29th International Cosmic Ray Conference Pune (2005) **10**, 173-184

Evolution of Scientific Research Ballooning

W. V. Jones
NASA Headquarters, Science Mission Directorate, Washington DC 20546, USA
Presenter: W. Vernon Jones (W.Vernon Jones@nasa.gov)

Balloons have been used for scientific research since they were invented in France approximately 220 years ago. The last major change in balloon design occurred in 1950 with the introduction of the so-called natural shape balloon with integral load tapes. The National Aeronautics and Space Administration (NASA) is currently pursuing development of a super-pressure balloon that would enable extended duration missions above 99.5% of the Earth's atmosphere at any latitude. The ultra-long-duration balloon (ULDB) flights enabled by this constant-volume balloon should result in an even greater sea change in scientific ballooning than the inauguration of long-duration balloon (LDB) flights in Antarctica during the 1990 – 91 austral summer. The ULDB technology advancements include utilization of a new structural design, a co-extruded film for the balloon envelope, and structural integrity provided by the highest strength-to-weight fibers commercially available. The ULDB vehicle development is complemented by a new ballooncraft support system that provides power, data handling and communications via a Tracking and Data Relay Satellite System (TDRSS) high gain antenna capable of 100 Kb/s real-time telemetry. Another technology key to realizing the full ULDB potential is an active balloon trajectory control system, which is now only in the design stage.

1. Historical Background

Balloons have been used for scientific research since the Montgolfier brothers invented and experimented with balloons more than 200 years ago in France [1]. See Figure 1. In the early days, balloons were usually coated fabric filled with hydrogen gas. Scientists used them to carry instruments aloft to make in-situ measurements of atmospheric pressure and temperature, among other things. Some of these intrepid scientists suffocated or died of exposure in the bitterly cold upper atmosphere. Victor Hess discovered cosmic rays in a 1912 experiment to understand radiation changes with altitude. See Figure 2. He subsequently, in 1936, received a noble prize for that discovery.

Stratospheric flights using large rubberized balloons capable of reaching about 20 km were introduced in the early 1930's. Aeronauts in sealed, air tight capsules were able to survive to 60,000 feet (~18 km). An altitude record of 72,395 feet set in 1935 stood for 12 years, indicating a limit for rubberized balloons. In 1950 Otto Winzen patented the modern-day, natural-shape balloon. These polyethylene balloons with integral load tapes could carry heavy payloads to around 100,000 ft (~30 km), and they played a significant role in paving the way for the manned space flight program. Figure 3 illustrates the evolution in balloon designs over this span of almost two centuries, starting with the Montgolfier invention.

2. Ballooning Since the Middle of the 20th Century

The zero-pressure (vented to the atmosphere) balloons used today have changed only incrementally from those introduced in the 1950's. Since that time, large polyethylene balloons have been employed for a large variety of scientific pursuits and technological developments. Figure 4 illustrates some vital statistics for a large balloon routinely flown today. The suspended load capabilities of the current suite of balloons used by the U.S. National Aeronautics and Space Administration (NASA) are shown in Figure 5 [2].

Figure 1. Montgolfier invented balloon in 1783.

Figure 2. Victor Hess 1912 balloon

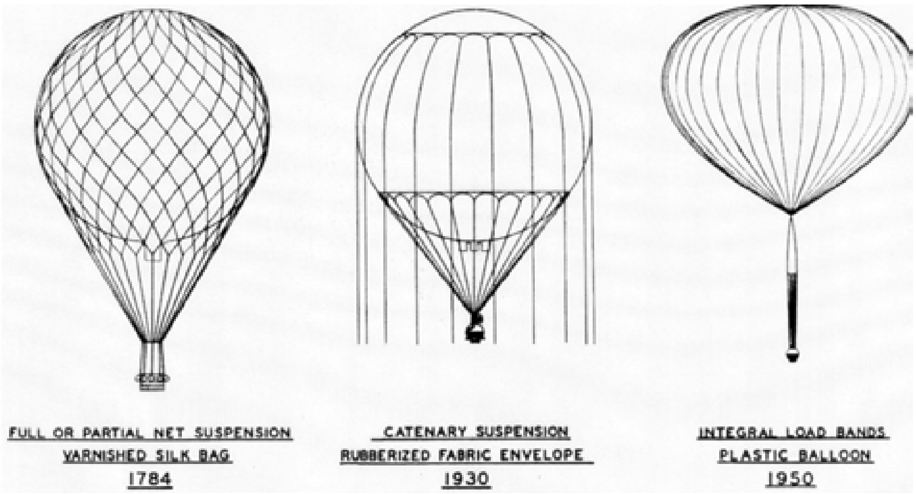


Figure 3. Evolution of balloon designs over almost two centuries.

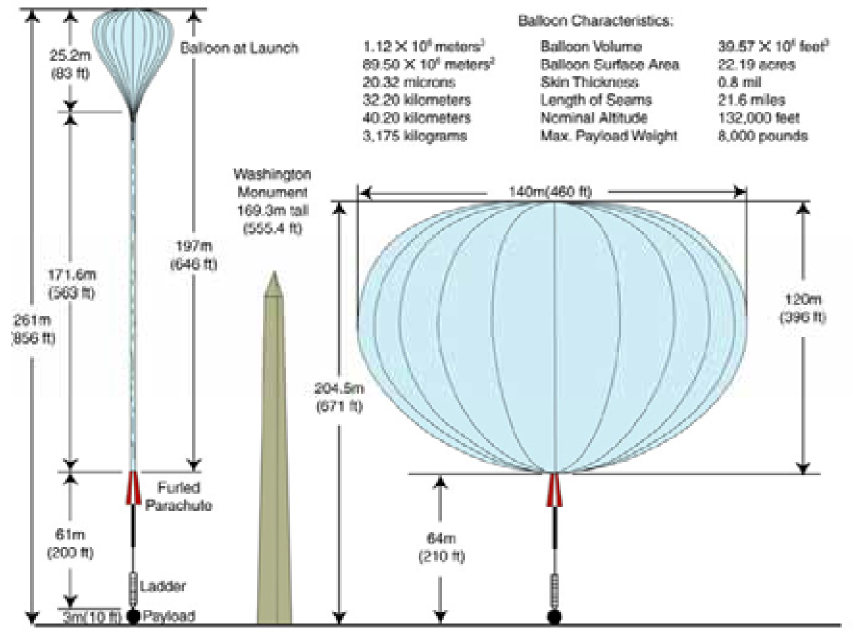


Figure 4. Illustration of the size of a large zero-pressure polyethylene balloon.

These high-altitude research balloons offer a unique capability for frequent access to near-space for science instruments ranging in mass from a few kilograms to more than 1000 kg. Balloon payloads for science, applications, and new technology development have been flown for periods of 1 - 2 days since the 1950's. In the 1990's NASA extended the flight times to 10 - 20 days by conducted launches in Antarctica during the austral summer. These so-called Long-Duration Balloons (LDB) float in the nearly circumpolar stratospheric wind vortex during the Antartic and Arctic summers. The LDB flights employ zero-pressure polyethylene balloons identical to those utilized for conventional 1 - 2 day flights, which are limited to a few days because ballasting is required to minimize their altitude excursions during day-night transitions.

The order of magnitude improvement in flight duration in the polar region is possible because of the constant daylight available during local summer. The nearly constant solar heating ensures nearly constant altitudes with minimal or no ballasting. The balloon Support Instrumentation Package (SIP) used for LDB flights is more sophisticated than the Consolidated Instrumentation Package (CIP) used for conventional flights intended to last, at most, a few days. In particular, the SIP includes Global Positioning Satellite (GPS) tracking, satellite (INMARSAT, ARGOS, and TDRSS) communications, and a photovoltaic array for its power needs. The users provide separate photovoltaic arrays to meet the power requirements of their science instruments.

Most LDB missions have been conducted from Antarctica during the Austral summer. These Antarctic LDB flights have been called "the jewel in the crown of the NASA balloon program." They typically carry suspended payloads of 2300 - 2800 kg, with scientific instruments of 900 - 1400 kg, to altitudes of 37 - 41 km for, typically, 10 – 20 days in one circumnavigation of the continent. In 2002, a record was set when a 0.83 MCM balloon carrying the Trans Iron Galactic Element Recorder (TIGER) payload flew for a duration

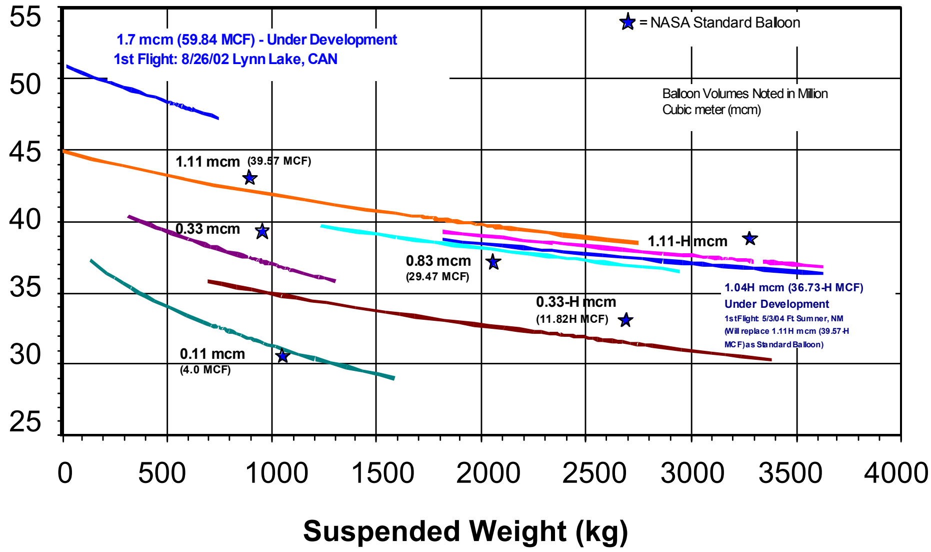


Figure 5. Suspended weight capability of the NASA's zero-pressure balloons.

exceeding 31 days [3]. In 2005 a new LDB flight record was set when a 1.11 MCM balloon carrying the Cosmic Ray Energetic and Mass (CREAM) experiment flew for nearly 42 days [4]. Figure 6 shows the trajectory of this record breaking flight. Its altitude and latitude profile are shown as a function of time from launch in Figure 7.

As indicated above, polar LDB missions are not limited to the southern hemisphere. In 1997 NASA launched a LDB flight from Fairbanks, Alaska that flew westward over Russia and was terminated 13 days later in Canada. This accomplishment was repeated in 1998. Recently, NASA and the Swedish Space Corporation/Esrange inaugurated a joint capability for medium-duration heavy-load scientific balloon flights from Sweden to Canada or Alaska. In June 2005, a 1.11 MCM balloon was launched from Kiruna, Sweden carrying the 2700 kg Balloon-borne Large-Aperture Sub-millimeter Telescope (BLAST) payload [5]. The westerly flight, which lasted for 4.2 days, was terminated over Northern Canada, approximately 315 km northwest of Cambridge Bay on Victoria Island. The average float altitude was 39 km.

3. Ultra Long Duration Balloons

Current scientific ballooning capabilities are generally limited to large and mid-size payload capacity zero-pressure balloons. These balloons are capable of maintaining their float altitude in the polar regions for extended durations, but they can maintain float altitude for only a few days at mid-latitudes. Spherical super-pressure balloons, on the other hand, have been successfully flown for over six months at an average altitude of 16 km (100 millibars) with small payloads [6]. In response to the growing needs of the scientific community, the NASA Balloon Program Office is pursuing the development of a super-pressure balloon capable of maintaining high-altitude, long duration flights worldwide with a load carrying capacity comparable to current zero-pressure balloons.

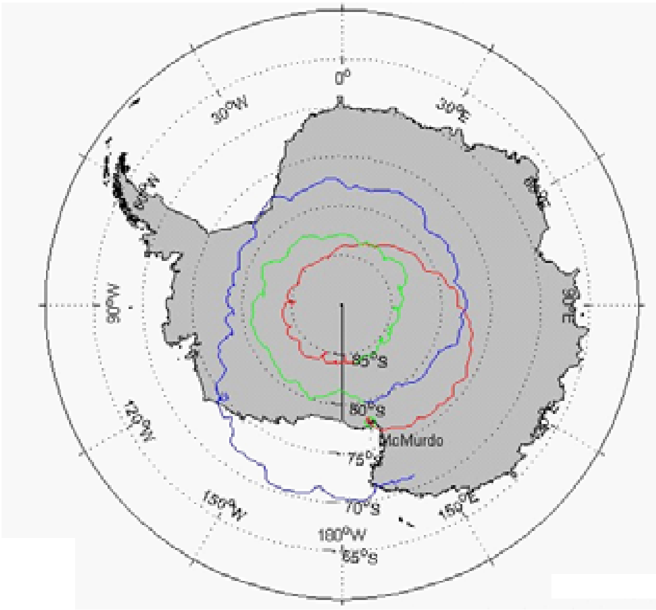


Figure 6. CREAM balloon trajectory. Red, green and blue lines represent 1st, 2nd and 3rd circumnavigations, respectively.

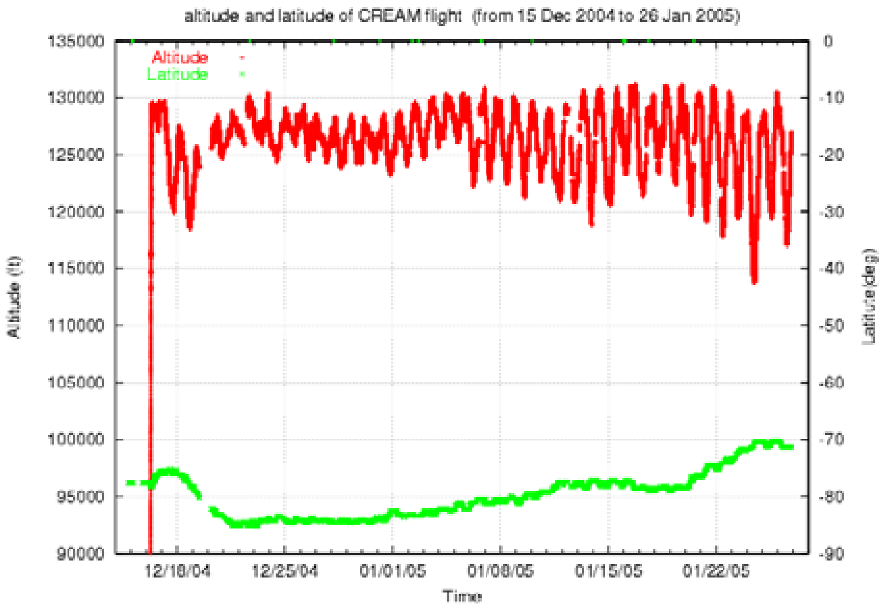
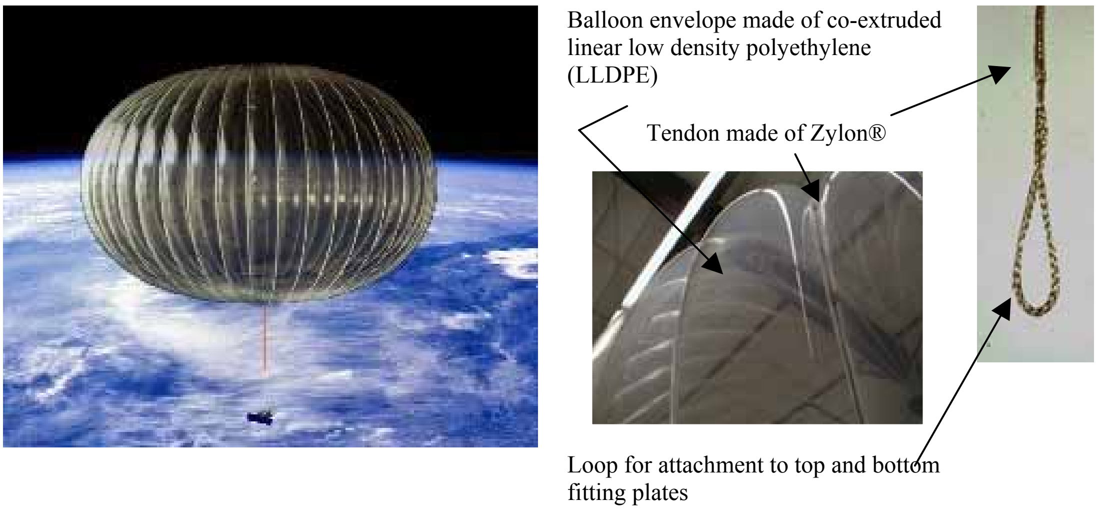


Figure 7. Altitude and latitude profile of the CREAM flight.

The proposed flight duration for these new balloon platforms is 100 days, or more, hence the label Ultra Long Duration Balloon (ULDB). The enabling technologies are improved lightweight membrane materials, high strength, high stiffness, light weight tendons, and the pumpkin shape introduced theoretically in the 1970's [7]. The pumpkin shape balloon concept (Figure 8a) allows clear separation of the load-transferring functions of the major structural elements of the pneumatic envelope, the tendons and the film (Figure 8b). In this lobed structural design, the film essentially provides the gas barrier and transfers only local pressure loads to the tendons, thereby minimizing the strength requirements on the film. The tendons provide the global pressure-containing strength. Thus, the film strength requirement for the design pressure level depends only on local parameters. The selected tendon, a key member of the structure, is made of p-phenylene-2, 6- benzobisoxazole (PBO), which is manufactured by Toyobo Co. Ltd, Japan, and sold under the commercial name Zylon®.

Superpressure balloons are essentially constant volume systems that require the balloon skin (gas bag) to be strong enough to withstand the pressurization created by solar radiation heating of the gas during the day, and still remain pressurized at night after the gas has cooled. The day-night altitude excursion is governed by the amount of strain (or stretch) in the balloon envelope due to pressure changes. No ballast is required to maintain altitude as long as the balloon remains fully inflated, i.e., pressurized. This is in contrast to a zero-pressure balloon, which requires dropping ballast equivalent to approximately 7% of the suspended load at each day-night transition, which severely restricts the flight time. Figure 9 illustrates the performance of a superpressure balloon in comparison with a zero-pressure balloon, which still droops at night even after the ballast drops.

A successful test of a mid-scale pumpkin-shaped ULDB vehicle with a 711 kg payload from Ft. Sumner, New Mexico in June 2000 broke the records for volume and payload mass on a super-pressure balloon [8]. This was followed by two full-scale test flights from Australia in early 2001 with 2038 kg payloads. The full-scale vehicle did reach float altitude and pressurize, and it established a new super-pressure balloon volume and payload record [9], but clefts developed at the top of the balloon.



(a) Pumpkin Shape Design (b) Major Components of Design

Figure 8. Pumpkin-shaped Design of the ULDB Vehicle

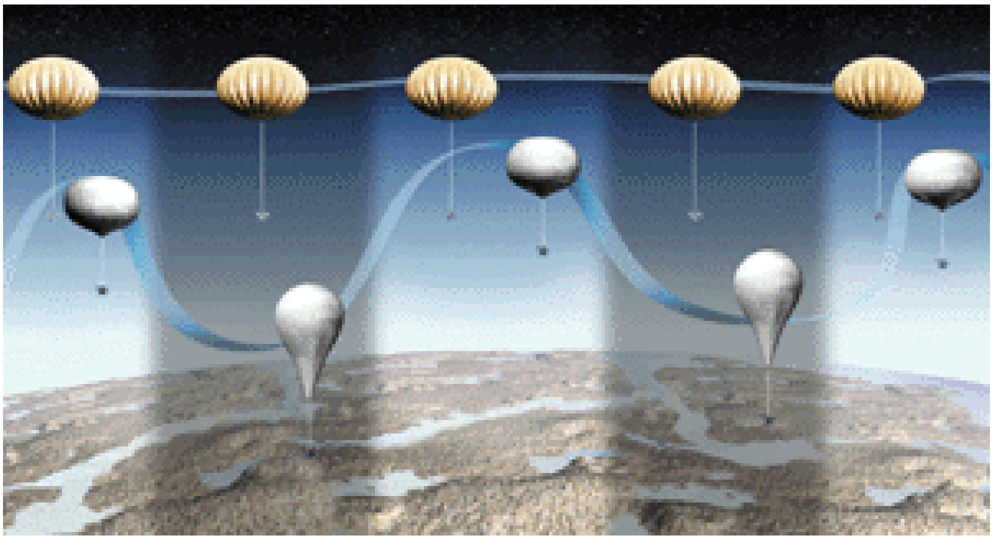


Figure 9. Altitude stability of super-pressure (top) versus zero-pressure (bottom) balloons.

The development effort has been re-planned to allow for a stair-step approach to the development, as well as increased emphasis on analytical modeling. Numerous scaled model balloons have been fabricated and tested to study their deployment and stability [2]. The analytical models have been compared to the physical results of the model tests, which were reproduced very well. The first balloon size in the stepwise development is a 0.17 million cubic meter (MCM) balloon capable of lifting 1360 kg to an altitude of ~30 km (100,000 ft). Figures 10 and 11, respectively, show the inflated scale model used for this balloon and the subsequent first inflation of this balloon at float altitude in February 2005. Unlike the previous pumpkin test flights, this balloon performed nominally throughout the ascent phase, and it fully deployed at the design float altitude with no clefts in the top region. However, an internal camera documented that the closing seal opened near the bottom of the balloon after reaching float altitude. The entire balloon was recovered, and post-flight investigation concluded that the peeled seal was due to a manufacturing issue.

After addressing the manufacturing problems with this test balloon, another 0.17 MCM balloon was fabricated and taken to Fort Sumner, New Mexico for launch in September 2005. Unfortunately, that launch was postponed because of Hurricane Rita and unacceptable launch conditions. The next opportunity for a test flight of this balloon is in June 2006 from Kiruna, Sweden. Following its successful test, a 0.34 MCM balloon will be developed to lift 1360 kg to ~33.5 km (110,000 ft). That will be followed by development and test of a 0.51 MCM balloon to lift 2721 kg to ~33.5 km. It is planned to use the latter to demonstrate a ULDB capability for flying a 1000 kg science instrument for a target duration of 100 days. Subsequently, it is planned to develop a balloon large enough to extend the altitude for such massive payloads to ~37 km (125,000 ft), which is needed for efficient measurements of gamma-rays and hard X-rays because of their attenuation in the upper atmosphere.

Figure 10. Photograph of the inflated scale model of the 0.17 MCM

Figure 11. Photograph of the inflated 0.17 MCM balloon at 30 km (~100,000 ft) float altitude

4. ULDB Support Systems

While the balloon vehicle has been under development and test, the NASA Wallops Flight Facility (WFF) has also developed and tested a support system that would complement the ULDB vehicle. This support system provides power, telecommunications, command and data handling (including flight computers), mechanical structures, thermal management, and solar array pointing for these anticipated long duration missions. The Command Data Module (CDM) houses the power distribution system, command and data electronics, and telecommunication electronics.

The new support system was launched for the first time in support of the CREAM mission in Antarctica in December 2004. Although the flight was operating nominally after circumnavigating the Antarctic continent three times in 42 days, it was terminated because of recovery concerns. As illustrated in Figure 12, the ballooncraft consisted of the science instrument provided by the University of Maryland, College Park [4] and the support systems. The CDM, which was attached to the bottom of the instrument structure, provided the science instrument with power and communications. The power system was designed to deliver 900 W of 28V-dc ± 4V unregulated power to the ballooncraft. It consisted of 10 solar arrays and 4 lithium-ion batteries that provide unregulated 28V power to the science instrument and 5, 12, and 28V (regulated and unregulated) power to the support system components. The batteries are capable of providing power at night for up to 11.5 hours for worst-case mid-latitude flights.

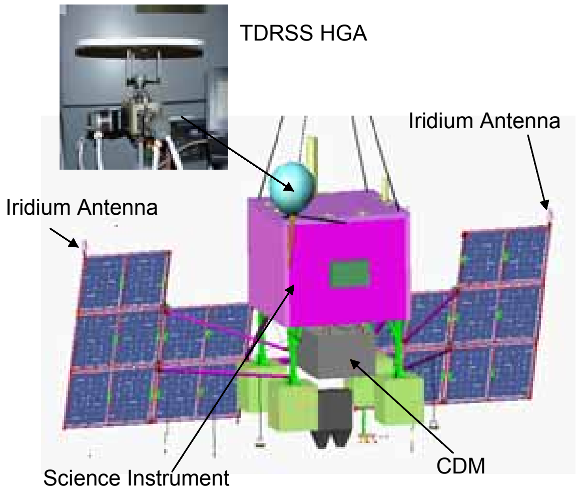


Figure 12. ULDB Gondola with Major Components Shown

The communication interface between the science instrument and the CDM is through the flight computers. The science flight computer is connected to the CDM flight computer by a 10Base-T Ethernet connection utilizing the Universal Datagram Protocol (UDP). All commands are up-linked via the TDRSS network, received by the CDM flight computer, and forwarded to either the science flight computer or the support system components. Telecommunications are provided through two independent systems. As shown schematically in Figure 13, the primary communications are provided through the Tracking Data and Relay Satellite System (TDRSS). Two antennas support the system: an Omni data downlink antenna rated at 6 kbps; and a High Gain Antenna (HGA) downlink rated at 100 kbps. The HGA is capable of providing nearly continuous down-link, as well as scheduled uplinks, at 125 bps.

Backup communications are provided by two Iridium-based communication systems. The primary Iridium system connected to the WFF flight computers can uplink commands and downlink data at a rate of 2400 baud. The second Iridium system is a stand-alone Over-the-Horizon (OTH) Termination System with its own control computer and Global Positioning System (GPS) receiver. The OTH system is used to receive termination commands and route them to the Universal Termination Package (UTP), independent of the flight computers. The ARGOS based µGPSI is another independent backup communication system, which is used to receive GPS position data and transmit critical parameters and position data through the ARGOS ground system via email.

4. Trajectory Modification

It has been realized since the ULDB inception that some level of trajectory modification will be required to realize its full potential. This technology, which is currently only at the conceptual design stage, is important for several reasons. In particular, payloads need to be recovered on dry land in accessible locations, and heavily populated regions must be avoided due to safety concerns. Geopolitical concerns about over-flights of sovereign territories are of special concern for global ULDB flights. The concept feasibility assessment currently underway is for a solar-powered electric-motor/propeller based Trajectory Control System (TCS) to be operated in a latitude corridor maintenance mode. This concept was selected as the one showing the most promise for bringing a simple short-term solution to operational deployment. Initial efforts in feasibility analysis and concept design have concentrated on the ability of the propeller to generate enough thrust to meet the stated requirements for operational control authority, while satisfying the constraints on launch size and power consumption.

Propeller efficiency at balloon altitudes (low Reynolds number) is a major technological challenge. A system performance model based on the combination of a blade element propeller model, a linear DC electric motor model, and a drag model of the balloon envelope was created. System parameters were optimized for the baseline ULDB 0.57 MCM vehicle operating at 37 km. Currently, it is expected that the TCS average continuous power consumption allowance will be no greater than 500W. The design goal is a system that requires less than 300W. The TCS will be designed to impart a wind relative velocity of no less than 1.3 m/s (approximately 1° of latitude per day). It will also provide a consistent level of control authority on demand, rather than dependence on favorable wind conditions. The current concept, illustrated in Figure 14, would attach the TCS system to the cable ladder of the flight train, in order to minimize impact on the gondola and improve the efficiency of the propellers.

6. Conclusions

Two key subsystems for ULDB development are the balloon vehicle and the associated support systems. The ULDB vehicle, which is currently in the final stages of development, is expected to be operational by 2007 - 2008. The specially designed CDM support system has been flown successfully on a record-breaking

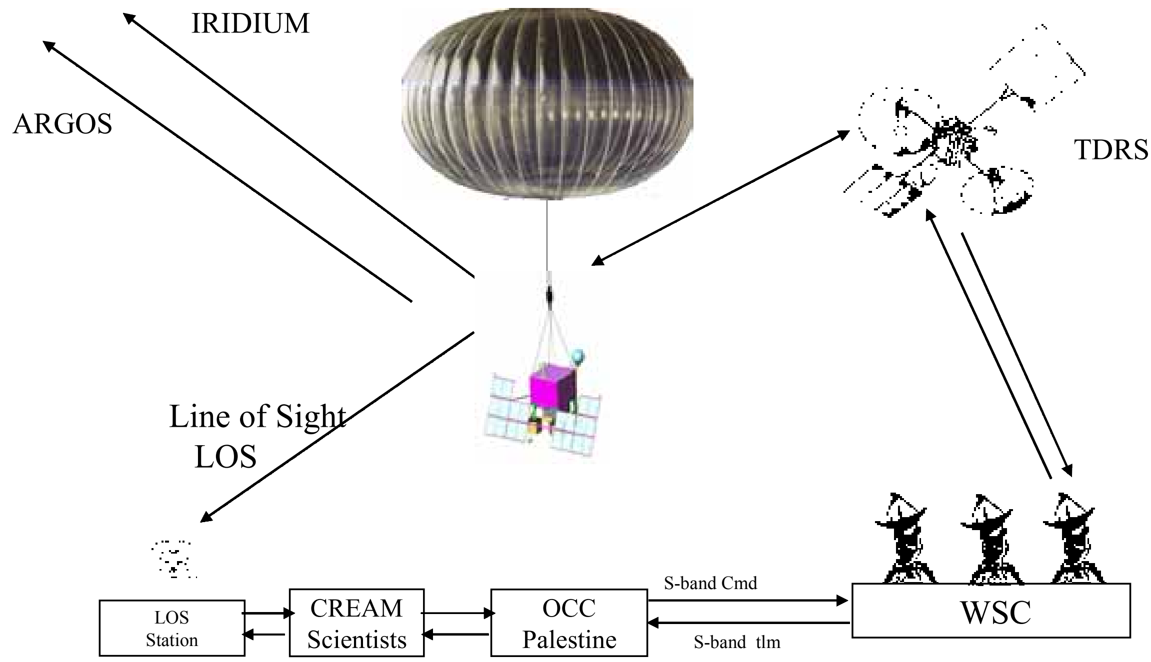


Figure 13. Schematic of CREAM command and data communications through TDRSS

42- day flight that circumnavigated Antarctica three times. The CDM provides power, telecommunications, command and data handling including flight computers, mechanical structures, thermal management, and solar array pointing. A trajectory modification system is currently being designed to increase the capability of ULDB missions. The successful completion of the ULDB development efforts would place world-class science within the reach of a large community of scientists. The payloads could be flown longer at virtually any latitude and at nearly constant float altitude, thereby enabling new science investigations not possible on existing balloon platforms.

While orbital platforms are still the optimum place for many measurements, building and launching space instruments is far too costly to afford the full range of needed scientific investigations and/or development of new instrument technologies. The ability to fly high-altitude superpressure balloons for months or years at a time offers a multitude of opportunities for high priority science investigations. Balloons are particularly suitable for research areas such as cosmic microwave background, x-ray, gamma-ray, and cosmic-ray investigations, where being above 99.5 % of the Earth's atmosphere is essentially as good as being in space. Experiments in these areas generally need to measure very low photon or particle fluxes, so the product of detector-area times flight-duration is often critical. Balloons meet this requirement by accommodating relatively large detector masses and/or areas, as well as flight times up to several weeks, and eventually even months when superpressure ballooning becomes operational.

Balloons missions are also ideal for providing “hands-on” training of young scientists, engineers, and technicians in the utilization of space for scientific research and applications. This includes building and operating instruments for scientific research, intrepreting data collected in space, and dissemination of the results through oral and written communications. The payloads can be recovered, refurbished, and reflown

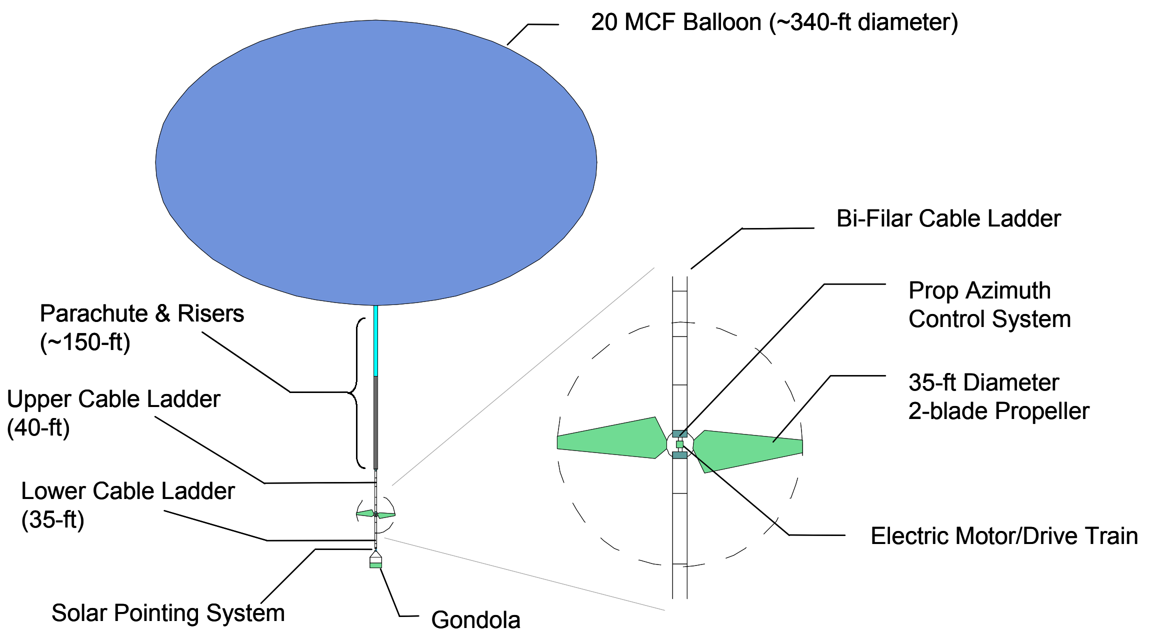


Figure 14. Schematic of propeller concept for Trajectory Control System.

several times. An experiment can be improved with successive flights to make higher quality measurements. Different students and young researchers can be involved in different flights. Launch costs are comparatively low, so a relatively large number of flights, or equivalently a substantial number of research groups, can be supported. Low-cost balloon-borne investigations are also ideal for international cooperation, and they offer realistic opportunities to involve researchers from developing countries in cutting-edge research projects in a variety of scientific disciplines. With appropriate international agreements a variety of balloon flight opportunities could be made available to a large fraction of the scientific population.

Acknowledgments

Special appreciation is due the staff of the Columbia (formerly National) Scientific Balloon Facility for a lifetime of contributions to ballooning, including LDB and ULDB flights, to the staff of Aerostar Inc. (a subsidiary of Raven Industries, Inc.) for innovative approaches to developing high-strength balloon films and pumpkin-balloon fabrication procedures, and to the National Science Foundation Office of Polar Programs for excellent cooperation in the Antarctic LDB program. It would be impossible to credit appropriately all the scientists, engineers, and technicians that have contributed significantly to the development of superpressure ballooning. This concept has been around for approximately four decades, but only recently have the design tools, film technologies, and fabrication techniques allowed successful development of this capability.

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