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RED-Data2 Commercial Reentry Recorder: Size Reduction and Improved Electronics Design

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Defunct, manmade objects in orbit regularly reenter Earth's atmosphere in an uncontrolled manner causing risk of both personal injury and property damage. To reduce uncertainty and improve our ability to predict surviving debris, impact time and impact location, reentry breakup dynamics and aerothermodynamics data is needed. The Reentry Breakup Recorder has demonstrated the ability to obtain inertial and thermal measurements during reentry that are pertinent to spacecraft breakup. Building on this concept, the present investigation explores the design space for this device and matures a smaller, lighter and more operationally flexible system, termed RED-Data2. This paper documents the conceptual design, modularity and operational benefits of RED-Data2.

I. Introduction

SPACE debris, a collection of defunct satellites, spent rocket stages, and other manmade objects, routinely reenters Earth's atmosphere. Most objects below a certain size and mass break up and disintegrate in the high heating and loading environment of reentry before ever reaching the ground. However, large, massive objects can and do regularly survive reentry, posing a risk to people and property. The incidence of such events will increase as more objects are placed into orbit and on-orbit collisions expand the orbital debris population. If possible, operators strive to deorbit an object in the ocean away from populated areas. However, even in these controlled entries, large uncertainties often exist in the footprint of the resulting debris. Furthermore, controlled deorbit often has associated negative economic or mission operations penalties.

Current reentry survivability models tend to under-predict the occurrence of space debris surviving to the ground[1]. To better quantify the reentry environment and, ultimately, improve reentry safety, analysts must validate and improve models. Relevant environment flight data is key to this work. The Aerospace Corporation initially conceived of a device to address such a need in the early 2000s – the Reentry Breakup Recorder (REBR)[1,2,3]. REBR was flown in 2011 and 2012 on four missions, three of which successfully returned data.

At present, Terminal Velocity Aerospace, LLC (TVA), is pursuing development of a family of commercial reentry devices (REDs) that leverage the REBR technology under license from The Aerospace Corporation. The TVA family of REDs includes RED-Data (a commercial equivalent to REBR, designed for data collection and transmission), RED-Sensor (for data collection from wireless sensors distributed across the host spacecraft), and a technology test platform called RED-Test. Simultaneously, TVA is focused on development of a next-generation reentry breakup recorder, RED-Data2, which is smaller, lighter and autonomously operable across a range of mission profiles. This paper documents the conceptual design of RED-Data2 and the future direction of the RED family of small reentry vehicles.

II. Design Heritage

REBR demonstrated the ability to record temperature, acceleration, rotational rate, position and other data of an attached host spacecraft during its reentry and breakup in Earth's atmosphere[1]. In the REBR concept, this data is

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recorded during the reentry event and transmitted via the Iridium satellite network before ground impact. Thus, REBR is not designed for recovery.

REBR is manually activated in-space by an astronaut aboard the International Space Station (ISS). At which point, the device and host spacecraft are released from the ISS, and REBR enters a reentry detection mode for up to about one month. During this period, a g-sensor monitors loads on the craft to identify the beginning of reentry. When reentry is detected, full data recording is initiated.

The REBR aeroshell configuration is based on the NASA Mars Microprobe geometry, with an approximate 31cm maximum diameter. REBR carries an electronics package that includes a flight computer board and sensor board containing accelerometers, gyroscopic sensors and thermocouples. The boards are powered by two sets of 24 AA cells. The boards and batteries are assembled to an aluminum and plastic chassis and installed into the aeroshell. The vehicle is enclosed in a two-piece copper housing which mounts to the host spacecraft via a skirt and adapter ring. The REBR outer mold line and assembly are detailed in Fig. 1.

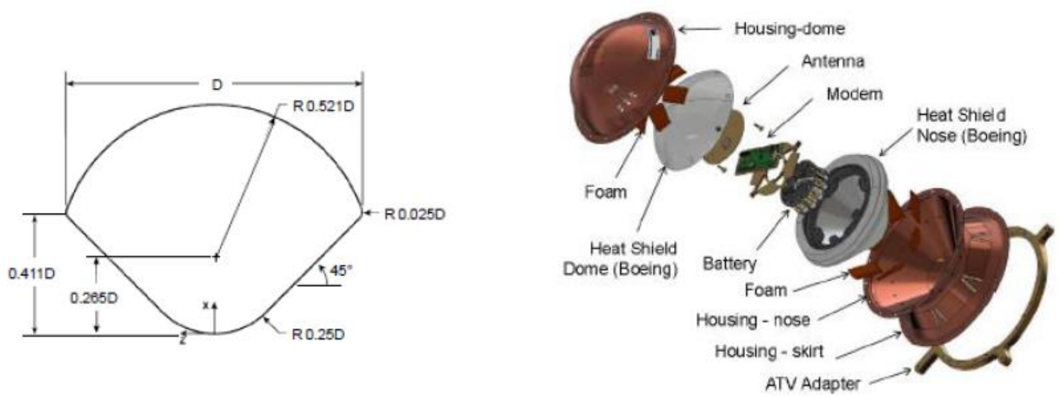

Figure 1. ReBR geometry (D=31cm) (left) and exploded view (right) from Ref. 1.

III. Objectives

Much of the REBR heritage is being retained for RED-Data2. RED-Data2 follows a similar concept of operations (attached to the host during launch and orbit, breakup and separation during reentry, and data transmission through Iridium network before ground impact). By increasing its utility and reducing cost, RED-Data2 is designed to provide this class of device to the commercial market. The overarching objectives for design of RED-Data2 are:

1) Reduce the size and mass of the reentry device
2) Maintain or improve upon total data return
3) Operate autonomously for the entire mission (from launch through reentry)
4) Record and return data for arbitrary entries from low Earth orbit

IV. Concept Study

A. Methodology

A concept study was initially undertaken to select the baseline RED-Data2 design. While appealing because of its REBR and Mars Microprobe heritage, the 45° sphere-cone was not an immediate choice for RED-Data2. Thus, several aeroshell geometries and methods of payload packaging were compared. The aeroshell geometries considered are outlined in Table 1. Four geometries were considered: a slender (12.5°) sphere-cone, a 45° sphere-cone, a sphere and a hemisphere. With regard to thermal protection system (TPS) sizing, two different bondline temperature limits were considered for each concept, 125°C and 250°C.

Recognizing the need to reduce the overall size of the vehicle, the design methodology followed an "inside-out" approach (Fig. 2). That is, the vehicle was designed around the

Table 1. Design study trade space.

Aeroshell Geometry	Bondline Temperature
12.5° Sphere-Cone	
45° Sphere-Cone	125°C
Sphere	250°C
Hemisphere	

payload (the electronics and instrument package) to maximize packing efficiency and create as small of a device as possible. The largest internal components (the Iridium modem and batteries) drive the overall size. Each concept design started with a layout and orientation for the payload components, then a basic aluminum structure was sized around it. Finally, the TPS thickness was sized to the target bondline temperature.

For each concept generated, several figures of merit were produced for comparison. These included (1) size metrics: estimated mass and maximum diameter, and (2) performance metrics: in-space lifetime, data transmit time, peak deceleration, peak heating and integrated heat load. The intent of the size metrics is obvious; however, the performance metrics warrant further explanation. Peak heating is the maximum aerothermodynamic heat rate encountered by the vehicle during entry and drives TPS material selection and size. Data transmit time is a surrogate for total data return. The data return of RED-Data2 is dependent on the time and bandwidth of the Iridium call placed during descent as well as sensor sampling rates and precision. With a given transmit time and known transmission rate, the total data return in bytes can be backed out and used to inform sampling.

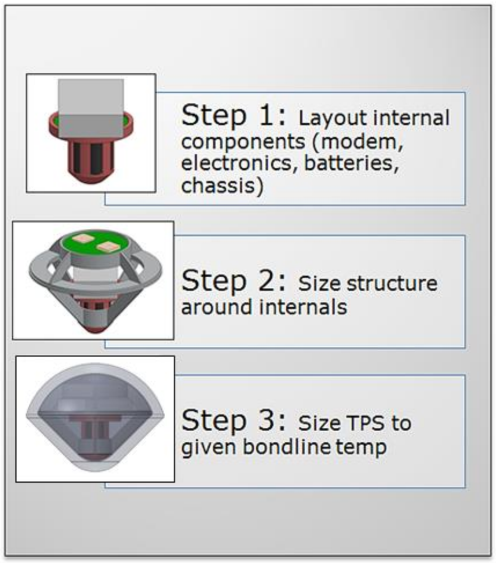

Figure 2. "Inside-out" design approach.

Transmit time and peak heating were computed from simulated trajectories. For the purposes of modeling, breakup of the host and release of RED-Data2 was assumed to be between 65km and 85km altitude, based on REBR analyses[1]. A zenith angle criteria, based also on REBR analyses, was adopted to quantify when the onboard Iridium antenna would have visibility to the Iridium network to to begin data transmission.

B. Results

The spherical and hemispherical concepts were quickly eliminated due to mass and performance concerns. Both geometries exhibited large mass in comparison to the other concepts which drove their ballistic coefficient higher and negatively impacted performance. The 45° sphere-cone and slender sphere-cone concept were deemed the most competitive. Concept study results are shown in Table 2 for both of these concepts. Data is for a breakup altitude of 75km. Note that TPS sizing is not available for REBR. Mass, maximum diameter and ballistic coefficient for REBR are actual values from the HTV-2 mission[1]; all other figures of merit were estimated in this study. It bears mentioning that the REBR flown on ATV-2 was slightly lighter at 3.95kg.

Table 2. Figures of merit, RED-Data2 concepts and ReBR.

	ReBR	45° Sphere-Cone	12.5° Sphere-Cone
Mass (kg)	4.44	1.92	1.82
TPS Sizing, fore/aft body (cm)	--	1.55/1.55	1.98/1.98
Bondline Temperature (°C)	(127 °C)	(250 °C)	(250 °C)
Max. Diameter (cm)	31.0	21.2	18.5
Hypersonic Ballistic Coefficient (kg/m^2)	55.4	51.2	174.6
Transmit Time (s)	359.8 (est.)	377.4	187.5
Peak Heating (W/cm^2)	203.3 (est.)	239.9	374.4

Due to ballistic coefficient considerations, the peak heating and transmit time of the 45° sphere-cone significantly outperforms the slender sphere-cone. The total transmit time is effectively doubled while peak heating is 56% less. Additional considerations also pointed to a 45° sphere-cone design – this aeroshell geometry has superior ability to re-orient from an initial tumble during hypersonic flight[4]. Also, the shape is an efficient one – it was estimated that mass and size growth would be limited if the payload grows in the future. Based largely on these considerations, the 45° sphere-cone was selected as the baseline design for RED-Data2.

V. Preliminary Design

A. Mission Profile

The concept of operations for RED-Data2 is outlined in Fig. 3. It is attached to a host spacecraft during launch and orbit. At the completion of the host's operations, a deorbit burn is performed to deorbit the spacecraft, or, in an uncontrolled entry, orbital decay due to atmospheric drag will cause reentry. When reentry is detected, RED-Data2 wakes up and initiates data recording and storage. Eventually, reentry loading and heating causes the host to break up, releasing RED-Data2. At that point, data recording is terminated and RED-Data2 begins to attempt communication with the Iridium network. When connection is established, the recorded data is transmitted through Iridium to a ground server. Data uplink must occur before impact as the vehicle is not designed for recovery.

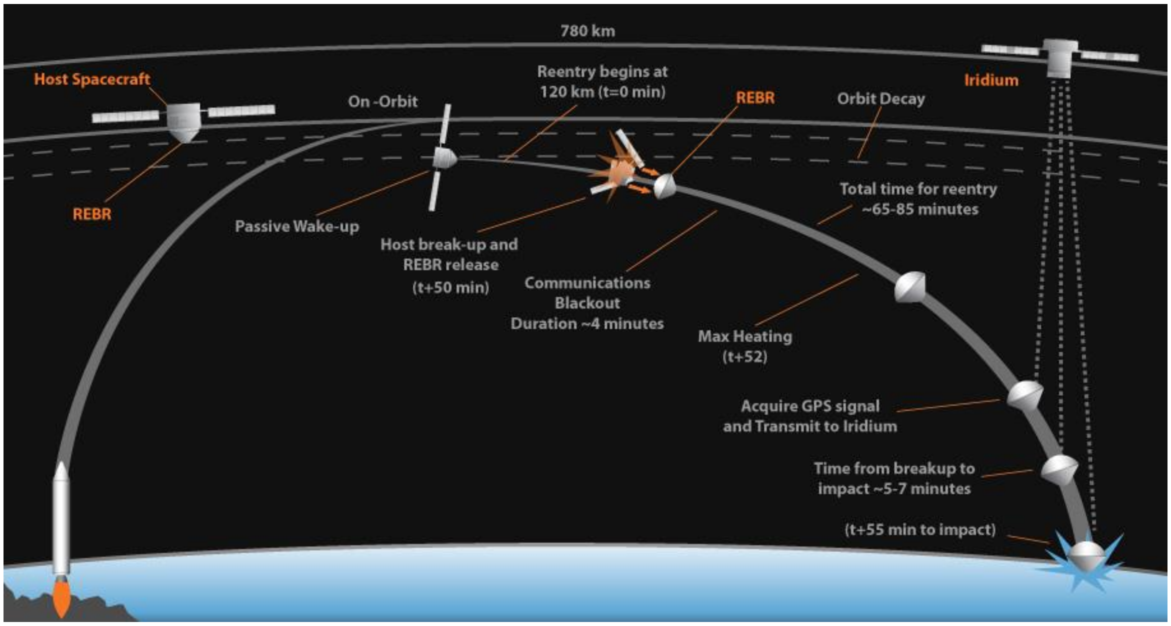

Figure 3. Concept of operations for RED-Data2 mission.

Based on expected reentry trajectories, RED-Data2 will encounter peak heating of 244 W/cm^2 and an integrated heat load of 15.8 kJ/cm^2 at the stagnation point. Peak deceleration of 7.8g is predicted. Figure 4 shows heating, heat load and deceleration for an orbital decay-type reference trajectory with break up occuring at 75km altitude.

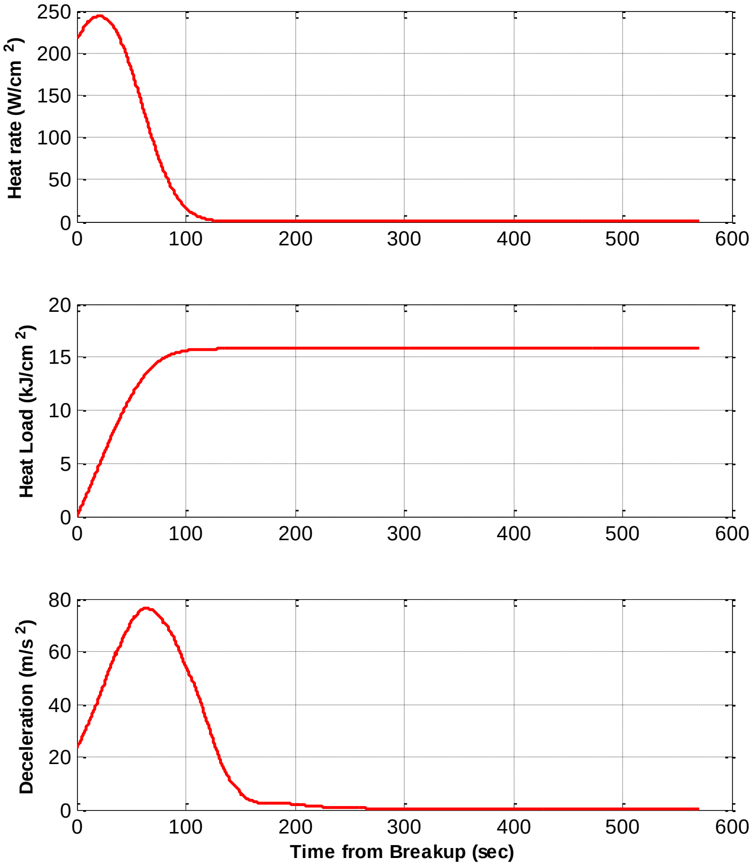

Figure 4. Heat rate, integrated heat load, and deceleration for breakup at 75km.

B. Design Overview

Design work has focused primarily on the electronics hardware and mechanical design. In addition to the objectives above, hardware modularity was deemed highly desirable so that the RED-Data2 electronics could be easily expanded to future vehicles in the RED family. As such, core functionalities that are common across RED vehicles are retained in one module and secondary, specialized functionalities are allocated to separate modules. In this way, a single flight computer can be mated with any number of secondary modules as mission need dictates. Refinement of the mechanical design and packaging realized further size and mass reductions from the baseline as well as reduced part and assembly complexity. Resulting improvements are outlined in Table 3.

Table 3. Comparison of RED-Data2 and ReBR designs.

	ReBR	RED-Data2	% Improvement
Mass (kg)	4.44	1.65	63%
Max. Diameter (cm)	31.0	20.0	35%
Hypersonic Ballistic Coefficient (kg/m^2)	55.4	49.4	11%
Transmit Time (s)	359.8	385.4	7%

C. Vehicle Design

The vehicle assembly consists of a foreshell and backshell and a small payload subassembly mounted to a Delrin chassis (Fig. 5). The modular printed circuit boards (PCBs) are stacked directly on top of each other to conserve space and screw in to the chassis. The modem is mounted just above these boards at a small standoff distance. The modem is removed from its case (included off-the-shelf) to save additional volume. Two Delrin cases also mount to the chassis. The top case covers the PCBs and modem and provides mounting for the GPS and Iridium antennas and ground planes. A custom 6-cell AA battery pack is contained in the bottom case. Using a battery pack also leverages some measure of modularity – this design allows all electrical connections to be made internally with a single wire harness to connect to the electronics. Future designs can simply expand the number of battery packs with minimal added design effort.

The payload bolts to a structural ring attached to the inside of the foreshell. Finally, the backshell is mounted at six bolt locations to tabs on the ring to complete the assembly. Small TPS plugs (small circles on exterior of backshell) cover the screws. A carbon-based ablative TPS will comprise the foreshell and a RF-transparent, silica-based ablative TPS will form the backshell (to allow GPS and Iridium communication). Each TPS segment will be adhered to the rigid composite aeroshell structure. Following the REBR specification, the structure is being designed to withstand a 100-g load in the axial direction. This is well above the nominal loads, allowing margin for an unknown breakup environment.

To maximize simplicity and ease of manufacturing, part counts were kept to a minimum and off-the-shelf parts used where possible. Materials and parts with prior REBR heritage were also used in several cases to minimize risk. For example, Energizer L91 AA cells and Delrin (for chassis parts) are the same as in the REBR design.

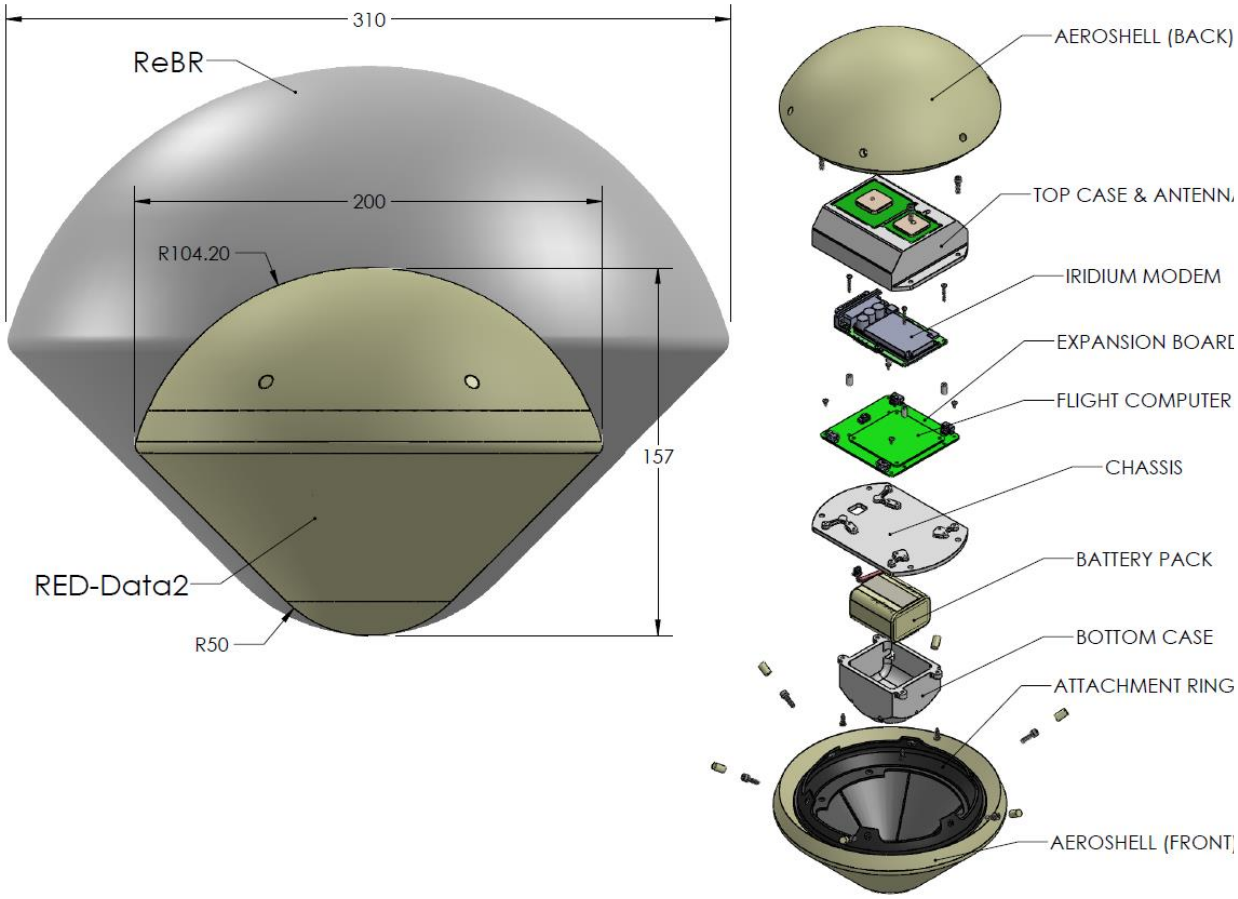

Figure 5. RED-Data2 Vehicle Design with size comparison to ReBR (Dimensions: mm).

D. Electronics

Enhancements to the electronics have enabled significant size reduction and improved hardware capability. RED-Data2 utilizes a low-power electronic g-switch for reentry detection. An off-the-shelf accelerometer originally designed for mobile phones affords low-power operation (0.5 mW) of this circuit, enabling a fourfold reduction in the number of batteries (6 AA cells vs. 24 AA cells on REBR) while increasing on-orbit lifetime to a year or more. The g-switch is being designed for completely autonomous operation, rather than requiring manual activation in space. Second, a new, smaller Iridium modem was identified to further reduce size.

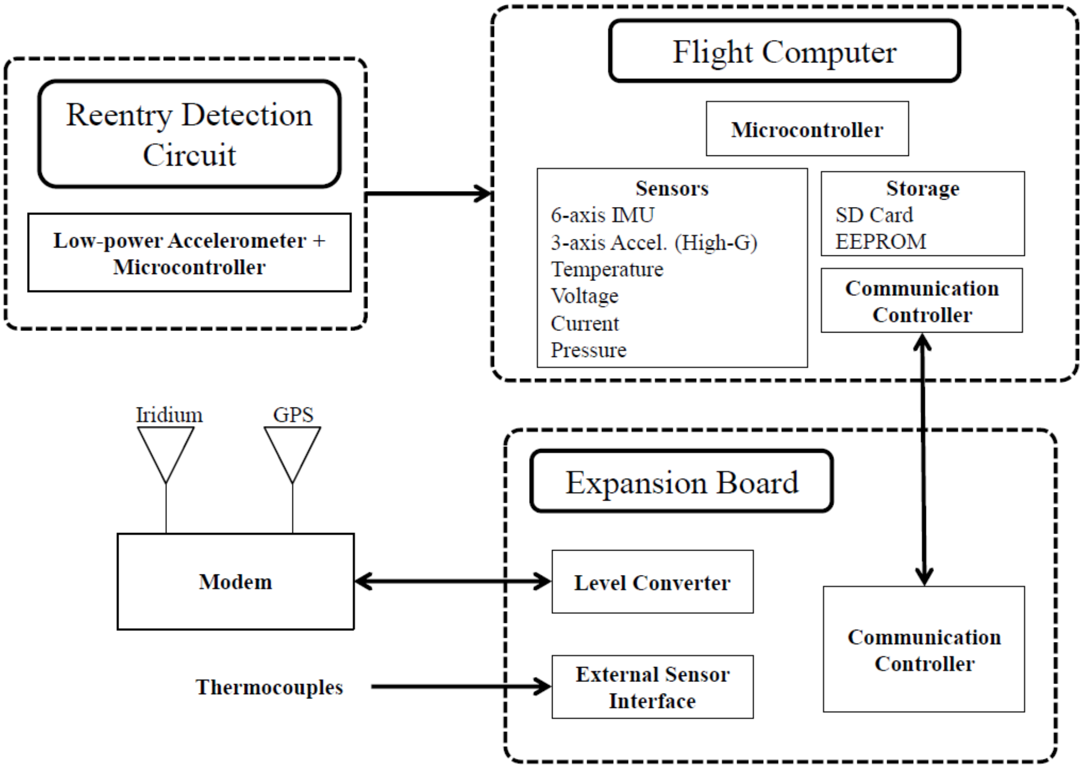

Figure 6. RED-Data2 Electronics Block Diagram.

The electronics package consists of the reentry detection circuit, a flight computer and an expansion board. A block diagram of the hardware is shown in Fig. 6. The accelerometer and microcontroller pair of the reentry detection circuit operate in tandem continuously throughout the mission. When reentry loading begins, this circuit activates the rest of the hardware, which then begins recording and storing data from its suite of sensors. After breakup from its host, RED-Data2 establishes a connection with the Iridium network through its modem to transmit collected data to a ground server.

The modularity of the design is apparent in Fig. 6. The flight computer maintains several onboard sensors and storage. However, it interfaces to other external devices and more specialized sensors (in this case, thermocouples for instrumenting a TPS) through an expansion board. This affords the flexibility to accommodate other sensors and devices as desired while maintaining a common base. A prototype flight computer and expansion board has been designed, fabricated and assembled (Fig. 7). This board is currently undergoing testing and programming.

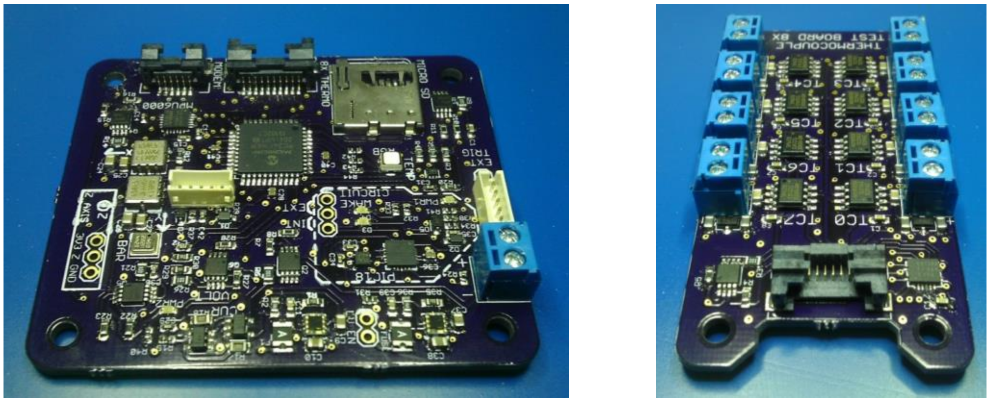

Figure 7. Prototype flight computer (left) and expansion board (right)

VI. Conclusion and Future Development

To reduce uncertainty and improve our ability to predict surviving debris, impact time and impact location, reentry breakup dynamics and aerothermodynamics data is needed. REBR demonstrated the promise of a device that can provide such information. The challenge now is to bring this technology to a broader commercial market by making it smaller, lighter and more usable across a range of missions and host vehicles. The design work presented here is the start of this effort.

Building on the REBR foundation, RED-Data2 offers several benefits. RED-Data2 is closer to the size of a softball as opposed to a basketball. It is also more than 50% lighter, autonomously initiated, and capable of passive in-space operations for years as opposed to months. In addition, the flexibility of the RED-Data2 design, manifested in the structural design and modular electronics approach, allows for expansion of functionality for future RED products. Where appropriate, connections with REBR heritage are maintained in the choice of several components and materials to limit risk.

Future work aims to produce the first RED-Data2 flight unit. The electronics are under active development with the goal to further reduce power usage. Software efforts are focused on autonomous activation of RED upon reentry as well as an intelligently adjusted sensor sampling rate according to user-specified priority (e.g. high frequency sampling during breakup). Work on the structure and aeroshell (TPS, especially) is also in progress.

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