

## **REPORT ON PROJECT TO CHARACTERIZE MULTI-JUNCTION SOLAR CELLS IN THE STRATOSPHERE USING LOW-COST BALLOON AND COMMUNICATION TECHNOLOGIES<sup>1</sup>**

Ali Mirza, David Sant and James R. Woodyard, Wayne State University, Detroit, Michigan 48202  
Richard R. Johnston, Lawrence Technological University, Southfield, Michigan 48075  
William J. Brown, High Altitude Research Corporation, Huntsville, Alabama 35758

### **ABSTRACT**

Balloon, control and communication technologies are under development in our laboratory for testing multi-junction solar cells in the stratosphere to achieve near AM0 conditions. One flight, Suntracker I, has been carried out reported earlier. We report on our efforts in preparation for a second flight, Suntracker II, that was aborted due to hardware problems. The package for Suntracker I system has been modified to include separate electronics and battery packs for the 70 centimeter and 2 meter systems. The collimator control system and motor gearboxes have been redesigned to address problems with the virtual stops and backlash. Surface mount technology on a printed circuit board was used in place of the through-hole prototype circuit in efforts to reduce weight and size, and improve reliability. A mobile base station has been constructed that includes a 35' tower with a two axis rotator and multi-element yagi antennas. Modifications in Suntracker I and the factors that lead to aborting Suntracker II are discussed.

### **INTRODUCTION**

The objective of this program is to investigate and employ current balloon, control and communication technologies for testing multi-junction solar cells in the stratosphere where near AM0 conditions exist. One flight, Suntracker I, has been carried out and reported earlier [1]. We report on our efforts in preparation for a second flight, Suntracker II, that was aborted due to hardware problems. Since the Suntracker I flight our efforts have been directed at developing separate electronics and battery packs for the 70 centimeter and 2 meter systems; addressing problems with virtual stops and motor-gearbox backlash; using surface mount technology in place of a through-hole circuit; and constructing a mobile base station that includes a 35' tower with a two axis rotator and multi-element yagi antennas.

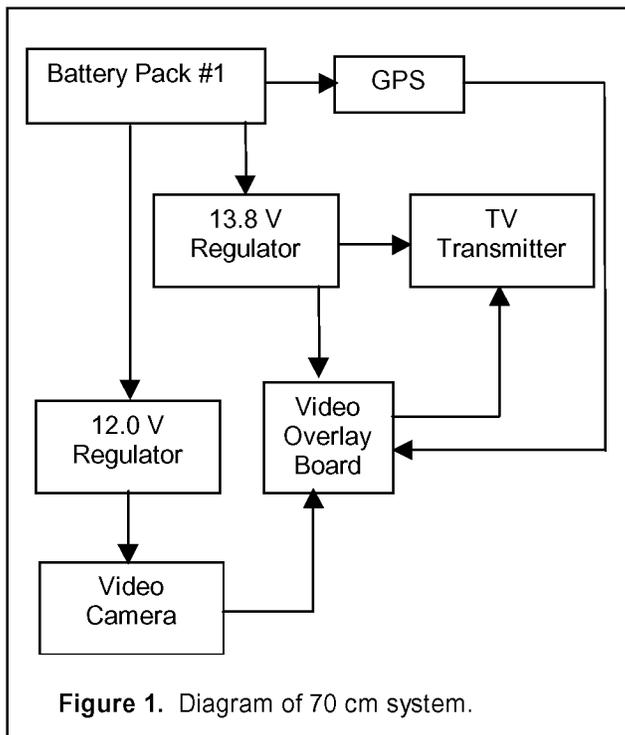
### **PAYLOAD DESCRIPTION**

The payload includes a suntracker, GPS receivers, transmitters, batteries, and a video camera. The suntracker is designed to point a collimator and solar cell at the sun as a balloon ascends and downlink data containing the cell short-circuit current, cell temperature, electronics module temperature, video and GPS data. It employs two motors and a collimator. Each motor assembly has a motor, gearbox and encoder. The motor assemblies are used to maintain the altitude and bearing angles of the collimator between 0° and 180°. 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" [1]. The dimensions of the collimator were selected to prevent light scattered from the balloon, earth, moon or clouds arriving at the solar cell. The video camera is mounted on top of the package and pointed at the suntracker to observe the operation of the suntracker as it ascends through low temperatures to the stratosphere. The payload is attached to a parachute and a latex meteorological balloon. The weight of the payload is about five pounds.

---

<sup>1</sup> This work was supported under NASA Grant NAG 3-2180.

## 70 CM AND 2 METER COMMUNICATION SYSTEMS



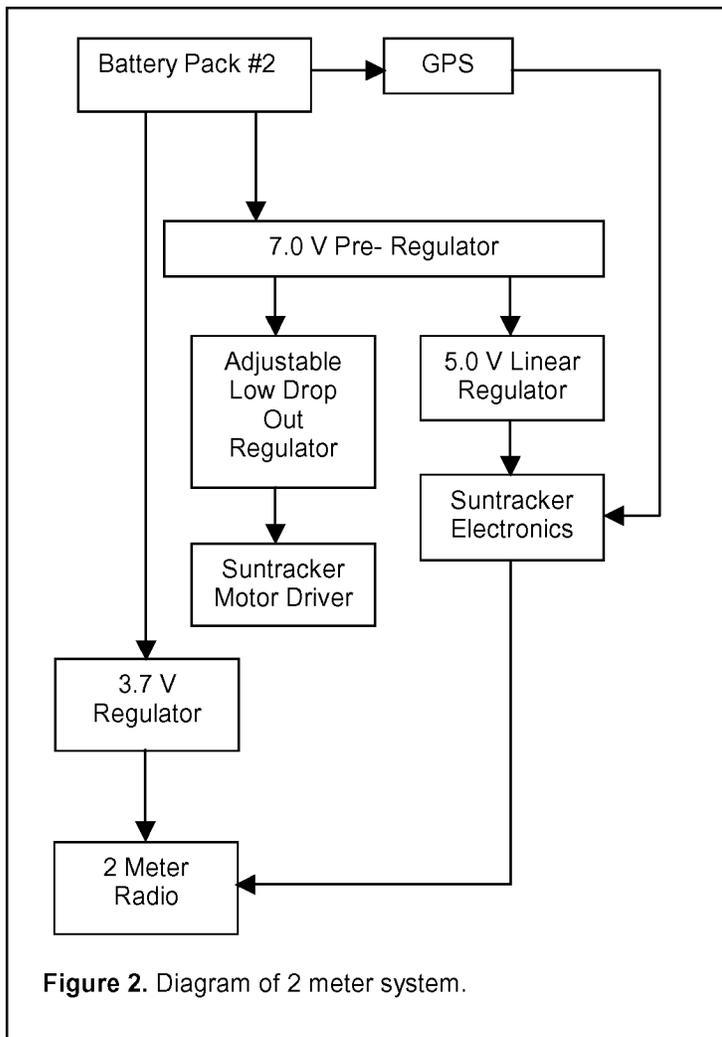
The suntracker system is designed to downlink data with two transmitters operating on the 70 cm and 2 meter bands at frequencies of 439.25 and 144.10 MHz, respectively. Cost considerations result in a design criterion for the Suntracker that emphasizes the use of commercially available devices wherever possible. The devices selected for the system operate at different voltages thereby requiring six voltage regulators. Suntracker I employed a single battery pack and linear regulators. A large fraction of the power was dissipated as heat because the device voltage requirements range between 3.7 and 13.8 V. Switching regulators were employed for Suntracker II in an effort to improve the efficiency of the regulators. Separate communication systems were designed for each frequency in order to maximize the probability that position data be available throughout the flight in the event of a system failure. Each

system has its own transmitter, GPS receiver, battery pack and supporting electronics.

The battery packs consist of four Saft LHS-14 lithium batteries. Each battery when operated at room temperature has an open-circuit voltage of 3.67 V and produces 14.7 V for a four-battery pack under no-load conditions. The terminal voltage of the battery packs under the load for each of the systems is about 13.2 V or 3.3 per cell. While the energy data sheet for the LHS-14 battery shows some energy remains down to a terminal voltage of 2.0 V, there is relatively little energy left once the terminal voltage drops below 2.9 V. Hence, voltage regulators must be employed to both boost and buck the battery output voltage for the devices used in the Suntracker.

Additionally, the power delivery systems must be designed to maintain the various voltages as the battery packs discharge from 13.2 to 11.6 V. This design requirement led us to consider switching power supplies. Since our future plans include powering the Suntracker with flexible ultra-light solar modules, it was decided to use available switching power supplies to determine their characteristics at low temperatures as well as their electromagnetic compatibility with the control systems and transmitters.

The 70 cm electronics and battery pack are shown in Figure 1. The system contains battery pack #1 that directly powers a GPS receiver and two voltage regulators; one is 12.0 V and the other 13.8 V. The 12.0 V regulator is an Astrodyne model MKCO3-12S12, a fully integrated and shielded DC/DC converter, has an efficiency of 80% and powers the video camera. The 13.8 V regulator is a National Semiconductor LM2585 based simple switcher that powers the 1.0 W TV transmitter and video overlay board. The GPS receiver output contains longitude, latitude, speed, altitude and direction data. The data are overlaid on the down-linked video camera image by the video overlay board.



**Figure 2.** Diagram of 2 meter system.

The 2 meter system is shown in Figure 2. It contains battery pack #2 that directly powers a GPS receiver, and 3.7 V and 7.0 V regulators. The regulators are Power Trends model PT6101 integrated switching regulators that are programmable and rated at an efficiency of 90%. The 3.7 V regulator powers a 2 meter radio rated at 300 mW. The 7.0 V regulator serves as a pre-regulator for two other linear regulators that power the suntracker motors and electronics. The adjustable low drop-out regulator permits adjustment of the voltage to the altitude and bearing motors on the suntracker collimator; the voltage adjustment and control algorithm are used to select a slew rate for meeting the tracking requirements. The 5.0 V linear regulator provides power to the suntracker electronics that includes the MIM module, Basic Stamp 2p (BS2p) and PIC 16F84 micro-controllers, and associated electronics. Figure 2 shows the output of the GPS receiver is input to the suntracker electronics that in turn inserts

it in the encoded data stream which is output to the 2 meter transmitter.

### SUNTRACKER CONTROL SYSTEM

Video downlinked during the Suntracker I flight showed that the collimator locked on the sun but was not able to track it. It was suspected that the inability of the system to track the sun during the flight was due to instability in the package because of the relatively high ascent rate of the balloon. Subsequent laboratory testing of the retrieved system suggested that backlash in the motor gearboxes and the loss of motor encoder pulses could also contribute to the inability of the system to track the sun.

Suntracker I employed MicroMo model 1016 DC motors measuring 10 mm in diameter and 16 mm in length with encoders and 256:1 gearboxes. The motor vendor was not able to provide zero backlash gearboxes in time for the scheduled Suntracker II flight. The motor assemblies were replaced with MicroMo model 1524 motors that measure 15 mm in diameter and 24 mm in length, encoders and 262:1 zero backlash gearboxes. The model 1524 motors provide higher torques at the cost of an increase in payload weight. Testing of the system showed that the BS2sx microcontroller used during Suntracker I flight was not fast enough to maintain both the virtual stops and control of the collimator. Virtual stops refer to the ability of the system to limit the collimator altitude and bearing angles to a range of 0° or 180° through the use of software. It is

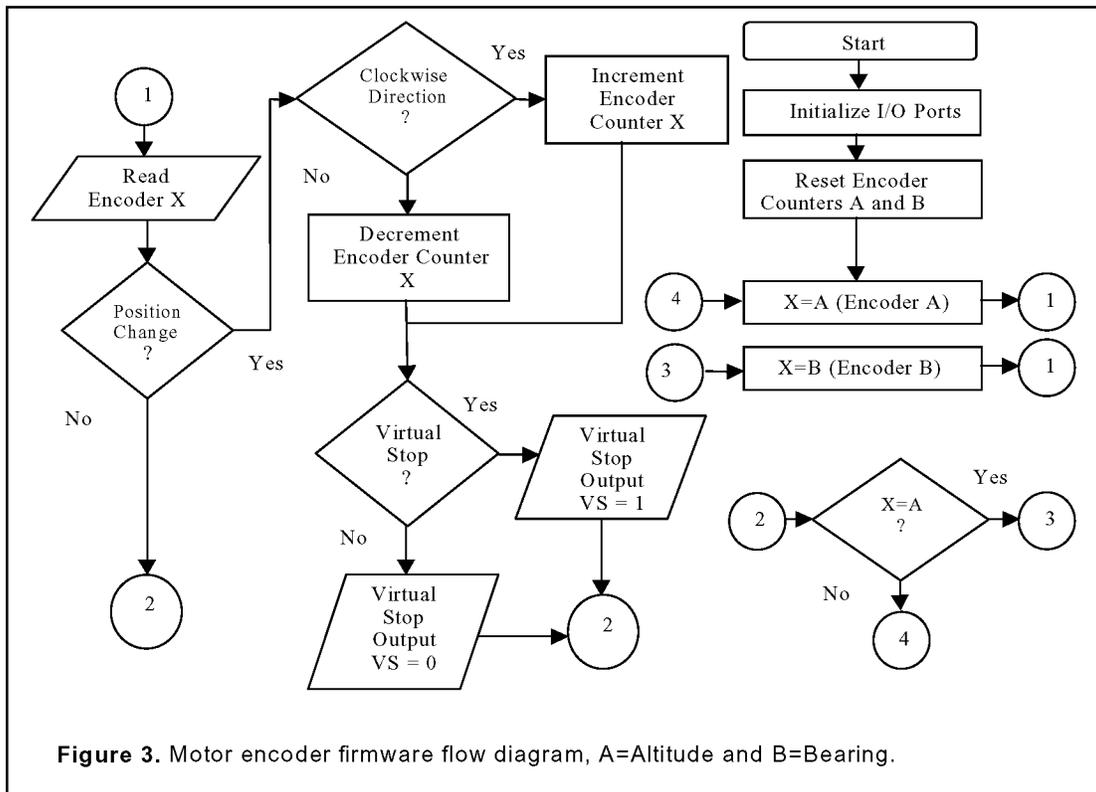
necessary to count all encoder pulses in order to maintain the virtual stops during a two-hour flight. In order to improve the counting of encoder pulses, the microcontroller was upgraded to the model BS2p. Subsequent testing showed the altitude and bearing angles still exceeded the 0° to 180° range and all the encoder pulses were not counted.

The electronics used in the Suntracker I flight were redesigned in an effort to count all the encoder pulses and effectively manage the virtual stops. A Microchip™ PIC 16F84 microcontroller was included in one of the circuits and dedicated to the task of counting encoder pulses. The PIC 16F84 microcontroller was selected because of its low support component count, small size, availability, speed, and development tools. The clock of the microcontroller utilizes an 8 MHz ceramic resonator. RAM memory in the microcontroller was used for two 16 bit encoder counters. Each encoder utilizes solid-state hall sensors with a low inertia magnetic disk to provide two output channels with 16 pulses per revolution that are in quadrature. Sixteen counts per revolution with a 262:1 gear reduction results in 2096 pulses per 180° of the collimator. The four encoder outputs are TTL compatible and connected directly to the PIC 16F84 microcontroller. The microcontroller monitors the output from the two encoders and counts all the encoder pulses. An output line connected to the BS2p microcontroller shows the status of the virtual stops.

The algorithm for the 16F84 microcontroller is shown in Figure 3. The collimator altitude and bearing angles must be set to 90°, their initial positions, before power is applied. The right side of Figure 3 shows the ports are initialized upon power up. The lines from the encoders to the 16F84 microcontroller are set as inputs. The output line from the 16F84 microcontroller to the BS2p microcontroller, VS, is set as an output. All other unused peripheral features of the 16F84 microcontroller are disabled to keep power consumption to a minimum. The two counters are initialized by setting the readings to 1048, the reading corresponding to altitude and bearing angles of 90°. The firmware in the 16F84 microcontroller first selects the altitude encoder, denoted by X=A in the flowchart. At point 1 in the algorithm polling of the encoder is carried out to determine if there has been a position change. Since quadrature encoding is utilized, both output lines of encoder A are read and compared with their previous values. If the values are the same, no position change has occurred and the firmware proceeds to check point 2 that alternately selects the second encoder, X=B, for polling. If a position change is detected then a test is performed to determine if the encoder has rotated in the clockwise direction. The A encoder counter is incremented if a clockwise direction was detected or decremented if a counterclockwise direction was detected. The encoder counter is then checked to see if it has reached the virtual stop at 0° or 180° corresponding to counter settings of 0 or 2096, respectively. If the counter setting is less than 0° or greater than 180°, VS is set to logic 1 otherwise it is set to logic 0. The firmware proceeds to check point 2 and sets X=B and proceeds to poll encoder B. The firmware alternately polls encoders A and B and manages the virtual stops until the power is turned off. The firmware was tested using an in-circuit emulator with timing analysis features. It was determined that the firmware can operate reliably at the rated maximum motor speeds. The modified circuit was tested in the laboratory. The altitude and bearing angles operated in the 0° to 180° range and all the encoder pulses were counted for periods of time in excess of two hours, the approximate time of a flight to 100,000 feet.

## CONTROLLER BOARD DESCRIPTION

The controller board used in the Suntracker I flight employed a through-hole prototype circuit. In an effort to improve reliability and as well as reduce the weight and area of the controller board for the Suntracker II flight, it was decided to use surface mount technology on a printed circuit board. The new controller board is composed of a 3" x 3.125" printed circuit board populated mostly with surface mount components. The printed circuit board area is about 11 in<sup>2</sup> smaller than the through-hole prototype circuit. It weighs approximately 1.5 oz., about 3.0 oz. lighter than the prototype board.

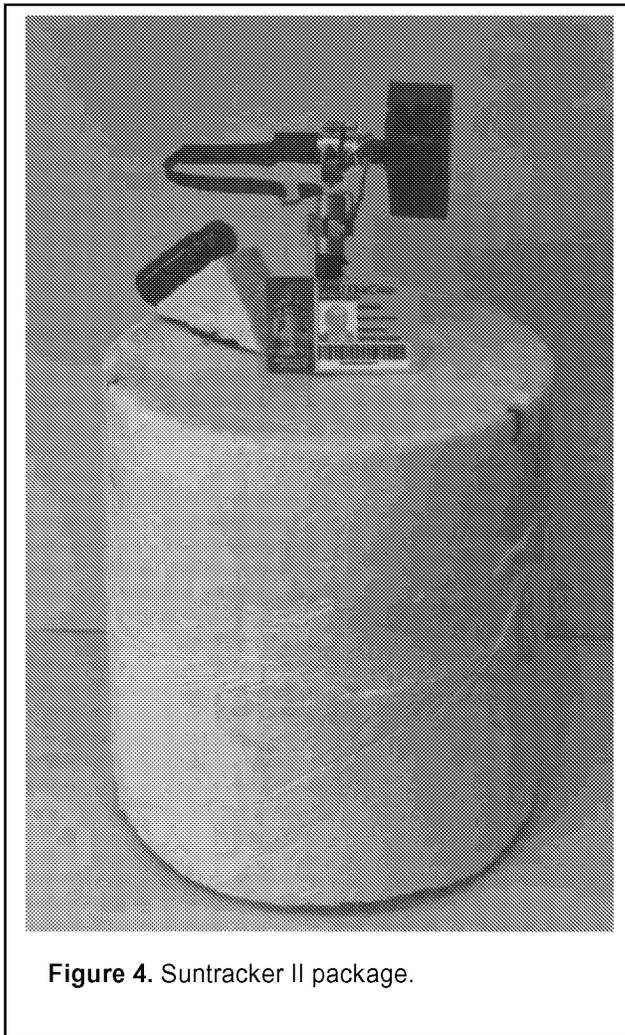


The cell current and temperature, and the internal package temperature, are measured with devices that are mounted on the controller board. There are devices mounted on the controller board that position the collimator and convert measurements to an AX.25 protocol for downlinking using a 2 meter transmitter [1]. The two linear power supplies discussed in the preceding section are mounted on the board. The low drop-out linear supply powers the BS2p microcontroller, A/D converter, operational amplifiers, motor driver and MIM module, all of which are mounted on the controller board. The low-drop out adjustable supply is used to vary the voltage to the motor driver in order to adjust the speed of the altitude and bearing motors. The motor driver is used to control direction and on/off states of both motors. Each motor has two control lines. By utilizing these control lines a motor can be energized in a forward or reverse direction. The driver also allows the motor leads to be connected together via an h-bridge to support dynamic braking. A built-in thermal shutdown is included in the motor driver to prevent damage to the circuit under an overload condition. Inputs to the motor driver are TTL compatible thereby simplifying the interface to the BS2p microcontroller.

Three operational amplifiers on the controller board are utilized for signal conditioning. One is used to linearize the output from a thermistor mounted on the back of the solar cell holder; the signal is used to determine the temperature of the solar cell. A second operational amplifier is used to amplify the voltage across a high precision resistor in series with the solar cell; it produces an output voltage that is proportional to the cell current. The third operational amplifier linearizes the output from a second thermistor that is used to determine the internal temperature of the suntracker package. The conditioned analog signals from the two temperature sensors and cell current are routed to the analog input lines of the MIM module. The MIM module is an ARPS compatible packet-radio telemetry unit that converts the three analog signals to 8-bit numbers via an internal A/D converter (ADC). The MIM module also has a serial port that is available at a connector mounted on the board; the port is used to receive data from a GPS receiver and configure the MIM module. Output timing of the various signals, user call sign, and message

formatting are some of the parameters that can be configured through the serial port. The MIM module packetizes the A/D data, GPS coordinates and user call sign, and sends the packets via a connector on the controller board to a 2 meter transmitter in an AX.25 protocol at 1200 baud.

The voltage from the operational amplifier that senses the solar cell current is also used as an input to the BS2p microcontroller. The analog voltage is converted to a digital form using an ADC configured in a free running mode. The ADC, once initiated, converts the output voltage from the operational amplifier to an 8-bit digital signal that is input to the BS2p microcontroller. The error rate of the ADC over the operating temperature range of 0°C to 70°C is +/- ½ bit. The BS2p microcontroller outputs logic signals to the motor driver while monitoring the VS line from the PIC 16F84 microcontroller. The algorithm used in the Suntracker I flight for programming the BS2p microcontroller has been previously described [1]. The algorithm was modified for the Suntracker II flight. The algorithm for Suntracker I employed searching and tracking modes. The tracking modes kept the motor speed constant while checking the solar cell current. The algorithm for Suntracker II decreased the motor speed as the collimator approached the position corresponding to the maximum solar cell current. The program for Suntracker II is faster and requires less of the BS2p microcontroller memory.



**Figure 4.** Suntracker II package.

#### **PACKAGE, EQUIPMENT AND BASE STATION**

The package for Suntracker II is shown in Figure 4. It measures about 10" in diameter and 10" high. It has a wall thickness of about one inch and weighs about five pounds including electronics, batteries, antennas etc. The package was fabricated using a two-part urethane pour foam and molds. The collimator and motors are located on top and the electronics inside the package. The video camera can be seen on the left-top side of the package. The antennas for the transmitters are not shown in Figure 4. The antenna for the 70 cm transmitter is mounted below the package and the antenna for the 2 meter transmitter is located inside the package. During flights the package is suspended 60 feet below a latex meteorological balloon that is pressurized with helium. The train from the balloon to the package includes a swivel, parachute attached to a hoop and three 0.010" diameter shrouds tied to the hoop and package. Two of the openings for attaching the shrouds can be seen on the top of the package.

One of the objectives for the Suntracker II flight was to design and build a mobile system with all the equipment needed for a flight, including

the base station, antennas, helium gas tanks, balloons and balloon inflation hardware. Figure 5 shows the system that was developed for the Suntracker II flight. The equipment for the flight was

transported with a trailer and van. A trailer was used to transport the 18'x3.3'x4" antenna box and four 8' tower sections. The trailer was equipped with a winch to raise the assembled tower, two-axis rotator and antennas. The yagi antennas measured about 17.5' in length; the 70 cm and 2 meter antennas had 25 and 12 elements, respectively. The gain of the 70 cm antenna is 16.2 and the 2 meter antenna gain is 12.6 dBd. The antennas were assembled prior to transporting them because of the task of assembling them is tedious and time consuming. The antenna box is shown in Figure 5 and is located on the left side of the trailer. The figure also shows the assembled tower supporting the rotator, antennas and cables. The antennas are about 35' above ground level. The 70 cm antenna is mounted in the horizontally polarized position while the 2 meter antenna is mounted in the vertically polarized position. The two-axis rotator enables pointing the antennas at the package during flight in order to take advantage of the directional gain of the yagi antennas. The remote-control box for the rotator and the 2 meter and 70 cm receivers are located in the van. A 12 V deep cycle marine battery is used to power the base-station equipment. The data downlinked on the 70 cm system are viewed and saved with a 9" video/VCR unit. The data downlinked on the 2 meter system are viewed and saved using a notebook computer. Mapping software is used to overlay the position of the balloon on a map to facilitate recovery of the package.

One of the design criteria for the mobile system is to minimize assembly and setup time at the launch site. Clevis pins were used in the assembly of the tower and snaps were employed for supporting the antenna and rotator remote-control cables. The antenna box can be supported on plastic horses and the top surface used for assembling the train and inflating the balloon.



**Figure 5.** Suntracker II base station.

## RESULTS

The Suntracker II flight was scheduled for September 2, 2001 from a farm in Findlay, Ohio. Arrival time at the site was 9:00 a.m. and launch time scheduled for 1:00 p.m. Balloon tracking software was used to predict that the landing site of the balloon would be some 40 miles southwest of the launch site. While all the components of the systems were tested in the laboratory, there was not enough time to carry out the final integration and testing of the systems in the laboratory prior to the day of the launch. The base station was set up and tested at the launch site. All indications were that it performed satisfactorily. The 70 cm and 2 meter systems were integrated into the package on the day of the launch. Testing showed that the power output level of the 70 cm system was inadequate to insure reception of the video signal throughout the flight. We did not have test instrumentation on site to measure the output power, however, experienced amateur radio operators reported the output power level to be

inadequate. Testing of the 2 meter system showed that no GPS data were in the data stream. Unsuccessful attempts were made to determine the sources of the problems. After several hours of fruitless efforts the Suntracker II flight was aborted.

It took several weeks of laboratory work to determine the basis for the problems that lead to aborting the Suntracker II flight. Test equipment had to be obtained and techniques developed to measure the input power to the antennas as well as the radiated power. It was determined that the problem with the 70 cm system was intermittent and due to a faulty connector on the cable that connected the transmitter to the antenna. The connector operated satisfactorily on the laboratory bench when the cable was straight. Bending the cable, as is necessary when it is connected to the transmitter in the package, shorted the connector pin to the cable shield. The problem with the loss of the GPS data in the 2 meter data stream was traced to reversed wires on the GPS input on the MIM module. It not understood how the wires became reversed since the 2 meter system did work satisfactorily at least at one point during laboratory testing.

### **SUMMARY**

Improvements were made in the Suntracker I system in preparation for the Suntracker II flight. A dedicated microcontroller was included in the electronics to eliminate a virtual stop problem. Zero-backlash gearboxes were installed in order to increase the probability that the suntracker will track the sun. A power distribution system was developed that has a higher efficiency and includes two separate battery packs, one for each of the frequency bands used to downlink data. A printed circuit and surface-mounted devices replaced a through-hole circuit to reduce size and weight and increase robustness. A mobile base station was developed that includes a tower with a two axis rotator and multi-element yagi antennas. One of the design criteria for the mobile system is to minimize assembly and setup time at the launch site. All the equipment was tested in the laboratory. The base station operated satisfactorily at the Suntracker II launch site. Problems developed with both the 70 cm and 2 meter systems when they were integrated into the package on the day of the launch and the Suntracker II flight was aborted.

### **REFERENCE**

1. Investigations to Characterize Multi-Junction Solar Cells in the Stratosphere Using Low-Cost Balloon and Communication technologies, Glenroy A. Bowe, Qianghua Wang, James R. Woodyard, Richard R. Johnston and William J. Brown, Proceedings of 16<sup>th</sup> NASA Space Photovoltaic Research and Technology Conference, August 31-September 2, 1999, NASA Document NASA/CP-2001-210747, page 189.