INVESTIGATIONS TO CHARACTERIZE MULTI-JUNCTION SOLAR CELLS IN THE STRATOSPHERE USING LOW-COST BALLOON AND COMMUNICATION TECHNOLOGIES[1]

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ABSTRACT

The use of current balloon, control and communication technologies to test multi-junction solar cells in the stratosphere to achieve near AM0 conditions has been investigated. The design criteria for the technologies are that they be reliable, low cost and readily available. Progress is reported on a program to design, launch, fly and retrieve payloads dedicated to testing multi-junction solar cells. The system investigated includes a state-of-the-art multi-junction solar cell and two-axis suntracker that weighs less than one pound. Data acquisition is carried out with programmable microcontrollers, A/D converters, digital I/O lines, AX.25 encoding and GPS, and VHF, UHF and HF transmitters. One flight has been carried with a 1000 gram extensible helium balloon and a payload that weighed under six pounds. During a flight that lasted about two hours, the balloon traveled to an altitude of 87,000 feet and data were downlinked. Th payload was retrieved about 40 miles from the launch site.

INTRODUCTION

Multi-junction solar cells are attractive for space-power generation. Triple-junction $GaInP_2/GaAs/Ge$ cells with areas of 2x2 cm^2 have been fabricated by two companies with lot average efficiencies of 24.2 and 23.8% [1]. Programs are underway to reduce fabrication costs and increase cell area and efficiency. Cells with four junctions are currently under development. It is anticipated that progress in the next ten years will include cell designs with at least five junctions and efficiencies approaching 40%. In order to achieve these goals, it is necessary to have access to AM0 cell standards and testing under AM0 conditions. NASA is developing a solar cell test bed for the Space Station that includes a single axis tracer which will be used to test solar cells and calibrate cells. The first mission is projected for 2004.

The objective of this program is to investigate current balloon, control and communication technologies in an effort to develop a system that is reliable and low-cost, and readily accessible to the photovoltaic community for testing solar cells in the stratosphere where near AM0 conditions exist. After exploring several approaches, it was decided to pursue the technology developed by amateur radio groups. One of the amateur groups that flies balloons on a regular basis is the Edge of Space Sciences (EOSS) located in the Denver, Colorado area. The group maintains a Web site, http://www.eoss.org/, that lists seven other balloon groups; the site has an EOSS Handbook that is a beginner's guide to ballooning. One of the authors of this paper, William J. Brown, has flown several balloon flights, both as an amateur and professional; he handled the ballooning aspects of this project while the other authors focused on the design, construction and testing of the suntracker system.

SUNTRACKER DESCRIPTION

The suntracker is designed to point a solar cell at the sun as a balloon ascends and downlink data containing the cell short-circuit current, cell temperature and electronics module temperature. The suntacker is shown in Figure 1; it includes a two-axis tracker and electronics module that together weigh less than thirteen ounces. The two-axis tracker has a collimator and two motors that are supported 5.06" above the electronics module by a 0.25" aluminum rod. The collimator is made of 0.062" aluminum plate and assembled with 00-90 brass screws in order to minimize

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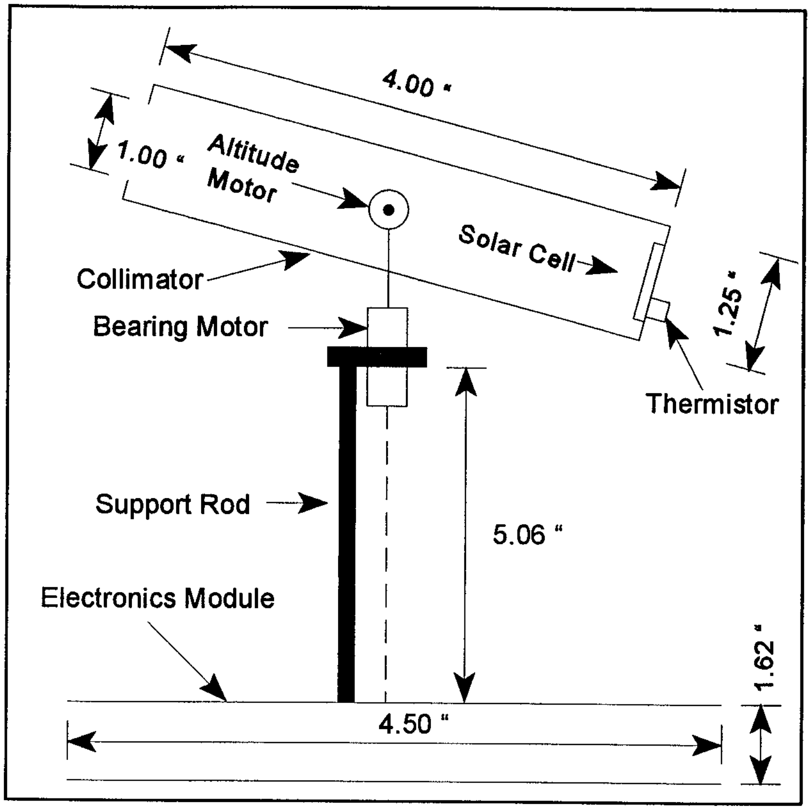

Figure 1. Diagram of suntracker

the weight. The dimensions of the collimator are 1.25"x1.25"x4.00"; the front aperture is 1.00"X1.00" and the cell area 0.79"x0.79". The design provides a plus or minus 3.0 ° collimation of the full intensity of the sun on the solar cell. Since the intensity of the sun varies as the cosine of the incident angle, the dimensions of the collimator insure the intensity of the sun varies less than 0.15% if the sun is tracked to plus or minus 3.0°. The full-width at half maximum is plus or minus 15° for the collimator. The dimensions of the collimator were selected to prevent light scattered from the balloon, earth, moon or clouds arriving at the solar cell. The solar cell was soldered on a copper plate that was affixed to the bottom of the collimator. A thermister was attached to the copper plate to measure the temperature of the solar cell. The collimator was painted with a flat black paint on the inside surfaces to minimize reflections of light. The exterior surfaces of the collimator, motors and support rod were also painted flat black to increase absorption of sun light for heating the suntracker and minimizing the effects of the low temperature environment at high altitudes.

The suntracker has two MicroMo series 1016 DC motors that point the collimator at the sun. Each motor assembly has a gearhead and magnetic encoder and weighs less than one ounce. The gearheads have a 256:1 reduction ratio enabling the motors and gearheads to deliver 13 oz-in torque. One motor controls the altitude angle of the collimator that ranges between 0° and 90°; the other motor controls the bearing angle between 0° and 360°. Each magnetic encoder produces two channels of square wave pulses in quadrature that are TTL/CMOS compatible; ten pulses are produced per revolution of the motor. The pulses are input to the electronic module to keep track of the position of the collimator.

The length and diameter of a motor assembly are 2.00" and 0.39", respectively. The altitude motor is supported by an aluminum bracket mounted on the shaft of the bearing motor. The shaft of the altitude motor is affixed to an aluminum collet that is attached to the collimator with four 1-72 screws. The collet is 0.25" thick and 0.50" in diameter, and the four 1-72 screws are equally spaced on a 0.31" circle . The bearing motor is held with a 0.25" aluminum bracket that is mounted on the aluminum rod and bolted to the top of the electronics module. All the aluminum parts were fabricated from 6061 aluminum stock. The specification for the temperature operating range of the motor assembly is -30 to 85 °C. Since temperatures as low as -60 °C can be expected at 40,000 feet, the grease in the gearheads was removed and replaced with light oil.

A challenging problem that had to be solved was transferring the electrical signals of the motors, encoders, solar cell and thermistor across the rotating interfaces of the two motors. Electrical slip rings are generally used for this purpose. However, available slip rings were too large and heavy for this application. The design that we adopted employed virtual stops and flexible wire. Virtual stops were effectuated using the pulses from the encoder, software and a microcontroller; the stops limited the altitude and bearing angles to 0° and 90° and 0° and 360° ranges, respectively. The wire that was used is a high-performance modified fluoropolymer-insulated wire with -65 to 200 °C specifications; it is a radiation-crosslinked, 28 AWG, 7 strands x 36 AWG, tin-coated copper wire manufactured by Raychem Corporation. The wire remained flexible during tests in a dry-ice acetone solution at -78 °C.

A diagram illustrating the suntracker telemetry and control system is shown in Figure 2. The signal from the solar cell is input to an operational amplifier. One of the outputs from the operational amplifiers is input to a MIM module that was purchased from Clement Engineering; it is a 1200-baud, AX.25, transmit terminal node controller (TNC) that can telemeter five analog and eight digital signals at user selectable intervals. The MIM module is slightly larger than a credit card and programmable via a serial port connected to a personal computer (PC). It draws less

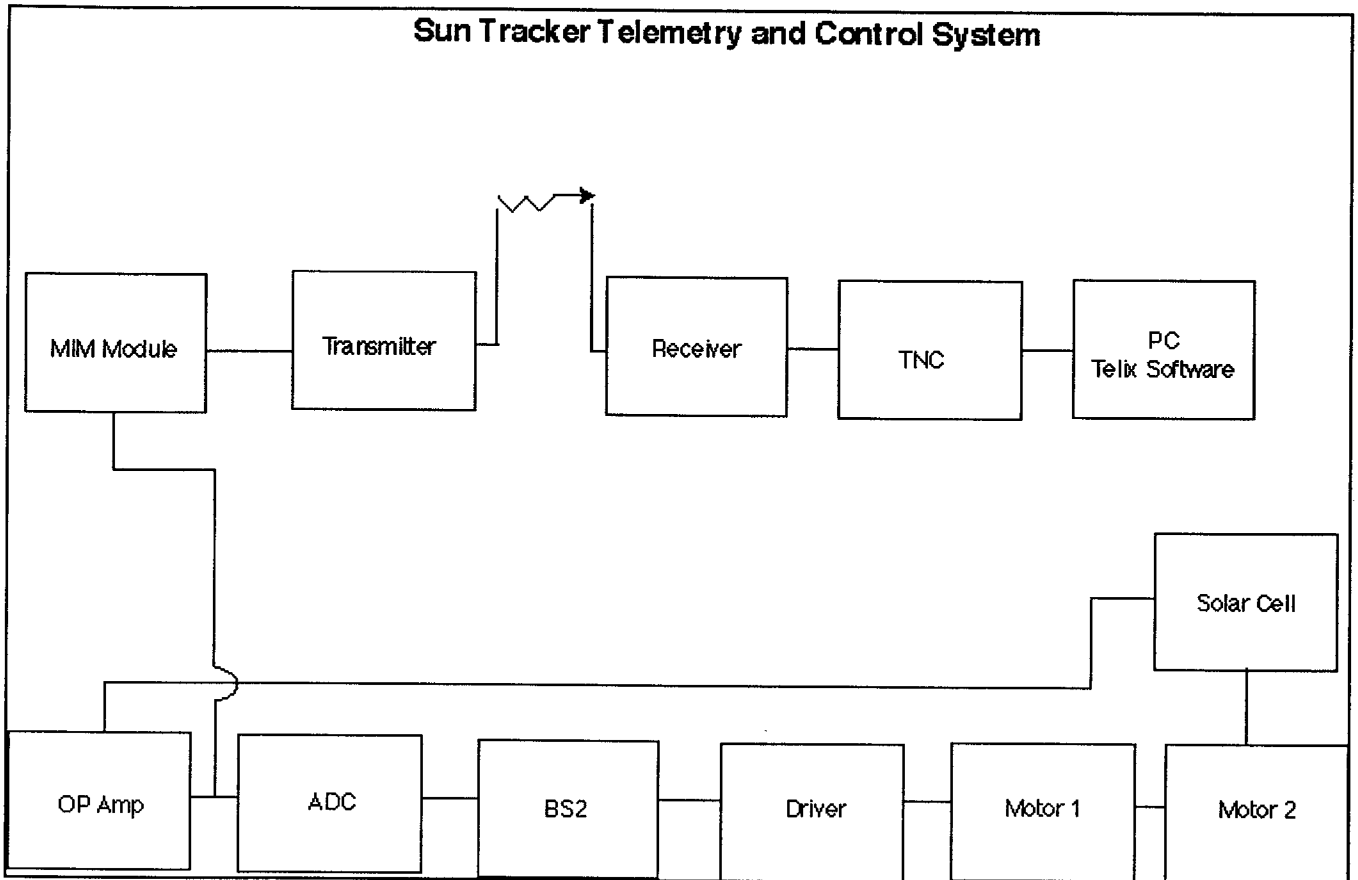

Figure 2. Suntracker telemetry and control system

than 15 mA and was powered during the flight by regulated 5.0 VDC from a battery pack. The unit was programmed to activate the push-to-talk function of the transmitter, and transmit data and a beacon message. The MIM module encodes data in the AX.25 format and inputs it to a credit-card size Alinco DJ-S11T 0.25 watt VHF transmitter. The transmitter power requirements are 9.0 V and 40 mA under quiescent conditions and 300 mA while transmitting. The data and beacon message from the MIM module are downlinked to a transmitter interfaced to a terminal node controller (TNC). The TNC translates the AX.25 code into ASCII text and outputs it to a serial port that is connected to a PC running Telix, a state-of-the-art communications software package. The data are saved in a PC file for analysis at a later time.

The signal from the solar cell is used to control the suntracker in order to produce a maximum in short-circuit current. The design specification is to control the suntracker in seeking the maximum in solar cell short-circuit current to better than 1 %. This is done with a controller consisting of an eight bit analog to digital converter (ADC) and a Parallax, Inc. Basic Stamp 2 microcontroller (BS2). Figure 2 shows the solar cell signal from the operational amplifier is input to the ADC that has a resolution of 0.39 % The digital signals from the ADC are input to the BS2 which is programmed to control the altitude and bearing DC motors. The BS2 is programed in PBASIC via a PC serial port. PBASIC instructions are executed by BS2 at a rate of over 10,000 per second. There are 16K of EEPROM space in 8 blocks of 2K Bytes each in BS2 for downloading up to 8 different PBASIC programs.

The suntracker was designed to be mounted on top of the payload and suspended about 50 feet below the balloon. It was expected that there would be instabilities in the motion of the balloon as it ascended. These instabilities will result in the instrument package rotating and oscillating like a pendulum. Some of the data available from balloon flights carried out by other groups show periods of rotation of the order of one revolution per minute. The period of oscillation for the pendulum for our system has been calculated to be about eight seconds. The design criterion for the suntracker system is that it be able to lock on an AM0 light source in about 10 seconds and track it with a response time of the order of one second. The pre-programmed minimum short-circuit current, PBASIC program and collimator dimensions were selected to enable the suntracker to discern the sun from light reflected from the balloon, earth, moon and clouds.

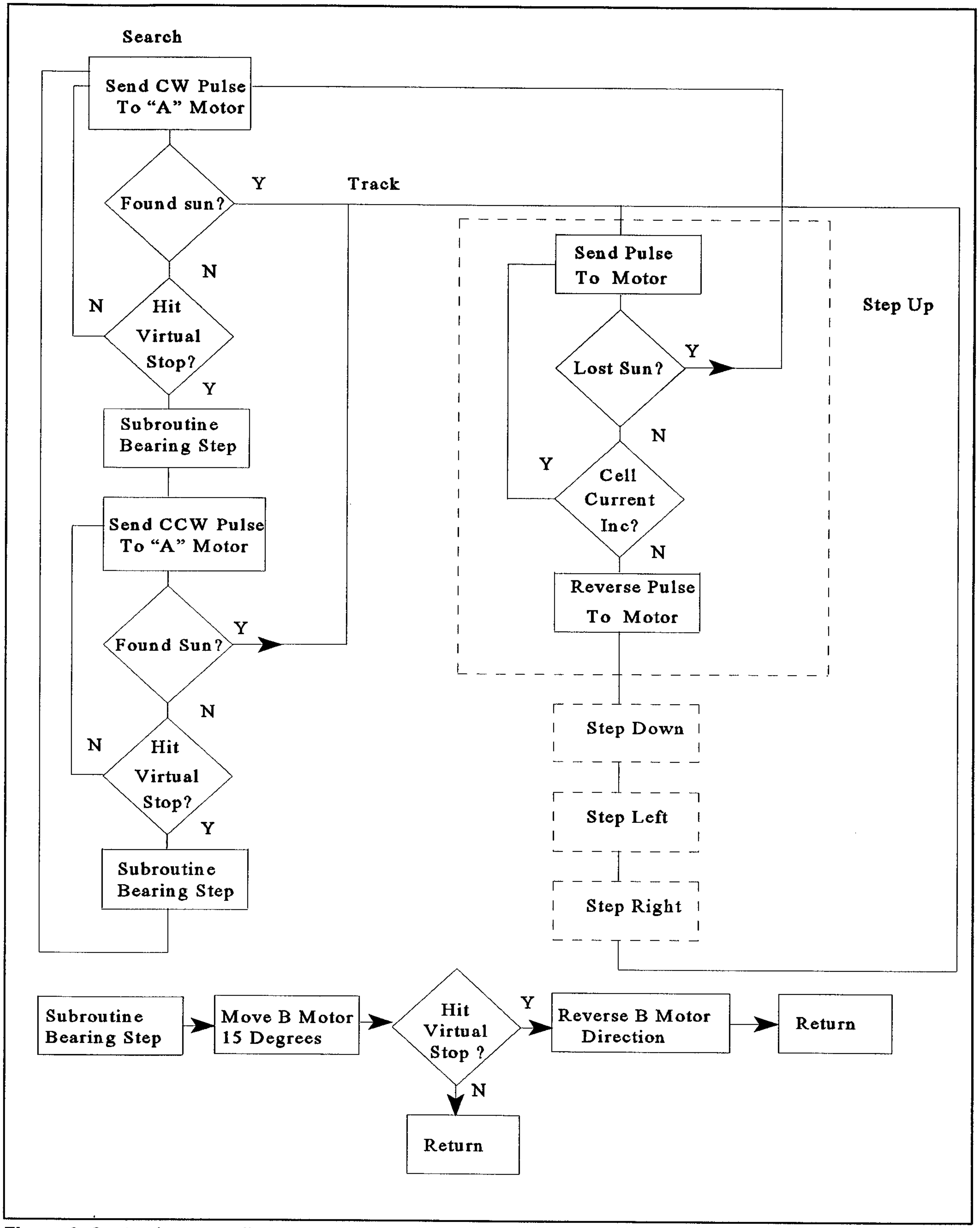

Figure 3. Suntracker controller program flow chart

The program algorithm for the suntracker is illustrated by the flow chart in Figure 3. The sun-tracking task has been divided into two sub-tasks: searching and tracking. In the search mode the collimator altitude is swept from zenith to horizon, the bearing is changed by about 15°, the collimator altitude is swept from horizon to zenith, the bearing is changed again by about 15°, and the process is repeated until the sun is located. The sun is located when the cell short-circuit current exceeds a predetermined threshold. In the tracking mode the controller takes a step up by increasing the altitude of the collimator by a few degrees. If this results in an increase in the cell current, another step up is taken. If the step up does not result in an increase in the cell current, the collimator is returned to its starting position, and a step down is taken. As long as a step produces an increase in the cell current, the step is repeated; when a step does not result in a cell current increase, the step is undone, and a step in the next direction is taken. The step order is up, down, left and right. If the cell current drops below a second predetermined threshold with any step, the controller has lost the sun, and the controller reverts to search mode. The virtual stops are produced by the controller continuously monitoring the pulses generated by the motor shaft encoders and calculating the altitude and bearing angles. The controller changes direction whenever an angle is equal to one of the range limits, i.e., 0° and 90° for the altitude angle and 0° and 360° for the bearing angle.

PAYLOAD DESCRIPTION

The payload included the suntracker, video system, GPS receiver, battery pack, beacon transmitter and antennas. The video system was included in the payload in order to monitor the operation of the suntracker and determine the stability of the payload during the flight. An ATV Research model BJ-3650WX color camera provided live video that was downlinked using a 1 watt UHF TV transmitter connected to an omnidirectional Little Wheel antenna manufactured by Olde Antenna Labs. A Motorola VP Oncore GPS receiver was used to determine longitude, latitude, heading, altitude and speed data. The GPS data were overlaid directly onto the live video with an Intuitive Circuits OSD-GPS video overlay circuit board. The electronics in the payload were powered by a battery pack that included 5 SAFT LX 3457 lithium D-cells with a 15 VDC output and 7.5 Ah capability. Lithium cells were used because they maintain high efficiencies in the -60 °C temperatures encountered in the upper atmosphere. The batteries have the capacity to supply power to the payload for a minimum of 6 hours. The beacon was a separate package with a transmitter and battery pack that was placed below the main package; it added redundancy to facilitate recovery of the payload in the event the main systems failed.

The payload, except for the collimator, solar cell, thermistor, motors and beacon, was encased in a 1.0" thick Styrofoam box to insulate the electronics from the low temperature environment during flight. The box was a rectangular parallelepiped with length=15", width=8" and height=20". The aluminum rod that supported the suntracker motors and collimator protruded through the top surface of the box. The video camera was mounted on top of the package and pointed at the suntracker. The weight of the payload weight was 5.5 pounds. The payload was attached to a Totex model TA-1000 latex meteorological balloon with a train that included three 0.020" Vectran shrouds and a four-foot diameter parachute.

The suntracker was flown without prior approval from any governmental entities. Payloads under 6 pounds may be flown by meeting the Federal Aviation Administration (FAA) requirement to file a verbal Notice to Airmen a few days in advance of the flight. Heavier payloads require FAA waivers and subsequent approval cycles which could take weeks of advance planning. UHF, VHF and HF amateur frequency bands were used for downlinking video, suntracker data and beacon signals. Since two of the authors (WLB and JRW) hold amateur radio licenses, prior approval of the Federal Communications Commission was not required.

FLIGHT RESULTS

There were 20 knot and higher gusting surface winds on the day of the launch. It was anticipated that the payload could be damaged during the launch due to the resulting relatively high horizontal balloon velocity. The balloon was inflated with helium to lift 13 pounds, considerably more lift than required for a 5.5 pound payload, in order to minimize the risk of damaging the payload. The 13 pounds lift resulted in a higher ascent rate at the cost of achieving the desired altitude of 110,000 feet. Signals were successfully received from the UHF, VHF and HF transmitters until just before launch. Minutes before launch the VHF signals ceased to be transmitted by the package. Because of the several delays that had already occurred, and the fact that the sun was moving to a lower altitude, it was decided to proceed with the launch. Liftoff occurred at 2:27 p.m. EDT on a farm located five miles southeast of Findlay, Ohio and the balloon ascended at a rate of about 1,300 feet/minute. The downlinked video signals from the UHF transmitter were used successfully to track the balloon throughout the flight. The video showed the payload was highly unstable. The suntracker operated throughout the ascent and locked on the sun only occasionally because of the unstable motion of the payload. The balloon burst at an altitude of 87,000 feet and the package began the descent. At about 65,000 feet, as observed on the video, the collimator became entangled in the shroud lines and was pulled off the shaft of the altitude motor. The collimator dangled from the electrical wires during the descent. The wires subsequently broke and the collimator dropped from the payload.

Chase vehicles equipped with notebook PC's, direction finding equipment and video receivers were used in the recovery of the payload. The video receivers were used to receive and display GPS data that was input to the PC's. The PC's ran mapping software that displayed the location of the package on local maps. The payload parachuted into a corn field just northeast of Marion, Ohio 40 miles southeast from the launch site. The payload was retrieved some 15 minutes after landing with the aid of handheld direction finders; it was located about 150 feet from a paved road. The suntracker motors and video system were still operating. Aside from the fact that the suntracker collimator and solar cell were lost during descent, the payload was in excellent condition. Inspection of the suntracker showed that the collimator collet was missing from the shaft of the altitude motor. The collet probably deformed and came free of the motor shaft as a result of the forces on the collimator during entanglement in the shrouds lines.

Conclusions

The suntracker operated successfully as it ascended to 87,000 feet in the low temperature environment. It did not continuously track the sun throughout the ascent. The instability of the payload resulted in the suntracker system response time being too slow to track the sun continuously. If ground winds had been lighter the balloon could have been flown with less lift resulting in a lower ascent rate. The lower ascent rate would have resulted in a more stable payload with less horizontal spin and vertical oscillation. A more stable payload would have placed less demands on the suntracker system and it would have spent a larger fraction of the flight tracking the sun. Additionally, the payload would most likely have achieved an altitude in excess of 110,000 feet before balloon burst. Future efforts will be directed at designing an aerodynamically more stable payload; improving the reliability of the electronics; decreasing the response time of the suntracker system; and increasing the mechanical integrity of the suntracker.

REFERENCE

1. David N. Keener, Dean C. Marvin, David J. Brinker, Henry B. Curtis and P. Michael Price, Proceedings of the Twenty Sixth IEEE Photovoltaic Specialists Conference, 1997, page 787.