Development of Advanced Ballooncraft Support Systems

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***Abstract* - The NASA Balloon Program is pursuing the development of an Ultra-Long Duration Balloon (ULDB) vehicle and its associated support systems. These new technologies will provide an extraordinary new capability for balloon-borne science investigations. The Ballooncraft Support Systems were developed by NASA Wallops Flight Facility for use on ULDB class missions. These systems are capable of providing command and control of balloon-borne payloads, providing up to 1KW of power, and delivering 100Kbps data flow through the TDRSS. The support systems have flown two missions in Antarctica supporting the Cosmic Ray Energetics and Mass (CREAM) experiment. CREAM I launched in December 2004 and flew for a record breaking 41 days, 21 hours. In December 2005, CREAM II flew for 28 days, 9 hours. These support systems provide CREAM with power, telecommunications, command and data handling, mechanical structures, thermal management and attitude control to help ensure a successful scientific mission. This paper will address the performance and success of these support systems over these two missions and their contribution to future scientific research.**

I. INTRODUCTION

The NASA Balloon Program provides high-altitude, heavy-payload science research capability to the user community on a global effort. Typical mission profiles vary from approximately 6-36 hours for 'Conventional' flights and can range from 4-42 days for 'Long Duration Balloon (LDB)' flights. There are up to five campaigns conducted each year resulting in 15-20 balloon flights. Three campaigns are carried out in the continental United States (CONUS) to support Conventional balloon missions, two in Fort Sumner, New Mexico during the spring and fall, and one in Palestine, Texas during the summer. Two foreign campaigns are implemented in support of LDB missions, one in Antarctica during the southern hemisphere summer and one with a flight trajectory originating in northern Sweden and ending in northern Canada/Alaska, also during the summer. This myriad of flight locations provides a robust capability for research and experimentation.

Fig.1, There are a variety of standard 'off-the-shelf' zero-pressure balloon sizes available to science customers. A zero-pressure balloon design has no differential pressure between the gas volume inside the structure and the external atmosphere at float altitude. These balloons are manufactured specifically for NASA pursuant to established design criteria. The balloon volumes range from four million cubic feet (MCF) to 60 MCF. The balloon volume selected for flight correlates to both the size of the payload and the desired float altitude. Balloon float altitudes are typically between 120,000-130,000 feet, but can vary depending upon science flight requirements and observed flight conditions.

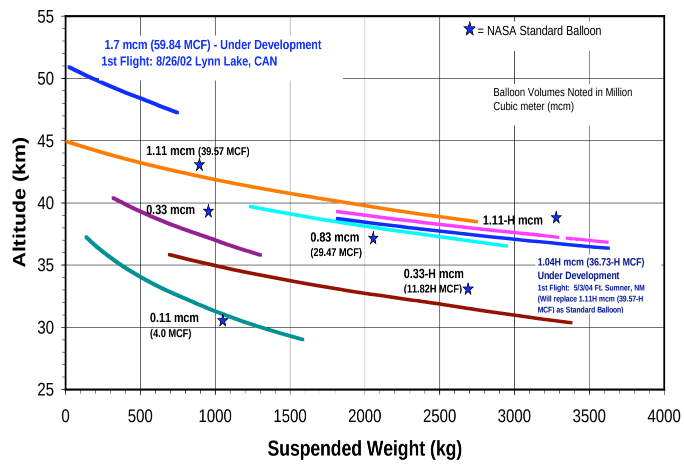

Fig. 1. Load Altitude Curve

A. *Science Payloads and Types*

Payloads flown on the balloon platform are as varied as the indigenous life on Earth. Space and Earth science customers comprise the majority of the annual flight manifest with special projects, such as exploration research and development, and balloon test flights assuming the balance. The science disciplines currently served are: IR/Sub-mm Astrophysics, Particle Astrophysics, Gamma Ray/X-Ray Astrophysics, Geospace Sciences, Solar and Heliospheric Physics, and Upper Atmosphere Research. The scientific knowledge that is derived from the research performed on balloon missions has been paramount to understanding both our Earth and the Universe. For example, balloon-borne payloads are used to correlate and validate data from Earth observing satellites and ground stations, measure cosmic microwave background radiation, and aide our understanding of star and galaxy formation.

Instrument weights can range from 500-8,000 pounds with the majority falling between 4,000-6,000 pounds. Fig. 2, The instrument footprints are as similarly varied as the weights. Gondola shapes range from horizontal cylinders to vertical 'egg shapes' to cubes with wings and many more variations. The sizes also comprise the gamut, as the gondolas can occupy as little space as a coffee table and as large a space as a 30' boat. The standard flight qualification process a scientific payload undergoes involves a developmental and engineering test flight, generally performed in the CONUS prior to proceeding to an LDB mission. This approach raises the probability of mission success by validating the payload is compatible with the balloon flight vehicle systems as well as confirming the payload's viability in the near-space environment.

Fig. 2. CREAM Ballooncraft in Antarctica

B. Environmental Conditions

In addition to altitude and duration, mentioned previously, there are two additional environmental conditions that balloon vehicles and payloads experience. The first is wind. The upper-level stratospheric winds dictate the overall flight trajectory of the balloon. Launch times and locations are directly attributable to the seasonal upper-level wind patterns, observed both locally and globally. When launching Conventional balloon flights, it is standard to operate campaigns that correlate to 'turnaround,' the period between the predominant easterly or westerly flow when the wind direction is varied around a geographical location. This is a seasonal occurrence in which the stratospheric winds literally change directions (i.e. from easterly to westerly and vice versa). In the United States, this occurs over New Mexico during the spring and fall. Flying during this time is done to increase flight time in a restricted geographical flight space. On the contrary, planning for LDB mission campaigns involves correlating to when the winds will be directionally headed in a stable direction. The goal here is to get the balloon to its terminate region, which is not typically in the same geographical location (i.e. launch in Sweden, terminate in Canada) or to fly circumglobally (i.e. Antarctica). Wind speeds vary significantly, as they are a product of global weather conditions and vary depending upon region and season. Float speeds can be as slow as a few knots to as much as 40 knots. Typically, however, float speed averages 15-25 knots.

Fig. 3, The second condition is the thermal environment. The thermal extremes observed during flight are significant. The coldest a balloon will get is in the Troposphere during ascent where temperatures typically can approach -70 degrees C or greater. At float altitude, balloons will experience temperatures ranging from -40 to -20 degrees C. These temperatures will fluctuate depending upon the time of year and current weather conditions. The payload structure temperature will also depend upon sun angle, geographical features, and its own inherent thermal profile.

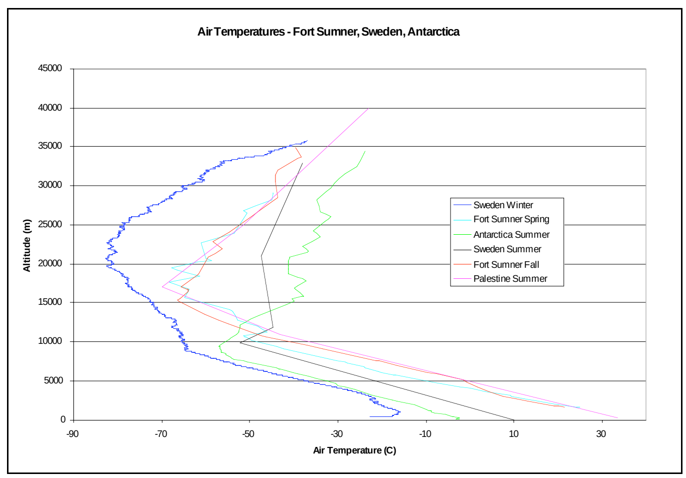

Fig. 3. Atmosphere Temperature Profile for the Launch Sites [2]

C. Command Data Module (CDM) History

The Ultra Long Duration Balloon (ULDB) concept plan was established in 1997. The concept included the design of a new super-pressure balloon capable of a 100 day mission. The super-pressure design is intended to maintain a differential pressure between the gas volume internal to the balloon and the external atmosphere resulting in a more stable float altitude. In addition, the concept plan was to also develop a support system which would support an instrument as part of an integrated system called a ballooncraft. The ballooncraft was considered all hardware below the attachment point to the mobile launch vehicle. This hardware, with the exception of the attitude control system, would be an integrated assembly of the instrument and support systems mounted on a primary support structure. The support system would be designed to support a 100 day mission providing global coverage of telemetry down-links and command uplinks, power, and command and data handling (C&DH) for the science instrument while monitoring and controlling the health and safety of the balloon vehicle and the ballooncraft. Fig. 4, The core of the support system became known as the Command Data Module (CDM). This 20"x20"x40" enclosure contained the flight computers, C&DH, power system, electrical switching systems, and telecommunication subsystems supporting both line-of-sight (LOS) and global over-the-horizon (OTH) capabilities. These subsystems were either designed in-house or were purchased as commercial-off-the-shelf (COTS) products. All subsystems were qualified to perform in the flight environment and in cases where the subsystem was considered critical, redundancy of those subsystems was incorporated.

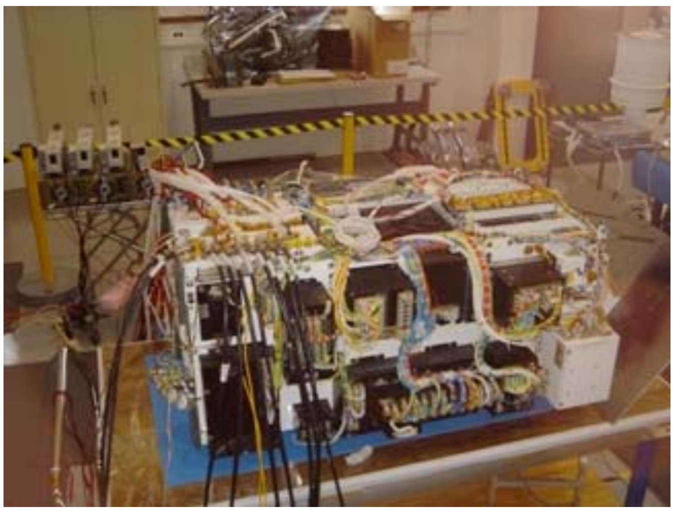

Fig. 4. Command Data Module

In 1998, the Cosmic Rays Energetic and Mass (CREAM) experiment was selected to be the first science instrument to be flown on an ULDB mission. NASA Wallops Flight Facility (WFF), Wallops Island, Virginia, and supporting contractors, provided engineering services which included power, telecommunications, command and data handling, mechanical structures, thermal management, and attitude control to enable the scientific investigations of the CREAM experiment. A spin-off of these decisions and designs was that a control center needed to be developed to support this mission. So, in addition to the flight CDM, WFF personnel designed and built multiple control centers in support of this mission.

- The Remote Operations Control Center (ROCC) will be set-up in the field to support the launch and early flight operations through line-of-sight.
- The Operations Control Center (OCC) located at CSBF in Palestine, TX. The OCC is responsible for the flight of the balloon vehicle and will monitor critical flight parameters to determine health and safety of the balloon vehicle. Termination of the balloon vehicle will be conducted from this control center or from the Columbia Scientific Balloon Facility (CSBF) ROCC or aircraft in Antarctica.
- The Engineering Support Center (ESC) located at WFF. The ESC will be used to display and provide playback of engineering data for subsystem flight status and diagnoses. This center will monitor the CDM and will execute CDM and science commands through the TDRSS link.

As the development of the ULDB, CDM and science instrument progressed independently from each other, it became apparent that the ULDB would not be ready in time to support the CREAM instrument. A decision was made to fly the CREAM instrument and the CDM on a Long Duration Balloon (LDB) mission. This reduced the original requirements to those required to meet the duration of a LDB Mission, from 100 days to 30 days.

The first flight of the 6000 lb. ballooncraft was launched from William's Field, Antarctica on December 15, 2004. Fig. 5, It was terminated on January 26, 2005 at the beginning of the fourth circumnavigation of Antarctica for a record breaking 41 days, 21 hours, and 36 minutes. Fig. 6, The second flight using the same CDM was launched on December 15, 2005 and at the conclusion of two circumnavigations was terminated with a flight time of 28 days, 9 hours, and 52 minutes. In both cases, the decision to terminate was based on the desire to recover the payload and not based on any reduction in the performance of either the CDM or the science instrument.

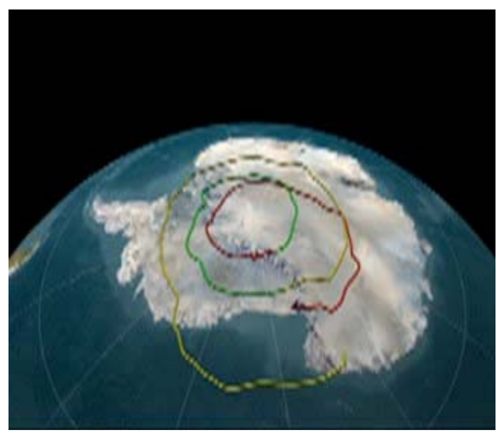

Fig. 5. CREAM I Trajectory, December 2004

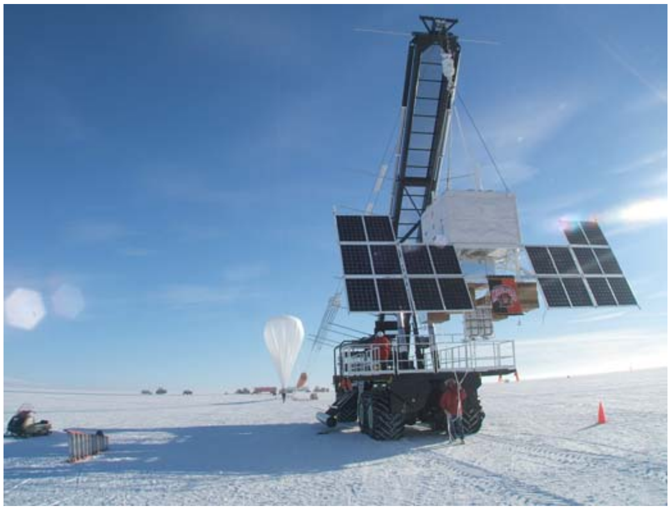

Fig. 6. CREAM II Launch, December 2005

II. DESCRIPTION OF THE COMMAND DATA MODULE

A. *Power Subsystem Description*

The power subsystem provides direct current (DC) power to both the CDM and the experiment. A design-to requirement of 800 watts (with contingency) is subdivided into 28V-dc $\pm$ 4V unregulated to the CDM and instrument and 5 and 12 volt regulated power to the CDM. The design is based on using photo-voltaic solar cells for power generation, Lithium-ion rechargeable batteries for power storage, and the use of voltage regulators and charge controllers to manage the power system. A series of power switching devices are designed to distribute and control power to both the CDM and instrument's subsystems. These devices are instrumented to down-link switch status, current, voltage, and temperature for health and status. The excess power is shunted by a set of three custom designed shunt regulators which diverts excess power to a set of externally mounted shunt resistors and dissipated as excess heat.

Ref. [1] The array design is based on using ten solar panels providing enough margins so that the loss of multiple panels due to anomalies would still result in sufficient power. Each panel is constructed of a string of commercially available solar cells with an estimated power output of over 100 watts per panel. These ten panels are arranged in five sets of pairs such that each of the five pairs of panels could be switched in or out of the power subsystem as needed. The batteries design use four battery packs, with each pack consisting of nine high-capacity lithium-ion battery cells. The battery packs are designed to provide approximately 44 amp-hours of power at 31 volts DC.

B. *Command and Data Handling Subsystem Description*

The Command and Data Handling (C&DH) subsystem acquires data from all the other subsystems through a variety of data interfaces, process the data, store the data on-board for recovery and/or in-flight data playback, format the data for transmission though the various down-links, and forward the formatted data to the down-link transmission systems. In addition, the subsystem is required to receive commands from the uplink command receivers, decode and error-check the commands, and either execute the commands or forward them to the desired destination.

The design is based on the use of a commercially available, Pentium computer with a PC-104 expansion buss capability, a backup command decoder (BUCD), and a set of data acquisition and command execution stacks. The CDM flight computers use a real-time operating system; VxWorks and a subsystem-level modular flight code designed in C++. The communication interface between the CDM and the instrument uses a standard Ethernet connection using the Universal Datagram Protocol (UDP). During the first mission, over 5700 commands were sent of which ~90% were for the experiment. Over 40 GBytes of data was transmitted, received and stored. During the second CREAM mission the CDM flight computers acquired, stored, formatted, and forward for down-linking over 64 million packets of near real-time or playback science data, and processed 4115 commands.

C. *Telecommunications Subsystem Description*

The telecommunications subsystem provides an independent LOS and OTH means of down-linking system, flight control, and science data. In addition, there are also multiple uplink command paths. The conventional LOS transmitters and receivers are for communications during pre-flight checkouts, launch and during the first ~ 350 nautical miles at which time the communication path is switched to OTH using satellite relay systems.

The secondary OTH subsystem uses a commercial Iridium transceiver connected to an OMNI antenna. At 2400 baud, a complete set of housekeeping data and the last science data packet before transmission data is down-linked every 15 minutes. Uplinked commands are available on demand. This subsystem has the capability to establish a continuous connection and streams data at the Iridium's maximum bit rate.

The prime OTH subsystem interfaces with the Tracking Data Relay Satellite System (TDRSS). Fig. 7 & 8, This system is composed of the following components: a TDRSS transponder, an attitude GPS system, an attitude control unit (ACU), a directional high-gain antenna (HGA), a polar omni-directional antenna and a custom PC-104 card; a TDRSS Data Interface (TDI) card which buffers the data from the flight computer and clocks the data out to the TDRSS transponder for down-link. The system supports 125 bps uplinks, 6kbps data down-link through the polar omni-directional antenna and 100kbps near-continuous data down-link through the HGA.

Ref. [1] The TDRSS transponder is used to transmit/receive science and other data between the ballooncraft and the ground through the TDRSS network. The transponder gathers data from the on-board flight computers for transmission to operators on the ground. Conversely, it also receives commands from the ground for distribution/disposition by the flight computer on the ballooncraft.

Fig. 7. High Gain Antenna

The attitude determining GPS system establishes the physical position and attitude of the ballooncraft and feeds this data into the flight computers. This data is used to determine the proper directional pointing of the TDRSS HGA. The CREAM system uses redundant GPS receivers, each with 4-antenna array combinations.

The HGA and ACU consist of a directional S-Band antenna used to send science and operations data from the ballooncraft to the ground during normal balloon flight for over-the-horizon operations. It exhibits an antenna beam width of 18° (at 3 dB down) and is kept pointed in the direction of a TDRSS satellite to maximize data flow. Data rates supported during both missions through the HGA was 100 kbps. The ACU receives GPS position and attitude data and uses stored TDRSS satellite location data to determine movement of and pointing direction for the HGA to maximize signal transmission/reception. The HGA and ACU were developed in-house at WFF.

During the second mission, the HGA and ACU autonomously made over 47,000 pointing adjustments to keep the HGA oriented toward the correct TDRSS satellite. Contact with the selected satellite was maintained during all periods of visibility with zero dropouts. Also successfully executed were 58 satellite swaps, where the HGA moves from pointing at one TDRSS satellite to another.

III. SUMMARY AND CONCLUSION

A. *Advantages of These Systems*

The advantages of theses systems as they pertain to balloon operations are prominent. The acquisition of near real-time data enables flight controllers and scientists to perform health and well-being monitoring around the clock as opposed to only receiving feedback during scheduled ground station passes. This operational scenario enables scientists to perform adjustments to their experiments in a more frequent and timely manner as to maximize science return. This near real-time data also facilitates the flight controllers' capability to maintain a robust system by which to support the science instrument as well as providing a more wholesome approach to flight safety. One prominent feature of receiving real-time data is that of 'Playback.' Playback, as it is appropriately named, is the act of transmitting data previously collected and stored onboard the vehicle data vault that was not able to be transmitted during real-time. This compensates for any ground network outages, satellite network outages (such as zones of exclusion), onboard transmission anomalies, and so forth. Additionally, all 'high-rate' data collected can be down-linked during the flight, thus allowing the scientist to observe the true quality of the data and make any appropriate adjustments to the instrument during flight.

The system is also scalable. Having scalability added to the capability allows the system to be easily sized for the science payload power and data requirements. This increased flexibility lowers the burden of maintaining multiple payload systems for different payload configurations and ultimately results in a more robust across-the-board solution.

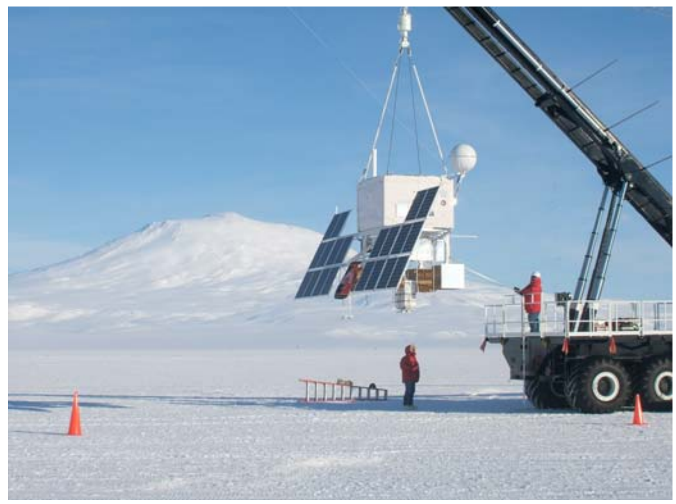

Fig. 8. CREAM Ballooncraft – HGA in Radome

B. *Impact to Program/Project/Flight Operations*

The development of the CDM has had a positive and evolving impact on the Balloon Program, Projects, and Flight Operations. With the near real-time data collection and playback capabilities, data vault recovery from remote locations is not required when all the science is received during the flight. For remote locations, such as Antarctica, this would allow for potentially longer flight durations and promote next-season recovery options in an environment where resources are limited and often scarce for this type of effort.

The implementation of this technology directly supports exploration and research in the form of providing a validation platform for spacecraft systems with both satellite and human space-flight applications. Flying in near-space, above 99% of the Earth's atmosphere, the balloon-borne platform provides access to the space environment for a large community of users at a low cost alternative to satellite and rocket missions.

Recovering, refurbishing and reflying balloon-borne science instruments and support systems is a proven process that places balloon science in a class of its own. Additionally, the demonstrated quick-turnaround and implementation feasibility of the CDM to support a flight mission give this platform a decisive schedule advantage over traditional space-based missions. With these developing CDM technologies being integrated to the balloon support platform, this capability holds a prominent stake in the future of Agency and academia research.

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