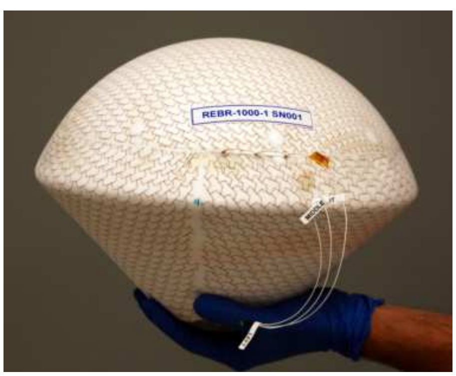


Figure 1. Reentry Breakup Recorder (REBR).

REBR's aerodynamic and mass properties are designed to provide a stable flight orientation with the aft end (the heat shield dome in Fig. 2) pointed toward zenith during subsonic flight. This orientation is critical, since as Fig. 2 shows, REBR's Iridium and GPS antennas are internal and below the aft dome.

For both the HTV3 and ATV-3 flights, the REBR devices were carried to orbit in a dormant state and were installed by astronauts inside the host vehicles and activated. Reference [5] contains detailed information on REBR sub-systems, activation, and operation.

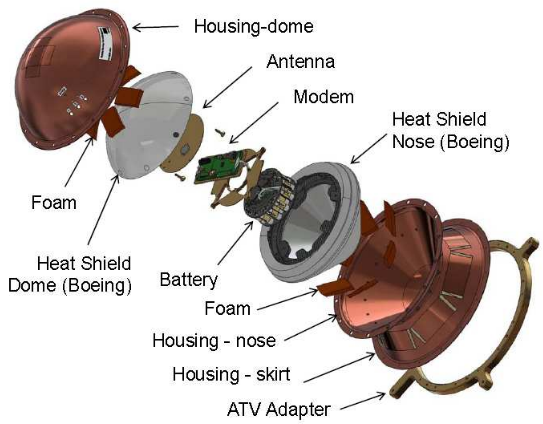


Figure 2. Exploded view of REBR.

After release during breakup, REBR flies free, decelerates, and is designed to reach a subsonic free-fall condition at about 30 km altitude, about six minutes before surface impact. Data recorded during the host vehicle breakup, supplemented with GPS data on REBR's position and altitude, are broadcast during this time.

While not designed to be waterproof or to survive impact with the Earth's surface, in two instances REBR survived ocean impact and continued to broadcast recorded data. In one case, transmissions continued for 17 hours, when the batteries were depleted (note that failure to maintain an orientation with the internal antennas pointed toward zenith while floating could prevent or limit communications after impact). While its precise location is known temporarily, REBR transmits all recorded data prior to impact and is not designed for recovery.

3 REBR INSTRUMENTATION

REBR instruments include three-axis low-g and high-g accelerometers, rate gyros, thermocouples in the heat shield and in REBR's interior, an internal pressure sensor, and GPS. GPS data are not received until REBR falls below the 18 km altitude limit set for commercial GPS receivers. The low-g accelerometer is limited to a maximum acceleration of 1.7 g and is used during the early portion of the reentry to activate REBR's recorder when accelerations on the host vehicle due to atmospheric drag reach 0.0125 g. The high-g accelerometer, which has a range up to 120 g, captures higher-level accelerations. The rate gyros have a limit of 300 deg/sec. Details on REBR activation and sensor limits are provided in [5].

4 HOST VEHICLES

As noted, two REBRs were carried to the ISS aboard Japan's H-II Transfer Vehicle, HTV3. Astronauts moved and installed one REBR on the European ATV-3; the second remained on HTV3 and was installed there.

The ATV and HTV host vehicles in space are shown in Figs. 3 and 4. Both are roughly cylinders of approximately 10 meters in length and ~4.5 m in diameter. ATV has a launch mass of approximately 20,000 kg; HTV's launch mass is approximately 15,000 kg. The ATV's solar panels are extended, while HTV's panels are mounted around portions of the vehicle.

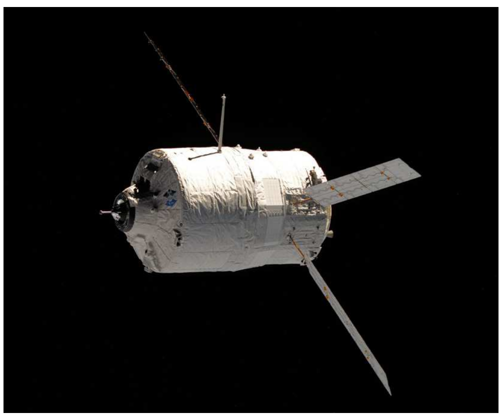


Figure 3. Automated Transfer Vehicle (ATV) (photo courtesy ESA and NASA).

Figure 4. Japanese H-IIB Transfer Vehicle (HTV) (photo courtesy JAXA and NASA).

Cut-away views of the two vehicles are given in Figs. 5 and 6. The HTV in Fig. 5 has two compartments; the compartment near the forward hatch is pressurized and maintains a shirtsleeve environment, while the aft compartment is open to the space environment. REBR was attached just inside the forward hatch for the previously successful HTV2 reentry and the HTV3 reentry.

The ATV in Fig. 6 has a single compartment that extends from the front hatch to the bulkhead separating the propulsive system. For the previous ATV-2 reentry, REBR was mounted toward the aft end of the pressurized compartment, not far from the bulkhead. An explosion of the propulsion system was a possible cause of REBR's failure for that mission, so REBR was located just inside the forward hatch for the ATV-3 reentry.

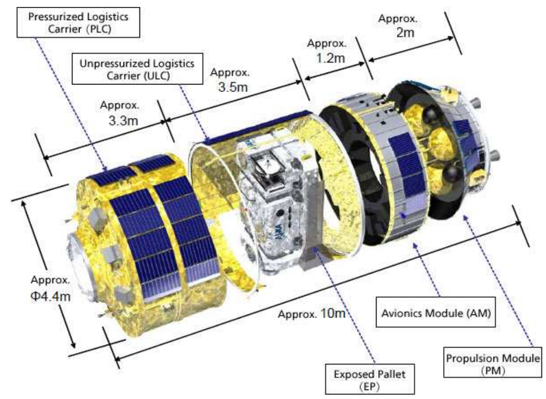


Figure 5. Japanese H-II Transfer Vehicle (HTV) (illustration courtesy Japan Aerospace Exploration Agency, JAXA)

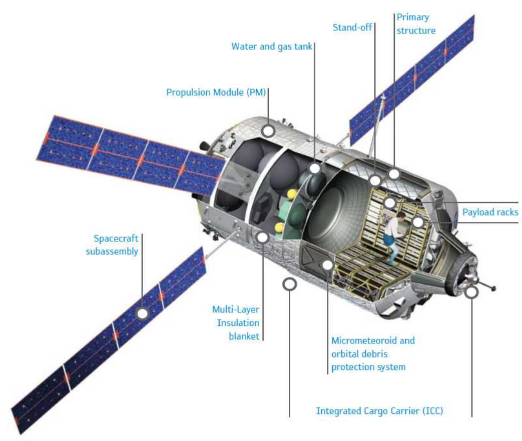


Figure 6. Automated Transfer Vehicle (illustration courtesy European Space Agency, ESA).

As Tab. 1 shows, the entry velocity and flight path angle at the atmospheric entry point, defined as an altitude of 120 km, were very close for the two vehicles. Note that ATV-3 was purposefully tumbled after the final deorbit burn. While the centripetal acceleration on REBR for this case exceeds 0.0125 g, which would nominally activate REBR's data recorder, REBR's false-reentry detection algorithm delayed activation until increasing acceleration was sensed upon encountering the atmosphere.

Table 1. Summary of atmospheric entry conditions for HTV3 and ATV-3.

	HTV3	ATV-3
Reentry Date	14 Sep 2012	3 Oct 2012
Vehicle Attitude at Reentry	Controlled	Tumbling
Flight Path Angle at 120 km	-1.426°	-1.663°
Velocity at 120 km (km/s)	7.591	7.593

5 REBR DATA FOR HTV3 AND ATV-3 REENTRIES

REBR's performance for the two reentry cases is summarized in Tab. 2. Both HTV3 and ATV-3 were targeted such that debris that survived reentry would impact in the South Pacific, and both REBRs landed in this area. REBR is designed to broadcast for a minimum of 300 seconds during its fall after release from the host, and REBR3 aboard HTV3 performed as desired; REBR4 on ATV-3 broadcast for about 40 seconds less than desired, but did relay all of its recorded breakup data. Note also that REBR3 survived the splashdown and continued to broadcast for 139 seconds, went silent for 23.1 hours, then transmitted again for 10 hours; REBR4 did not broadcast after impact. As discussed earlier, REBR was not designed to survive, and local weather conditions could have contributed to the breaks in broadcast time and/or failure to broadcast.

Table 2. Summary of REBR performance for HTV3 and ATV-3 reentries.

	HTV3/ REBR3	ATV-3/ REBR4
Reentry Date	14 Sep 2012	3 Oct 2012
Time of REBR Ocean Impact (hh:mm UTC)	05:42	01:33
Impact Latitude (deg)	-51.76	-46.90
Impact Longitude (deg)	-132.67	-145.23
Transmission Duration before Impact (sec)	362	263
Survived Impact?	Yes	No
Transmission Duration After Impact (hours)	10.0	0

The best-estimate trajectories (BETs) for HTV3 (REBR3) and ATV-3 (REBR4) are compared in Fig. 7. Note that the steeper entry flight path angle for ATV-3 gave a slightly different entry profile, but in both cases, REBR went subsonic and in terminal fall at about 30 km, as designed.

Key events derived from REBR data are highlighted in Fig. 8. Note that for reentries of both host vehicles and despite the fact that one vehicle reentered at a steeper angle and was tumbling, REBR detected drops in internal pressure, initiation of main structural breakup (indicated by rapid changes in the dynamics as sensed by the gyros), and REBR release (confirmed by a rise in the temperature of REBR's heat shield) within a fairly tight altitude range.

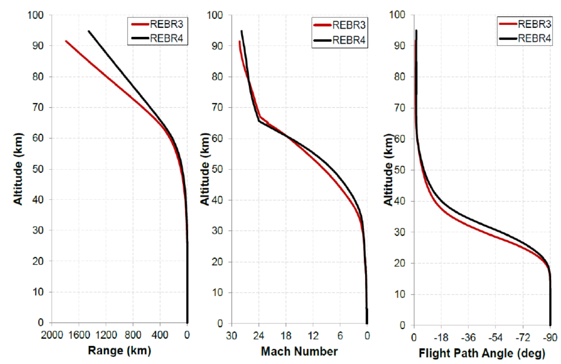


Figure 7. Best estimate trajectories for HTV3 (REBR3) and ATV-3 (REBR4) reentries.

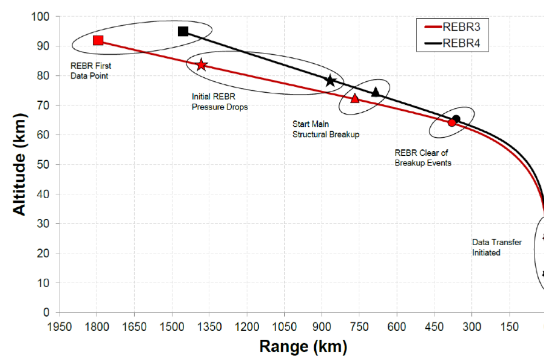


Figure 8. Key events during HTV3 and ATV-3 reentries (best-estimate trajectories).

REBR data for internal pressure, normalized heat shield temperature (the dimensional data is proprietary) and the root-sum-square (RSS) of the gyro rates are shown in Fig. 9. It should be noted that REBR is not air tight, so the rate of change of REBR's internal pressure simply reflects REBR's leak rate, not the pressure within the host vehicle. Also, the RSS rate data reflects the fact that the maximum rate was exceeded on REBR's rate gyro—a gyro with a higher rate limit will be used on future REBRs.

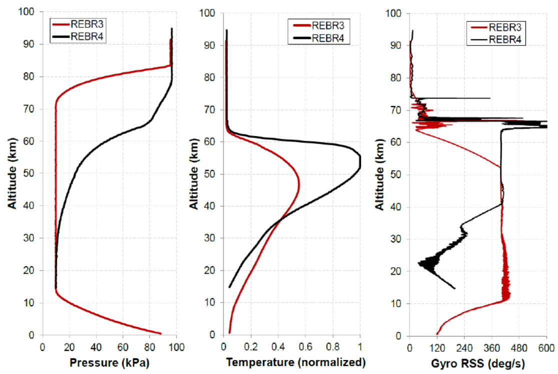


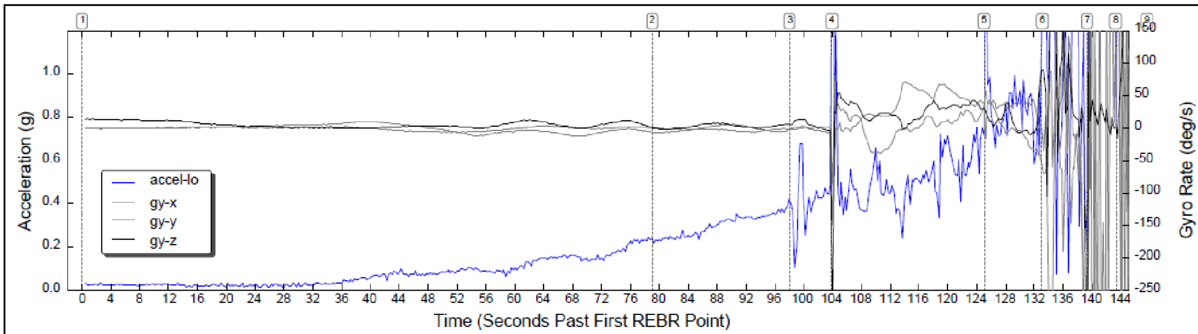
Figure 9. REBR internal pressure, normalized heat shield temperature, and rotation rates.

An example of how REBR flight data were interpreted is shown in Fig. 10, in this case, for ATV-3. For ATV-3, REBR began recording when the acceleration reached 0.022 g rather than when the 0.0125-g threshold was exceeded. As noted earlier, this is because ATV-3 was put into a tumble mode after the final deorbit burn, and the tumble rate gave a centripetal acceleration exceeding REBR's nominal activation threshold of 0.0125 g. REBR's activation software requires acceleration to be at least 0.0125 g and increasing, and this second requirement was not satisfied until the slightly higher acceleration was reached.

At 79 seconds from the initiation of recording (78.7 km altitude), REBR's internal pressure begins to decrease, indicating that an event has occurred causing drop of ATV-3's pressure. While no acceleration jump was noted at that time, it is possible that it was not recorded, since REBR records accelerometer data at a 4 Hz rate (a small jump in the acceleration was noted at the instant the pressure drop began on HTV2).

At 98 seconds (74.9 km altitude), minor acceleration and rotational disruptions are beginning to occur, interpreted as initial debris shedding, and the motion becomes increasingly erratic, until a significant trend change, interpreted as the start of main structural breakup at 73.7 km, possibly with REBR and its copper housing bouncing around inside the vehicle. Another bump detected at 125 sec may be the REBR assembly striking or being struck by another object.

As noted earlier, REBR's copper housing (with the REBR inside) is mounted (strapped down) just inside the front hatch of ATV-3. REBR's accelerometers and rate gyros begin very erratic motion at 67.8 km, possibly indicating that REBR and its protective



- **Line 1 (0 sec, 94.9 km)—REBR begins recording: Rotation rate present at beginning of REBR data due to intentional ATV-3 spin**
- **Line 2 (79 sec, 78.7 km)—REBR internal pressure begins to decrease. Breach of pressure containment in ATV-3**
- **Line 3 (98 sec, 74.9 km)—Bump in accelerometer data, beginning of more pronounced motion.** *Possible ATV-3 debris shedding?*
- **Line 4 (103.9 sec, 73.7 km)—Large bump in low-g, high-g accelerometer and gyro data.** *Initiation of main structural breakup of ATV-3? REBR Housing released, bouncing around inside ATV-3?*
- **Line 5 (125 sec, 69.4 km)—Large bump in accelerometer data.** *REBR Housing strikes another object?*
- **Line 6 (133 sec, 67.8 km)—Pronounced movement in both gyro and accelerometer data.** *REBR Housing exposed to airstream?*
- **Line 7 (139.25 sec, 66.5 km)—Both gyro and accelerometer data go erratic. First rise in REBR heat shield temp.** REBR released from housing.

Figure 10. Interpretation of significant events for ATV-3/REBR4 reentry.

copper housing have been released to the airstream. REBR's heat shield temperature is not rising at that point, but the rise does begin about six seconds later (66.5 km), indicating that REBR is away from the host vehicle and free of its housing. The main events for HTV3 and ATV-3 are summarized in Tab. 3.

Comparing breakup events with the VASP data mentioned earlier is difficult, since there is insufficient detail available on the VASP tests and the definition of terms such as "major breakup" in that report. For example, for ATV-3 REBR may have been carried inside a large fragment and shielded from major heating until it was released at approximately 73.7 km, which we used as the beginning of "major breakup." In the VASP and VAST tests the major breakup event was reported to occur at approximately 78 km. While it is not clear how these two events relate, in general, the low altitudes for the HTV3 and ATV-3 events are consistent with the findings from the VASP and VAST tests that reentry breakup occurs at lower altitudes than expected for current breakup models.

Table 3. Main events for HTV3 and ATV-3 reentries.

EVENT	EVENT ALTITUDE (km)	
	HTV3 REBR3	ATV-3 REBR4
REBR Begins Recording	91.7	94.9
Loss of Internal Pressure	83.6	78.7
Possible Initial Debris Shedding?	77.9	74.9
Start of Main Structural Breakup? REBR Housing Released and Bouncing?	72.1	73.7
REBR Housing Exposed to Airstream?	67.0	67.8
First REBR Heat Shield Temperature Rise. REBR Released from Housing.	65.3	66.5
REBR Clears Breakup Event	64.0	64.8
Peak REBR Heat Shield Temp	46.9	53.6
Start of REBR Data Transfer	25.0	12.7
REBR Data Recorded (sec)	694	386
Quality of GPS Data	Poor	Poor

6 GOALS FOR FUTURE REBRS AND REBR TESTING

When considering the recorded data, it is important to remember the following:

1. The trends noted were obtained for vehicles reentering after controlled deorbit maneuvers. As a result, the entry flight path angles are steeper than would be typical of orbit decay reentries. Space debris mitigation requirements specify that space hardware whose casualty expectation for random orbit decay reentry exceeds a specified limit (1 in 10,000 in the U.S.) must be deorbited into a safe area at end of mission. Orbit decay reentries have flight path angles near zero at the entry interface altitude (120 km), and as a result, reentering hardware spends more time at higher altitudes and in the transition region between free molecular and continuum flow—precisely the region where there is evidence that aerodynamic heating models may not accurately represent the true environment. A major goal is to fly REBRs on vehicles that will undergo very shallow reentries to collect data directly relevant to orbit decay. Data from such reentries will help verify hazard prediction models used to assess compliance with the reentry disposal requirement.
2. The data REBR has collected so far were for two vehicles of generally the same design. A goal is to collect data on vehicles of various types (orbital launch stages, several different spacecraft designs), again to help verify hazard prediction models for design-for-demise applications. REBR was designed to be inexpensive and minimally invasive (requires only a physical connection to the host vehicle), so a goal is to collect data on as many reentries as possible to assess variability in breakup characteristics.
3. The data for all test flights to date were collected from REBR's internal sensors only. There are no data on the aerodynamic heating environment or how the host vehicle's skin or critical structural elements are responding to that environment. As a result, there is uncertainty as to what breakup events are happening when. The next version of REBR, REBR-Wireless, is designed to fill these gaps. REBR-Wireless will utilize perhaps ten small, wireless sensors placed at critical locations in the host vehicle to collect and transmit temperatures and other data to the REBR core vehicle, which will record and later transmit this data. Sensors could be placed at locations where responses to the reentry environment are directly modeled in breakup prediction models, enabling direct comparisons between models and actual flight-derived data. The availability of such data will help harmonize worldwide reentry prediction model results.
4. Interpreting REBR measurement data would be enhanced by collecting and comparing visual and other data on the same reentry. As noted earlier, REBR currently provides data from its own internal sensors, so relating these events to what is actually happening to the host vehicle is difficult and open to conjecture. The conclusions about VAST and VASP breakup were based mainly on observational data, and equivalent data on reentry of a vehicle carrying REBR-Wireless

would help harmonize our understanding of reentry breakup.

7 SUMMARY

A major conclusion that can be drawn from the ATV-3 and HTV3 data is that the REBR core vehicle will survive the reentry and breakup of a reentering host vehicle and will successfully return recorded data. These flights have demonstrated the robustness of the device in a very challenging environment.

Based on REBR data, the major breakup events support the implications of the VAST and VASP tests that reentry breakup occurs at lower altitudes than expected for current breakup models. More data are needed to isolate the cause of the discrepancy. This will permit calibrating at a minimum, or fundamentally improving reentry hazard prediction models. Again consistent with VAST and VASP tests, the altitudes of major events was not significantly affected by initial tumbling of the host vehicle, though major breakup inferred from REBR data occurs at lower altitudes than observed in VAST and VASP tests. Visual data of the breakup of a spacecraft with REBR inside would significantly help resolve details of breakup and the definition of major breakup events.

As is evident, REBR data provide a macroscopic view of what is happening to the host vehicle, but do not provide a more detailed view of the heating environment or of how the host vehicle structure is responding to that environment. Evolution of the REBR system to include recording data from a number of small, wireless sensors placed at strategic locations on the host vehicle will provide new insights into reentry breakup, enable direct comparison with model predictions, and lead to space hardware design techniques that minimize hazards from surviving debris with verifiable performance.

8 ACKNOWLEDGEMENTS

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