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HIGHPOWER™ SOLAR ARRAY SYSTEM FOR BALLOONS

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ABSTRACT

A lightweight solar array pointing system is under development for application to balloons. The system suspends solar panels from their corners by cables. By raising and lowering diagonally opposite corners, the parallel solar panels can be simultaneously pointed to any point more than 20 degrees above horizontal. The system acts as a two-dimensional Venetian blind. The system eliminates the need for slip rings, and can point normal to the sun without regard to the azimuthal rotation of the balloon gondola. The number of panels can be tailored to the power needs of each particular flight. The system can provide about 2.5 kW of solar electric power at 35-km altitude. Additional stow/deploy cables are used to extend and retract the set of panels compactly into a protective compartment at the bottom of the gondola, allowing the system to be reused many times. Significant development has been funded by NASA Small Business Innovations Program (SBIR) Phase I and Phase II efforts.

THE CHALLENGE

Figure 1 shows the Tiger payload at the end of its record-breaking flight[1]. Unfortunately, this final condition is fairly typical of many scientific balloon payloads. Often, the primary structure is robust enough to survive landing and, in some cases, dragging across the ground by the recovery parachute in the wind when the chute fails to release, but appendages are frequently damaged beyond repair. In particular, solar array panels are quite fragile and they will often sustain irreparable damage.

Figure 1 Tiger Payload at the Mission End (Photo courtesy Washington University)

THE INNOVATION

The HighPower™ solar array subsystem, shown in Figure 2, provides a lightweight, modular means of generating power for scientific balloons. By restowing the panels, also referred to as Solar Array Modules (SAMs), within a protective structure, the HighPower™ solar array subsystem will significantly increase their survival rate, allowing them to be reused many times.

An integral part of this patented[2] design is the ability to track the sun without the need for gimbals or slip-rings. The panels are suspended from their corners by cables. By raising and lowering diagonally opposite pairs of cables, the panels are all pointed simultaneously to any point more than 20°

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above the horizon. The system operates as a two-dimensional Venetian blind.

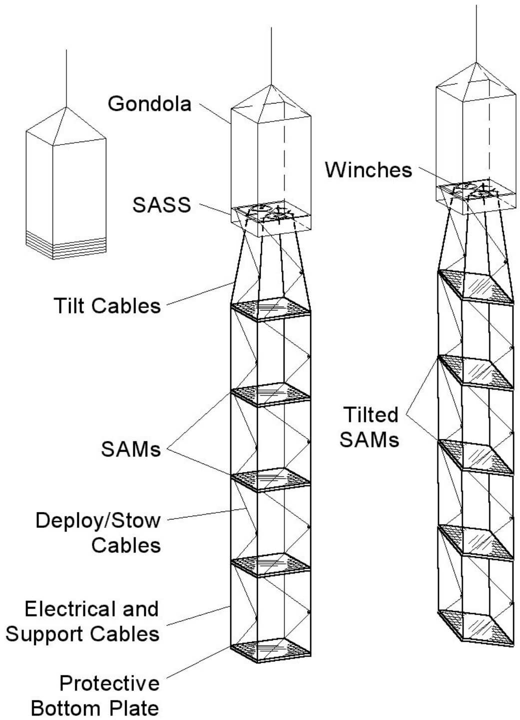

Figure 2 HighPower™ Solar Array Subsystem

The system exploits the Earth's gravity field with vertical cables supporting the weight of the panels. This reduces the mass of the mechanism for deployment, stowing, and tilting of the panels.

The use of a modular approach allows selection of the appropriate number of Solar Array Modules (SAMs) for each mission. This approach allows much more power to be made available to payloads than in the past as the total array area is not limited by available mounting area on the gondola. Furthermore, the panels are maintained perpendicular to the sun most of the time, allowing all cells to produce power optimally.

The ability to restow the solar array modules allows reuse and refurbishment to achieve reduced life cycle costs. Amortizing costs over several flights allows higher efficiency cells to be used economically. When programmatic needs require the lowest possible array costs, less expensive lower efficiency cells may be substituted, although overall mass would then be expected to increase.

BENEFITS TO NASA BALLOONING

The Ultra Long Duration Balloon (ULDB) program is an ambitious and revolutionary extension of NASA's scientific ballooning capabilities. The ULDB Program is managed by the NASA Balloon Projects Office at NASA/GSFC Wallops Flight Facility (WFF). The goal of the ULDB program is to fly up to 2000-pound science payloads above >99% of the Earth's atmosphere for at least 100 days, a factor of 3 to 30 times longer than current balloon flights. The move from 15-30–day flights (the Long Duration Balloon or LDB program) to 100-day flights (ULDB) brings many new lifetime-related issues. More ambitious payloads will be flown with greater power needs for longer periods of time. Although the development of the HighPower™ solar array subsystem was motivated by the new needs of the balloon program, the system provides the same benefits to conventional balloon flights.

In the past, solar arrays have been sacrificed on landing, as there was no feasible means of protecting them. Solar arrays are usually mounted at a fixed elevation angle on the gondola to keep costs acceptably low. In some cases, panels have been mounted on all four sides of the gondola to provide power regardless of gondola rotation. In other cases, the gondola's rotation angle about the vertical has been controlled to keep the panels aimed generally towards the sun. Of course, this approach is not feasible with payloads that need to point the gondola in arbitrary directions. Because it has to operate while carrying very high loads, the gondola rotator alone masses about 91 kg[3]. This mass, which is eliminated by the HighPower™ solar array subsystem, is more than 70% of the estimated mass of the entire operational HighPower™ solar array subsystem. Neither omni-directional or rotated fixed-elevation-angle arrays can provide the maximum power that can be available with all panels pointing at the sun at all times.

The development of the HighPower™ solar array subsystem is a phased activity whose ultimate goal is the development of an operational system for use by the ULDB program and other commercial entities. Currently, a prototype system exists made up of 3 fully-populated solar panels. This current system requires further ground testing and development before a stratospheric flight test can be carried out. Additional work is required to fully develop the deploy/stow mechanisms, construct an outer solar array support enclosure, design and build the gondola interface module, carry out a full, 6-panel deployment, stow and tracking test (perhaps from a tethered balloon), and environmentally test the key elements (motors, electronics and mechanisms) prior to a stratospheric test flight.

The HighPower™ solar array subsystem offers the following benefits:

- Higher power levels are available
- Full power is available for a large portion of the daylight segment
- Power level can be tailored to different missions with no new design work
- Gondola rotation is unconstrained and thus heavy rotators, with slip rings, not required
- Structural mass is arranged efficiently
- System is refurbishable
- High array output voltage may be convenient for some payload instruments
- Cost per watt per flight is reduced
- New science capabilities are enabled

In summary, the HighPower™ solar array subsystem is important to the NASA ULDB program because it provides more power than previous systems, it is modular, allowing the power level to be tailored to specific payloads, it reduces cost when averaged over several flights, and it enables the operation of more ambitious scientific investigations requiring higher power levels over much longer periods of time

SYSTEM DESCRIPTION

As shown in Figure 2, the HighPower™ solar array subsystem consists of several square panels, referred to as solar array modules, or SAMs. The SAMs are suspended by their corners such that the panels remain parallel at all times. A solar array support structure, or SASS, is attached to the bottom of a balloon gondola and supports the SAMs and actuators for manipulating the SAMs, as well as providing power, command, and data interfaces between the HighPower™ solar array subsystem and the gondola. The SAMs are oriented by raising and lowering tilt cables in diagonally opposite corners. The tilt cables also conduct electrical power from the SAMs to the SASS.

Solar Array Module (SAM)

The heart of the system is the solar array module (SAM) as shown in Figure 3. Each SAM is a square panel about 2m x 2m covered with two strings of 300 solar cells each and attached at the corners to tilt/power cables, as well as to a separate set of stow/deploy lines. The panels are fabricated of aluminum honeycomb to which laminated solar cell modules are bonded. The unusual arrangement of the solar cells is intended to reduce the effects of shadowing along the sides and corners of the panels to balance the effects on each of the parallel SAMs. Each cell produces about 0.5V, so the total nominal output voltage from the array is about 150V. This is higher than originally specified, however, allowing the array to operate at a higher voltage was a compromise driven by the cell layout and shadowing concerns.

The design of the SAM corners, at which the power-conducting tilt cables and stow cables interact with the SAM, ensures acceptable cycle life, electrical connectivity, and strength.

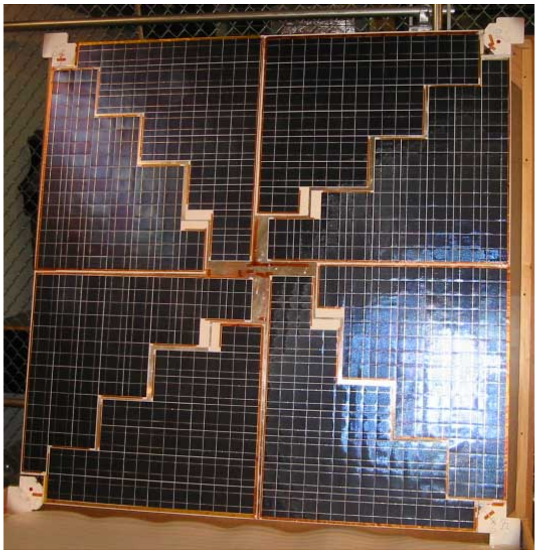

Figure 3 Solar Array Module

Solar Array Support Structure (SASS)

The Solar Array Subsystem Structure (SASS) is shown in Figure 4 with stowed SAMs, but without stow/deploy or power/tilt hardware nor the outer shear panels. The prototype SASS is a welded cage of square aluminum tubes forming a space frame. It supports all the hardware of the HighPower™ solar array subsystem and provides mechanical mounting points for attachment to a balloon gondola. Aluminum sheet metal will be attached to the exterior of the frame to provide shear stiffness and to protect against intrusions into the interior of the SASS. At the bottom corners of the SASS are latches that are released by a small, motorized mechanism.

Figure 4 Solar Array Support Structure

Power/Tilt System

The power/tilt cables, made of a copper alloy, support the SAMs and carry electrical power from the SAMs to the gondola. These cables are connected via pulleys to the tilt mechanism. Actuation of the SAMs is accomplished by raising and lowering diagonally opposite tilt cables, allowing the SAMs to track the sun throughout the day.

The copper cable is braided to provide flexibility, and has high strength and low electrical resistance. These properties are important as these cables both support the SAMs mechanically and conduct electrical power from the SAMs.

The power/tilt cables are required to support the SAMs without breaking for all loading conditions. It is a safety-related requirement that no part of the HighPower™ solar array subsystem detach, posing a hazard to people or property on the ground, during any reasonably anticipated event.

During stowing or deployment, the geometry of the partially folded lines increases the tension in the lines over the levels when either fully deployed, or completely stowed. The worst-case situation would therefore be a premature balloon cut-down with 10-g deceleration due to the parachute opening shock in the middle of the stowing or deployment process. Such an emergency off-nominal event would most likely lead to tangled panels, but would not result in severing of any parts of the HighPower™ solar array subsystem.

The tilt mechanism consists of a custom chain-driven linear actuator carrying two insulated pulleys to increase or decrease the effective length of the power/tilt cables used to control the tilting of the panels and to provide contacts for the main power output from the arrays. The two cables passing through each tilt mechanism are connected to diagonally opposite corners of the panels and therefore are of the same polarity. One tilt mechanism provides two positive (+) pick-off points, and the other tilt mechanism provides the negative (-) pick-off points. The motors are driven by 28 VDC power from the gondola and are commanded by the controller.

Stow/Deploy System

During normal sun-pointing operation of the SAMs, all the weight is supported by the copper power/tilt cables. An additional loose set of stow/deploy cables zig-zag up the stack of SAMs. These lines are used to retract the SAMs at the end of the flight. The line used for the stow/deploy cables is multi-strand Spectra that is coated for UV protection. The line was selected for its high strength, flexibility, and resistance to both abrasion and UV degradation. These lines are sized to easily withstand the 10-g loading corresponding to parachute opening with the lines in the worst-case geometry for load amplification. Stowing is accomplished by winding these stow/deploy cables onto large diameter pulleys. As these lines are retracted, the bottom plate starts to rise after all slack in the lines is taken up. One by one, the SAMs stack on top of the bottom plate and the winching continues until the entire stack is raised up inside the SASS and the bottom plate engages its latches to complete the stowing operation. A stow/deploy cable runs up each corner and over pulleys and onto four large take-up spools, one for each corner. The stack of four wheels is driven by a highly geared electric motor driving a chain and sprocket. The motor is driven by 28 VDC power from the gondola and is commanded by the controller.

Eggs

At the midpoint between SAMs, a pulley housing is attached to each length of copper power/tilt cable. The stow/deploy cable runs through the pulley in this housing. As the stow/deploy cables are retracted, the tension folds the power/tilt cables neatly and confines them to lie along the edges of the SAMs. The pulley housing is egg-shaped, see Figure 5, to eliminate the possibility of snagging of the stow/deploy cables if they should wrap around the power/tilt cables. This is unlikely, as there is always a small amount of tension on the "slack" stow/deploy cables to prevent such wrapping.

Figure 5 Egg

Bottom Plate

The bottom plate suspended below the SAMs carries no solar cell modules. It is a mechanical support structure that latches into position at the bottom of the SASS to support and protect the stowed SAMs during launch and landing. Once latched into position, this bottom plate also increases the stiffness and strength of the SASS. The bottom plate is formed as a space frame of square aluminum tubes welded into a stiff, lightweight structure, with sheet metal reinforcements to add shear stiffness and protection from intrusions into the interior of the SASS. The bottom plate also carries electronics and a few solar cells arranged to function as a sun sensor providing signals for controlling the pointing of the SAMs (see Figure 6).

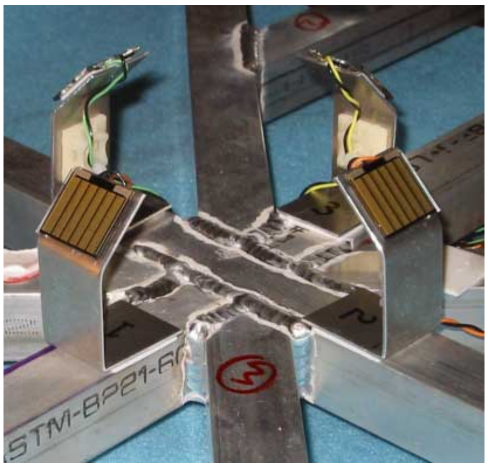

Figure 6 Sun Sensor Assembly

Controller

The controller is a set of electronics, based on a microprocessor, that is used to control the various functions of the HighPower™ solar array subsystem. The controller electronics are split between two housings, one mounted inside the main SASS, and the other mounted on the bottom plate.

The SASS electronics use 28 VDC from the gondola. The controller reads various sensors, processes commands from the gondola, and controls deployment, tilting, and stowing. The controller also provides status to the gondola. The electronics mounted to the bottom plate take a very small amount of power directly from the solar array. A small rechargeable battery powers the circuitry through the night (so sunrise can be sensed).

The bottom plate electronics encode the current produced by each of the sun pointer solar cells and transmit the values to the main control electronics in the SASS. A small RF transmitter transmits the information, although the option exists to use the copper power wires to transmit a small AC-coupled signal.

Interface Module

An interface module in the SASS provides the electrical and data interfaces between the HighPower™ solar array subsystem and the gondola of the balloon system. The interface module provides connectors to carry the high voltage, unregulated solar array power to the power subsystem of the gondola. In addition, the interface module provides communication between the HighPower™ solar array subsystem and the balloon gondola for transferring data and commands between the gondola and the HighPower™ solar array subsystem. Rather than duplicate the power conditioning and battery charging functions already in the gondola, the interface module also obtains regulated power from the gondola for operation of HighPower™ systems.

Launch

The HighPower™ solar array subsystem is stowed beneath the balloon gondola at launch. When the system reaches float altitude, the SAMs are deployed and automatically start tracking the sun.

Operation

In sun-tracking mode, power to the tilt motors is controlled by circuitry connected to four small solar cells mounted on the bottom plate and inclined 45° (see Figure 6). The tilt motors are driven until the current levels from opposite pairs of cells are equal, indicating that the sun is at the same angle with respect to each of the four cells. A selectable deadband is implemented to prevent excessive hunting of the system. The deadband is set to correspond to a few degrees. The reduction in output power from the array is negligible over this small range of non-orthogonal pointing. At ±5° the loss of power is less than 0.5%. Even at 10°, the power loss is less than 2%.

When the sun is within 20° of horizontal, the sun-tracking algorithm is modified to prevent the panels from getting too close to the absolute mechanical limit of 15°, with the concomitant chance of overturning and tangling the lines. Accelerometers mounted to the bottom plate sense the tilt of the plate. The output of the accelerometers is used to limit the stroke of the tilt actuators. Simple limit switches are not sufficient as the limit is different when the corners of the square SAMs are down versus when the sides of the squares are down. Greater stroke is needed to lower the corners to 70° than to lower the sides to the same angle. The combined effect of the accelerometers and the sun sensors is that the perpendicular to the SAMs remains close to the azimuth direction of the sun during this period.

When the sun is within 30° of vertical, which may occur during operation near the tropics near midday, shadows from one panel start occluding edges of the lower panels. Depending on the height of the flight train and the diameter of the balloon, the balloon's shadow will also start to shade the gondola and with it the HighPower™ solar array subsystem. The self-shadowing by the panels will take out successive sub-strings of solar cells, and the total array output voltage will drop, although the current should remain about the same depending on the design of the power converter in the gondola. The layout of the cells on the SAMs is arranged to balance the voltage drop in all strings, so the various parts of the array will not be fighting each other. The sun-sensing cells are mounted close to the middle of the bottom plate, so they continue to keep the partially shaded SAMs perpendicular to the sun direction until almost half of the panel is shaded. At this point, the panels are commanded to go level and wait until the sun is reacquired on all four sun-sensing cells, indicating that the sun has moved sufficiently far so normal sun-tracking operation can resume.

When the light level sensed by all four of the sensing cells falls below a preset level, it is assumed that it is nighttime and the SAMs are commanded to their level position to await sunrise.

At sunrise, the panels are horizontal, and the sun will be below horizontal. This means that the sun-sensing cells will still be in the shade of the bottom plate. However, light reflected from the balloon and the bottoms of other SAMs will raise the ambient light level so there should be a discernable signal from the sensors. At this point, when the sun is rising, the panels are commanded to start a scan to seek the sun. The panels are tilted about 20° in an arbitrary direction and then the pointing direction is commanded to rotate in azimuth about the vertical, also in an arbitrary direction, until a significant signal is sensed on one or more of the sun sensors. At this point, the mode is switched to sun tracking. Of course, when the panels attempt to track down towards the sun, they will run into the 20° limit, but they will still aim the panel normal direction to approximately the same azimuth as the sun. This will produce a significant amount of power, although the intensity of the sun will be quite low as it is traveling through the equivalent of several atmospheric air masses. As the sun climbs in the sky, the array output current will increase due to increasing solar intensity and incidence angles closer to 90°.

At the end of the flight as part of preparation for commanded balloon cut-down, a command will be issued to the HighPower™

solar array subsystem to stow the SAMs. The SAMs will first be commanded to level. Then the stow/deploy motor will be commanded to retract the stow/deploy cables. Due to the high gear ratio, this process takes about 15 minutes with three SAMs, and about 30 minutes with six SAMs. As the lines are drawn in, the slack-take-up devices in the bottom plate first extend to their fullest, at which point the increasing tension in the cables starts to lift the bottom plate. The tension in the stow/deploy cables pulling on the egg-shaped pulley will begin the process of folding the power/tilt cables. As the bottom plate rises, eventually, it comes in contact with the lowest SAM and starts supporting it. The power/tilt cables above that SAM will then starting folding more noticeably until the next SAM is resting on the stack. This process continues until all the SAMs are resting in a stack on the bottom plate. During this stowing process the stack of panels aligns itself with the opening in the base of the SASS. Once the top SAM enters the SASS, contact between the walls of the SASS and the protruding corners of the SAMs keeps the stack aligned, and the whole stack continues to rise up inside the SASS. Finally, the bottom plate makes contact with the bottom of the SASS and the angled surface ensures the final alignment just as the latches engage, locking everything securely in place.

<u>Mass Breakdown</u>

Table 1, below, shows an estimate of the mass breakdown for the HighPower™ solar array subsystem. The table shows the major elements plus subtotals for the large, separate pieces: SASS, Bottom Plate, SAMs.

On the left side of the table are the masses for the prototype system, as currently fabricated and estimated. Although the masses listed are based on weighing elements, in some cases the masses are estimated because they were assembled before weighing and some elements have yet to be fully designed and fabricated.

Table 1 System Mass Estimates

Component	Mass Estimates, kg	
	Proto-type System	Opera-tional System
SASS	**90**	**56**
SASS Structure	41	30
Stow Mechanism & cable	16	5
Tilt Mechanisms	8	5
Tilt cables inside SASS	2	2
Pulleys, etc.	10	6
Electronics & wiring	1	1
Latches	2	2
Shear plates	8	4
Interface module	2	1
Bottom Plate	**37**	**19**
Bottom Plate Structure	18	9
Corner hardware	2	1
Shear plates	12	6
Slack-take-up Mechanism	4	2
Electronics & wiring	1	1
SAMs (6)	**61**	**53**
SAM substrate with cells	35	35
SAM corner plus hardware	16	10
Power/Tilt cables	10	8
Total System	**188**	**128**

On the right side of the table are estimates for a future operational system. The current prototype design is meant as a proof of concept system in which considerable mass reductions can be made. For example, we have used heavier than desired items to meet the stringent SBIR program schedule and cost constraints. For example, the stow/deploy motor is much larger and powerful than necessary. For the structure, we used a common wall size for all the aluminum tubes that we knew would be strong enough without needing to perform detailed finite element modeling. By using a more detailed analysis, we could reduce the weight in many areas. By going to extremes, we could fabricate a system with even lower total mass than shown. However, this would tend to start driving costs up, which would only be warranted for an extremely weight-limited gondola, perhaps with a very large payload, for which weight would be at a premium.

SYSTEM LIFE CYCLE OPERATION

Because solar arrays can be expensive there must be some attention paid to solar array system life cycle times because this parameter factors into life cycle costs. System life is estimated at ten missions, which corresponds to 1000 days of ULDB operation, at which point, refurbishment costs are assumed to become excessive. Typical factors that determine system life for space solar array systems are radiation damage of solar cells, UV degradation of materials and cells, mechanical wear of moving parts including motors, thermal cycling of solar cells, fatigue of flexible structures, and electronics failure.

For a balloon-borne solar array system, thermal cycling of solar cells is not expected to be a serious concern because there are fewer day/night cycles than for space systems and slower rates of temperature changes as compared to space. Also, high-energy particle radiation damage is not a problem at 35-km altitude. However, an additional factor for a balloon-borne solar array system is damage by high g-loads at gondola cut-down and/or landing.

SYSTEM COMPARISONS AND PERFORMANCE

In this section we compare various balloon solar array systems in terms of cost per Watt per flight and specific power. In addition, we compare the initial HighPower™ solar array operational goals with the performance of the actual prototype and the estimated operational solar array systems.

Balloon Solar Array Comparisons

For a reusable system, as the number of flights increases, the cost per Watt per flight decreases steadily almost inversely in proportion to the number of flights. This can be seen quite clearly in Figure 7. Two non-HighPower™ solar array systems are displayed, namely a typical long duration balloon (LDB) solar array (880 W) and the ULDB Ballooncraft solar array (1200 W).[4] The LDB array, usually flown in polar Summer conditions, consists of 4 sets of fixed panels of terrestrial crystalline silicon cells arranged on four sides of a gondola, all at a fixed elevation angle that is optimized for the latitude of operation. Expected array output is only about 220 W at any one time. The ULDB Ballooncraft solar array, made of thin-film amorphous silicon cells, is deployable in three panels at a fixed elevation angle and is pointed at the sun by means of a rotator system, which currently weighs about 91 kg. The power required for the rotator has not been included in this analysis but will further lower the overall specific power.

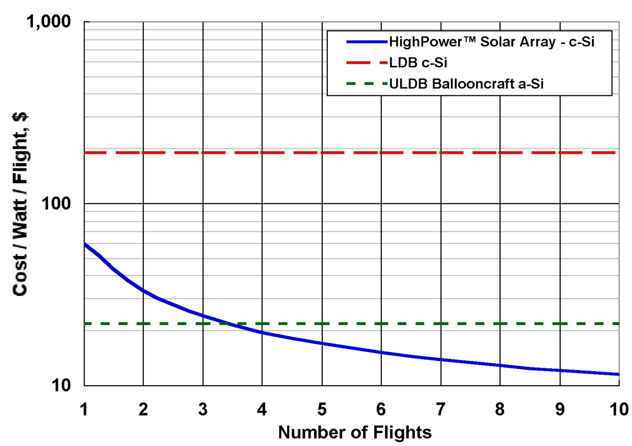

Figure 7 Comparison of Balloon Solar Array Costs

Costs for these non-HighPower™ systems were estimated with knowledge of their solar cell type, the basic design concept, and assuming GAC fabrication costs, since the actual costs were unavailable. The cost per Watt per flight of these options is constant because the entire system is considered expendable each flight. Note, that the incremental cost of flying a rotator assembly was not included in the ULDB Ballooncraft solar array costs. This chart indicates that the reusable HighPower™ solar array cost per Watt per flight is comparable with the LDB costs even on the first flight, and the HighPower™ system costs are lower than the ULDB Ballooncraft system after only three flights.

Figure 8 compares the specific power of these solar arrays as a function of system cost per Watt per flight.

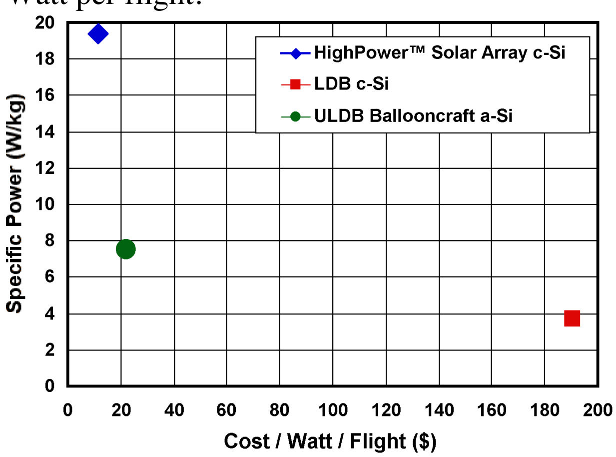

Figure 8 Comparison of Balloon Solar Array Specific Power with Cost

Comparison of Solar Array Goals with Actual and Estimated Performance

Table 2 summarizes the HighPower™ system operational goals as compared to the performance of the actual prototype and an estimated operational system. Power level, quoted at beginning of life (BOL) for both the prototype, with 6 SAMs, and the estimated operational systems is 2486 W, which is nearly 500 W greater than the operational goal.

The operational goal for sun tracking cycles was 2,400 based on one gondola/balloon rotation per hour over a 100 day ULDB flight. This number was exceeded in ground testing by a factor of 10. Tracking cycle life needs to be validated in the relevant environment, however if it stands, major refurbishment of the SAM corners may not be necessary between flights.

As discussed earlier the desired voltage was between 50-100 V. The designed higher voltage of 150 V results in a more robust array, with respect to shadowing and resistance losses, and is expected to be handled easily by conventional power conditioning hardware in the gondola. In fact, many payloads require higher voltages than the nominal 28 VDC.

Table 2 Comparison of Solar Array Goals with Actual and Estimated Performance

Element	Operational Goal	Actual Prototype	Operational Estimate
BOL* Power Level, W	2,000	2,486	2,486
Solar Tracking Cycles	2,400	24,000	24,000
Azimuth Tracking Rate, deg/s	6	12	12
Panel Voltage, V	50 to 100	150	150
Array UV Degradation, %	6	TBD	TBD
System Mass, kg	100	188	128
System Specific Power, W/kg	20	13.2	19.4

* - beginning of life

Observed UV degradation was only 2% on sample cells for exposures equivalent to about three ULDB 100-day flights during day/night operations. More UV exposure testing will be necessary to be able to estimate the degradation for the full 1000 days. Because of the nature of UV degradation on the solar array, namely, that it approaches an asymptote, we would not be surprised to have only 2-3% of total degradation versus the goal of less than 6%.

The total prototype system mass is considerably larger than the operational goal and the reason for this higher mass was explained earlier as the result of the stringent SBIR program schedule and cost constraints. However, even the current estimate of an operational system is about 28 kg heavier than our original operational goal. We feel that a 100-kg system mass is feasible, however, it would require use of exotic materials and fabrication techniques that will increase the overall costs, and therefore may not be cost effective for ULDB flights. Even still at 128 kg, the overall specific power of the estimated operational system is nearly 19.4 W/kg versus the goal of 20 W/kg.

SUMMARY AND CONCLUSIONS

A lightweight, modular, low-cost solar array has been described that can provide almost 2.5 kW of power to balloon gondolas. This system is refurbishable and reusable which enables a very low cost on a per flight basis. This system also avoids use of a gondola rotator assembly for sun tracking that requires significant mass, cost and the usage power, and which has reliability and data quality concerns due to the use of slip-rings. Originally designed for use on the ULDB, HighPower™ solar array could provide a significant cost-effective capability to LDB flights that require high power levels. Finally, the HighPower™ solar array system requires further development before test flights and operational use can be contemplated.

ACKNOWLEDGEMENTS

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