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ACTS Battery and Solar Array Assembly On-Orbit Measured Performance

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February 2005

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ACTS Battery and Solar Array Assembly On-Orbit Measured Performance

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Summary

The Advanced Communications Technology Satellite (ACTS) is a NASA experimental communications satellite system designed to demonstrate on-orbit Ka-band communications and switching technologies that will be used by NASA and the commercial sector in the 21st century. The ACTS, developed and built by Lockheed Martin Commercial Space Systems (Newtown, PA) for the NASA Glenn Research Center, was launched on September 12, 1993, on the Space Shuttle STS–51 mission and has performed over 10 years of successful experimental operations. The purpose of this report is to describe the ACTS power subsystem, ACTS solar array and battery assemblies located within the power subsystem and document on-orbit measured performance from launch to mission end on April 28, 2004. Solar array and battery performance data is presented in tables and graphs, and respective conclusions are drawn. The total solar array power available to the spacecraft was measured each year on day 266 at 1840 G.m.t., and battery voltage performance measured each year on day 080 and day 266 (day 264 in 1994 and 1995) during peak solar eclipse. At the highest spacecraft power demand, ACTS uses approximately 1113 W of electrical power to operate all six satellite subsystems during the low-burst-rate experiment. After 10 years of on-orbit operation, solar array available output power measured 1508 W normal to the Sun, which represents 395 W of excess margin. The ACTS batteries have successfully supported the ACTS experiment program for over 10 years and operated in excess of 900 charge and discharge cycles through 21 eclipse seasons. Battery longevity can be contributed to several factors: maintaining battery temperature between 0 and 25 °C, maintaining maximum cell divergence or voltage spread between battery pack cells to less than 100 mV, maintaining the depth-of-discharge ratio to less than 50 percent and maintaining the charge-to-discharge ratio between 1.0 and 1.1. NASA considers the 10-year history of ACTS on-orbit solar array and battery performance successful with adequate design margins.

ACTS Background

The Advanced Communications Technology Satellite (ACTS) is a NASA experimental digital satellite communication test bed system that demonstrated on-orbit Ka-band communications and switching technologies NASA and the commercial sector will use in the 21st century. ACTS was launched into geostationary orbit on September 12, 1993, and has accumulated over 10 years of trouble-free operation and has met all program objectives. The original spacecraft hardware design was for 4 years of on-orbit experiment operation, but because of a robust design and successful program advocacy, the experiment demonstrations were extended to mission end on April 28, 2004.

The challenge to all satellite manufacturers is to design and build satellites that will reliably operate in the harsh space environment for many years. During the 10-year ACTS experiments program, spacecraft engineers from Lockheed Martin Commercial Space Systems (Newton, PA) have successfully maintained and operated all ACTS subsystems. ACTS provided a Ka-band transponder testbed from launch until original geostationary experiment demonstrations were concluded at the end of July 1998. The decision to extend the life of the program to inclined orbit was made by NASA because of the excellent performance of the communications payload and the versatility of the spacecraft bus subsystems. In May 2000, ACTS was maneuvered to a parking orbit located at 105° west longitude. In May 2001, the Ohio Consortium for Advanced Communications Technology (OCACT) formally assumed control of ACTS, under the provisions of a Space Act Agreement executed between the NASA Glenn Research Center, the Ohio Board of Regents, and Ohio University (ref. 1). OCACT reimburses NASA for the cost of continuing ACTS operations.

The Ohio University School of Electrical Engineering and Computer Science and J. Warren McClure School of Communication Systems Management assumed the role of Managing Member of OCACT under the provision of the Consortium Agreement (ref. 2). Each OCACT member executes such an agreement with Ohio University, as well as any addenda needed to accommodate any specific needs the member may have.

Introduction

This report concentrates on the successful electrical performance of the solar array and battery assembly from launch to mission end on April 28, 2004, by presenting supporting spacecraft telemetry data in tables and graphs that will be used to analyze, summarize, and draw conclusions. The data presented will illustrate the successful electrical performance and adequate design margins over a 10-year history of on-orbit operations.

To conduct the required ACTS communications experimental operations, six satellite subsystems are used onboard the spacecraft to supply communications and maintain a healthy and stable satellite platform in geosynchronous orbit. The six satellite subsystems are thermal control; attitude control; multibeam communications package; command, ranging and telemetry (CR&T); reaction control; and the power. Only the ACTS power subsystem and the telemetry circuits located within the power subsystem will be reviewed in this report.

The ACTS power subsystem (fig. 1) is a direct-energy-transfer configuration consisting of solar array panels, storage batteries, and power regulation equipment. Primary power is generated by high-efficiency solar cells mounted on deployable panels that are oriented toward the Sun by the solar array drive (SAD). Solar array power is distributed to the six spacecraft subsystem electrical loads and is also used to charge two nickel-cadmium storage battery assemblies located in the power subsystem. The two batteries are name plate rated at 19 Ah (ampere-hour) each for a total of 38 Ah capacity and supply the essential payload and housekeeping energy path through the discharge diodes during solar eclipse periods. However, because battery capacity is insufficient to provide adequate power for experiment operation during eclipse periods, experiment operations were not planned during these periods.

Power Subsystem Assemblies

The ACTS power subsystem (fig. 1) consists of seven major electrical assemblies: (1) two solar array drives (SADs) with redundant motor windings for each SAD as well as primary and redundant array drive electronics (ADE) units to power each SAD, (2) primary and redundant shunt control amplifiers (SCA) and shunt assemblies (SA), (3) primary and redundant charge regulators, (4) primary and redundant discharge diodes assembly, (5) primary and redundant CR&T circuits, (6) four Sun-oriented solar array panels, and (7) two nickel-cadmium storage batteries.

(1) *SAD–ADE Assemblies*: The purpose of the primary and redundant SAD–ADE is to point the solar array towards the Sun during spacecraft operations. The SAD is an incremental stepping motor that rotates the solar array in forward or reverse direction. The incremental stepping motor is coupled to the solar array through a reduction gear and rotates the solar array at either of two speeds in either direction. Two sets of winding provide redundancy for the SAD.

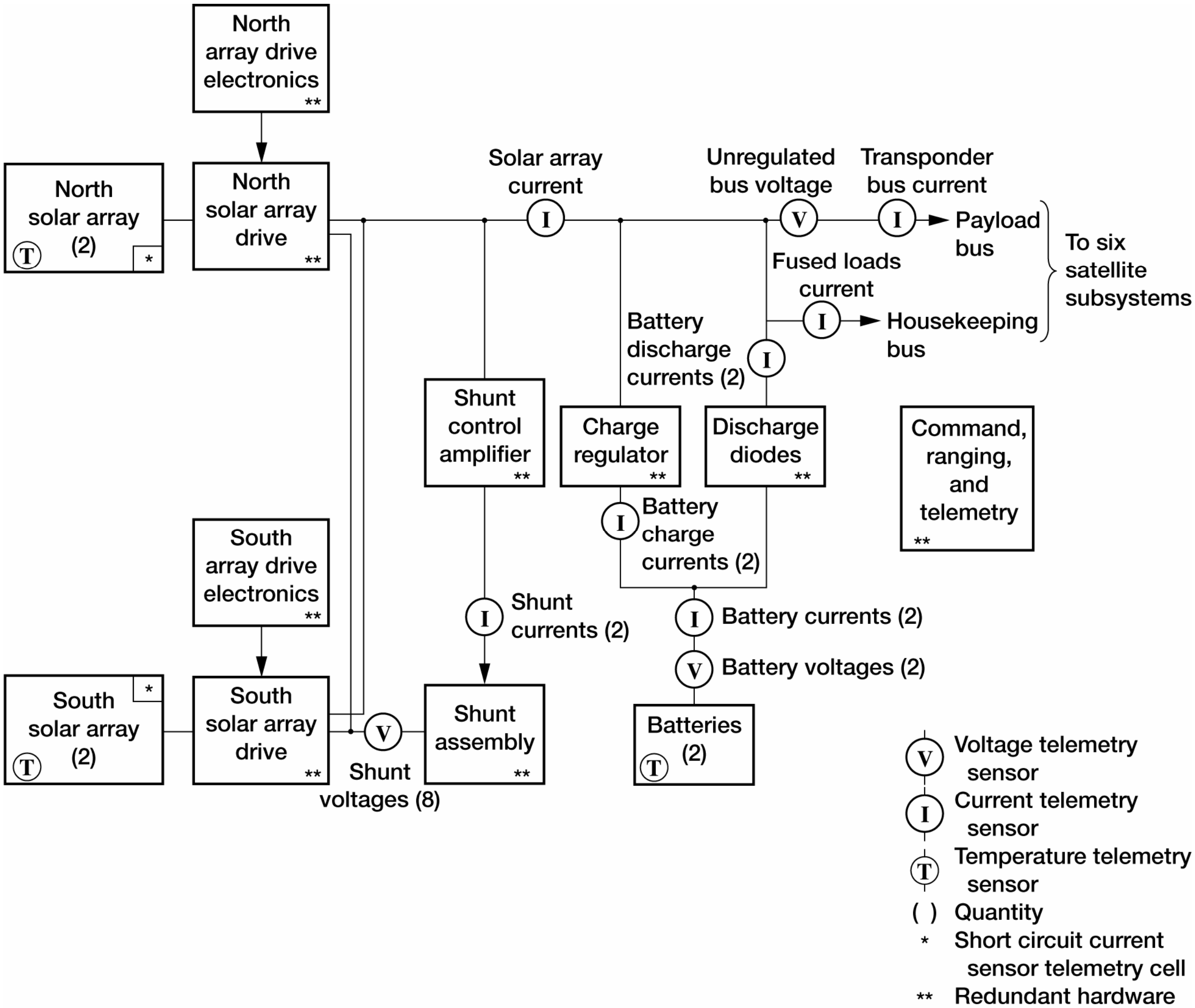

Figure 1.—ACTS power subsystem.

The ADE provides control pulses to the SAD stepping motor to cause the solar array rotation. SAD position information is obtained from a rotating potentiometer.

(2) *SCA and SA*: The purpose of the primary and redundant SCA and SA is to provide regulation of the spacecraft bus voltage when excess solar array power is available. The SA has been designed to handle the full solar array power output capability with a minimum spacecraft load. It is desirable to operate with as little partial shunt current as possible to minimize shunt heat dissipation within the spacecraft. The shunt current in orbit can be adjusted to suit operational requirements by rotating the solar array away from the Sun until the shunt current is reduced.

(3) *Charge Regulator Assembly*: The purpose of the primary and redundant charge regulator is to charge the spacecraft batteries; charge rate in amperes is selectable by ground command. Various charge rates may be commanded from the ground in order to achieve optimum battery charging, temperature, and operating performance.

(4) *Discharge Diodes Assembly*: The purpose of the primary and redundant discharge diode is to provide a discharge energy path to the unregulated bus from the two batteries when the solar array is in eclipse. Each discharge diode has failure detection circuitry that automatically switches to a redundant discharge diode.

(5) *CR&T Assembly*: The purpose of the satellite primary and redundant CR&T is to receive and respond to command and control signals from the ground while the satellite provides state-of-health analog and digital performance signals to ground. Satellite telemetry circuits consisting of analog sensors that measure voltage and current data plus thermal transducers that measure temperature provide the documented data in this report.

(6) *Solar Array Assembly*: The purpose of the ACTS solar array assembly is to provide electrical power to the spacecraft. The ACTS solar array contains four planar solar panels, two on each side of the spacecraft for a total area of 144 ft^2. High-efficiency N-on-P, 2- by 4-cm solar cells are bonded to a 9.0-mil Kevlar face sheet that is bonded to 1.08-in.-thick aluminum honeycomb core panel. The solar cells are electrically connected to each other with custom-cut silver mesh and wire. Solar array electrical performance data was collected during the 10 years of on-orbit experiments and compared with beginning-of-life (BOL) performance data after launch.

(7) *Battery Assembly*: The primary purpose of the ACTS batteries is to provide electrical power to the six satellite electrical subsystems during solar eclipse periods. Because of budget and weight constraints in the late 1980s, ACTS was not designed to support experiment operations through the daily eclipse period and all nonessential circuitry must be turned off during this period. For 277 days out of each year, ACTS is illuminated by the Sun throughout each daily orbit, with the load power requirements supplied entirely by the solar array. During the two eclipse seasons that are 44 days long and centered on spring equinox and autumnal equinox, the spacecraft experiences eclipses each day that range from a few minutes to 70 minutes. During eclipse, all electrical power is supplied by the batteries.

Accuracy of Received Telemetry

The ACTS contractor, Lockheed Martin Commercial Space Systems, performed BOL worst-case telemetry system analysis and documented the accuracy results in DRD 113, ACTS Flight System, CR&T and Data Handling Analysis (1988, General Electric Company, Astro-Space Division, Princeton, NJ, internal document). Analog voltage and current accuracy was calculated to be ±3 percent and temperature sensor accuracy was calculated to be ±6.0 °C BOL. Lockheed Martin did not provide end-of-life worst case telemetry accuracy so the accuracy of the more recent data in this report is unknown.

Solar Array

During the highest spacecraft power demand, ACTS uses approximately 1113 W of electrical power to operate all six satellite subsystems during the low-burst-rate experiment (DRD 422, Telemetry, Command, and Database Handbook. Martin Marietta Astro Space, 1993, internal document). The electrical power generated by the solar arrays and not used by the six satellite subsystems needs to be reduced or shed as excess heat.

Two methods are used to reduce and shed excess solar array electrical power on ACTS. The first method is to dissipate and remove excess power as heat through a bank of shunt resistors located in the shunt assembly. Excess electrical power that is not needed by the spacecraft six satellite subsystems is passed automatically through shunt resistors under control of the shunt control amplifiers and radiated into space as heat. When the unregulated spacecraft bus voltage exceeds 35.3 V, the shunts begin to conduct electrical current from electrical taps located throughout the solar array passing electrical current to ground and clamping the spacecraft bus voltage to a maximum of 35.5 V. The second method used to reduce excess electrical power generated by the solar arrays is to tilt the solar array panels slightly away from the Sun. This reduces the solar energy collected and electrical energy generated. ACTS solar array has been canted or turned approximately 35° away from the Sun during the entire experiments program to help reduce the excess power collected. Not all of the excess power is dissipated in the shunts or reduced by tilting the solar arrays. Approximately 50 W is held in reserve to provide margin for transient loads within the six satellite subsystems while maintaining 35.5 V across the two batteries.

All solar array measurements in this report are recorded on day 266 at 1840 G.m.t. for each year of operation. Day 266 at 1840 G.m.t. was chosen for two reasons. The first reason was to record data from the solar array during the same time of day each year to keep the solar constant energy factor and Sun declination factor constant from year to year. The solar constant energy factor and Sun declination factor change from day to day throughout the year and measuring the solar array on day 266 at 1840 G.m.t. simplifies mathematical calculations. The second reason to record data on day 266 at 1840 G.m.t. is the ACTS solar array were deployed on day 266, 1993, and the solar array output power initial conditions, offset angles, and calibration factors were made and recorded. In addition, at 1840 G.m.t. each day, solar array calibration offset angles are known and calibration adjustments can be easily made. Solar array surface temperatures remain constant at 41.5±2.5 °C when measured at 1840 G.m.t. on day 266 each year. Stable and repeatable solar array surface temperatures contribute to the accuracy and repeatability of the measured data.

Measured Performance and Available Output Power

Changes in the solar array performance occurring during the first 10 days in orbit can be attributed primarily to ultraviolet degradation of the cover glass adhesive. Changes after that are attributed to charged-particle radiation degradation in the solar cell itself. Calculation of solar array degradation due to charged particle damage cannot be made directly in the ACTS spacecraft power subsystem because of the partial shunt configuration and solar array offset angle. Two methods are used to approximate the solar array degradation due to charged particle damage on the ACTS spacecraft.

The first method used to approximate ACTS solar array degradation is to measure and multiply the unregulated bus voltage (*UBV*) telemetry by the solar array current telemetry (*SAC*) then add the product of the shunt current (*ShC*) telemetry and the sum of the eight shunt assembly telemetry voltages (*ShV*) to obtain total solar array electrical power (*SAP*) generated:

$$SAP = (UBV)(SAC) + (ShC)(ShV_1 + ShV_2 + \ldots + ShV_8)$$

The solar array panels have been rotated or canted away from the Sun during the entire mission to reduce the excess solar array energy collected. In order to approximate the total solar array power available to the spacecraft in watts, the total measured power in watts generated by the solar array is divided by the cosine of the angle at which the array has been canted away from the Sun. This value represents the approximate ACTS solar array output power available in watts when the array is pointed perpendicular to, or facing, the Sun.

Figure 2 illustrates and plots the approximate ACTS solar array output power available in watts measured normal to the Sun at 1840 G.m.t. on day 266 each year from 1993 to 2003. During the highest spacecraft power demand, ACTS used approximately 1113 W of electrical power to operate all six-satellite subsystems during the low-burst-rate experiment (Telemetry, Command, and Database Handbook. DRD 422, Martin Marietta Astro Space, 1993.). Solar array failure is defined as solar array output power less than 1113 W available to operate ACTS on-orbit experiments, including the six ACTS subsystems. Approximate total solar array power available to the spacecraft measured 1833 W normal to the Sun BOL on day 266, year 1993. After 10 years of on-orbit operation, the approximate solar array output power available normal to the Sun measured 1508 W in the year 2003.

The second method used to approximate total solar array degradation is to measure the approximate current in milliamperes across a solar array short circuit current sensor telemetry cell mounted on each of the outboard solar array panels (see fig. 1). Each short circuit current sensor telemetry cell has a parallel 1.0 Ω resistor, which measures the approximate cell short circuit current in milliamperes. These current

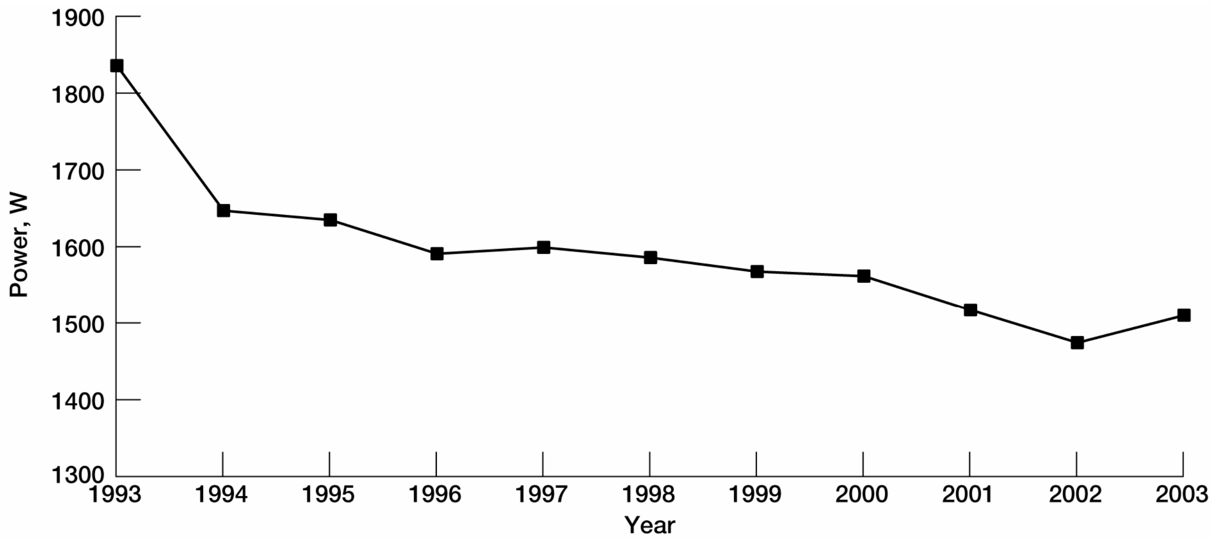

Figure 2.—Approximate ACTS solar array measured output available to spacecraft measured normal to the Sun each year on day 266 at 1840 G.m.t. Approximate solar array temperature measured, 41±2.5 °C.

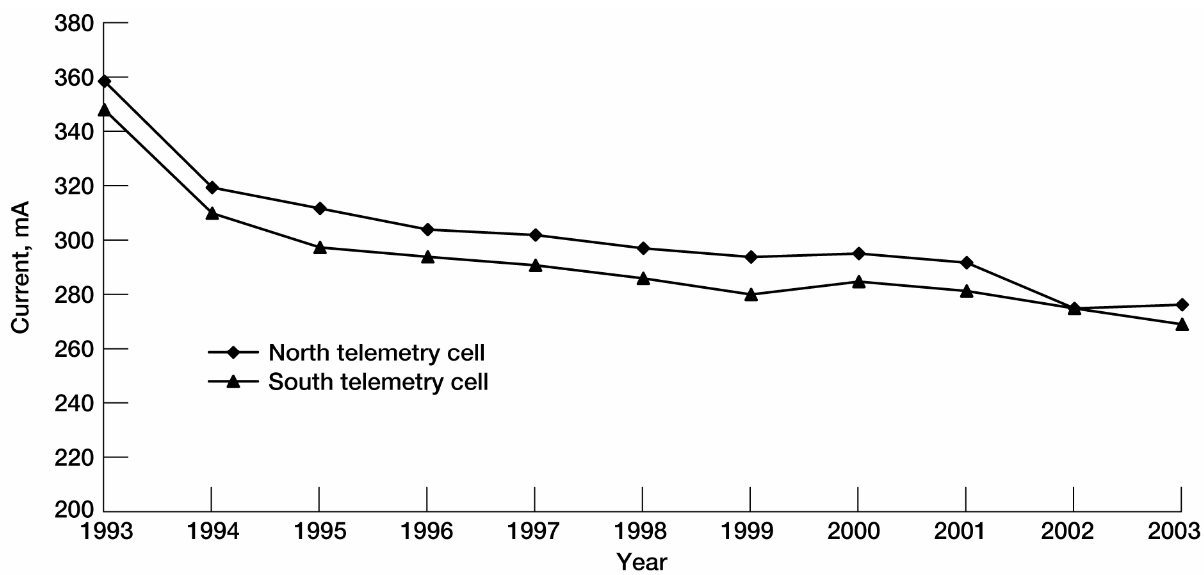

Figure 3.—Approximate ACTS solar array north and south short circuit current sensor telemetry cells measured normal to the Sun each year on day 266 at 1840 G.m.t. Approximate solar array temperature measured, 41±2.5 °C.

sensor telemetry cells approximate the change in array illumination, degradation, and performance and do not contribute to electrical power generation for the spacecraft. The approximate current in milliamperes is measured in each short circuit current sensor telemetry cell and divided by the cosine of the angle at which the solar array has been canted away from the Sun. This value represents the approximate ACTS solar array short circuit current from the sensor telemetry cell measured normal to the Sun at 1840 G.m.t. on day 266 each year from 1993 to 2003 as illustrated in figure 3.

Approximate short circuit current sensor telemetry cell BOL measured 357 mA on the north sensor and 347 mA on the south sensor on day 266 at 1840 G.m.t. in year 1993. After 10 years of on-orbit operation, the solar array short circuit current sensor telemetry cells measured 275 mA of telemetry current on the north cell and 268 mA of telemetry current on the south cell on day 266 at 1840 G.m.t. in year 2003.

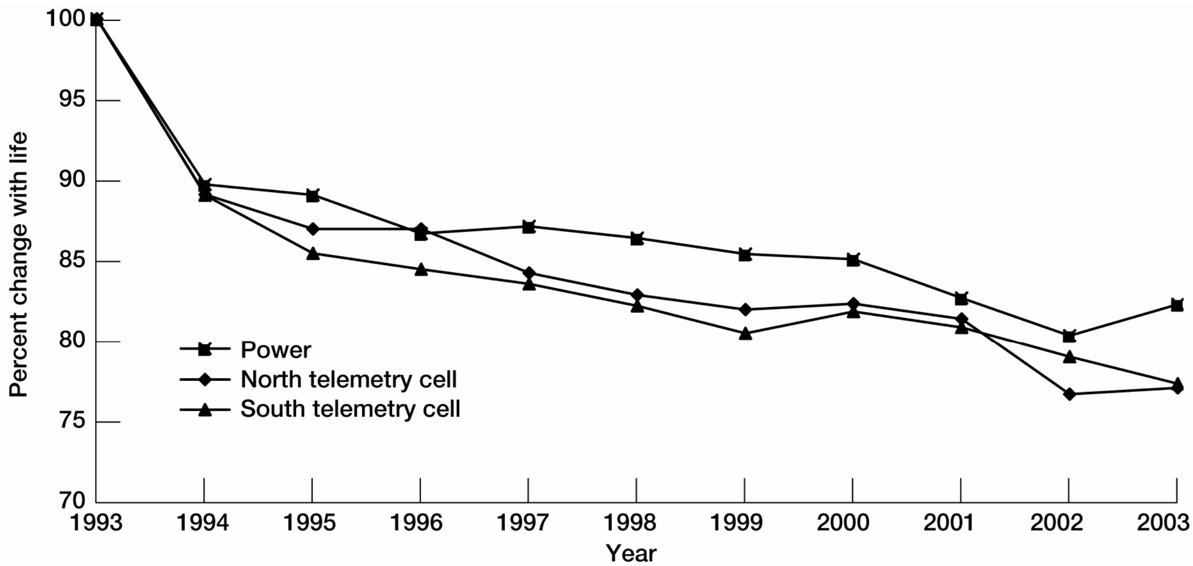

Figure 4.—Approximate ACTS solar array output power as well as north and south short circuit telemetry cell percent change with life. Measurements made normal to the Sun each year on day 266 at 1840 G.m.t. Approximate solar array temperature, 41±2.5 °C.

Figure 4 illustrates and plots the approximate solar array power and solar array north and south approximate short circuit current sensor telemetry cell percent change with life referenced to their BOL values. Each value of solar array output power available in watts measured normal to the Sun from figure 2 is divided by the BOL value of 1833 W, multiplied by 100, and plotted in figure 4 as the percent change in life. Also, each solar array north and south short circuit sensor telemetry cell value measured normal to the Sun from figure 3 is divided by its BOL value of 357 mA for the north or 347 mA for the south, multiplied by 100, and plotted in figure 4 as the percent change with life.

The solar array output power and solar array north and south approximate short circuit current sensor telemetry cell percent change with life represent three separate telemetry circuits measuring solar array cell degradation over the operational life of ACTS. Figure 4 illustrates that the approximate solar array output power available to spacecraft percent change with life and the solar array north and south approximate short circuit current sensor telemetry cell percent change with life in track each other to within less than 4 percent. Analog voltage and current accuracy was calculated to be ±3 percent and temperature sensor accuracy was calculated to be ±6.0 °C BOL by the contractor Lockheed Martin Commercial Space Systems. Lockheed Martin did not provide end-of-life worst-case telemetry analysis, so the accuracy of the data in this report may have a larger uncertainty. The spacecraft requires 1113 W maximum for on-orbit experimental operations and the measured solar arrays are providing approximately 1508 W of output power available to the spacecraft which translates into an excess margin of 395 W after 10 years of successful on-orbit operation.

Performance Conclusion

After 10 years of on-orbit operation, the accuracies of both the approximate solar array output power available in watts measured normal to the Sun illustrated in figure 2 and the solar array north and south approximate solar array short circuit sensor telemetry cell values normal to the Sun illustrated in figure 3 are unknown. The contractor Lockheed Martin Commercial Space Systems did not provide end-of-life worst-case telemetry analysis, and the accuracy of the data in this report is unknown. Although the accuracy of the solar array output power available to the spacecraft is unknown, telemetry data illustrated in figure 4 indicate solar array outputs track each other to within 4 percent. Telemetry measurements tracking to within 4 percent indicates that the spacecraft telemetry electronics, the solar array solar cells that generate electrical power to the spacecraft, and the north and south short circuit current sensor telemetry cells are degrading at the same rate with no significant damage observed in the power subsystem or CR&T subsystem.

Solar array failure is defined as solar array output power less than 1113 W available to operate ACTS on-orbit experiments including the six ACTS subsystems. ACTS approximate solar array output power available has been calculated to be 1508 W on day 266 at 1840 G.m.t. in year 2003 leaving approximately 395 W of excess margin after 10 years of on-orbit operation. The original spacecraft hardware design was for 4 years of on-orbit experiment operation, but because of a robust design, and successful experiment program, the experiment operation was extended and lasted 10 years, or 2.5 times beyond the design life. NASA considers the 10-year history of ACTS on-orbit solar array performance successful with adequate design margins.

Battery Assembly

The ACTS battery contains two parallel-connected 19 Ah nickel-cadmium battery packs for a total battery capacity of 38 Ah. Each battery pack contains 22 series connected cells for a nominal voltage of 33 V. Each battery pack is provided with redundant charge control circuits that limit the battery pack charge current to C/60, C/30, C/20, and C/7 Ah, where the letter “C” represents the 19 Ah name plate capacity for one battery pack.

The ACTS individual battery cells were purchased from Gates Battery Division (Gainesville, FL) as modified heritage hardware, were filled with electrolyte, sealed, tested, and space qualified at Gates Battery Division in 1990. The ACTS battery cells are not a NASA standard cell design and therefore contain little reference documentation from the manufacturer. In 1990, Gates Battery Division requested and received a waiver deviation from the ACTS contractor (Lockheed Martin) to change the battery cell design separator material from pellon 2509 to pellon 2536. Separator material is used to electrically isolate the positive and negative electrodes in a battery cell and allow oxygen gas to diffuse through. This change was necessary because the manufacturer of pellon 2509 discontinued manufacturing the separator product, batteries manufacturers were stockpiling this product, and supplies were not available for new battery cell designs. After much research and testing by Gates Battery Division, pellon 2536 was chosen to be substituted for ACTS Ni-Cd spacecraft battery design. As of April 28, 2004, ACTS batteries have successfully supported the ACTS experiment program for over 10 years and operated in excess of 900 charge and discharge cycles through 21 eclipse seasons. It is noteworthy that ACTS battery life surpassed the spacecraft design life of 4 years by over 2.5 times.

Each battery pack contains voltage monitoring telemetry circuits that measure the voltage across each of the 44 individual battery cells and across each of the two battery packs. The voltage monitoring telemetry circuits across battery pack number 2 cells 1, 4, and 5 have failed during the past 10 years and are no longer able to record voltage telemetry. The failure of the three voltage monitoring telemetry circuits does not impact the nominal performance of these battery cells, the power subsystem, or ACTS operations. Measuring the telemetry voltage across battery pack number 2 minus the telemetry voltage across remaining 19 good telemetry voltage cells can approximate the voltage across the three battery cells.

Measured Performance

ACTS batteries successfully provided electrical power for 21 eclipse seasons over 10 years and have gone through approximately 900 charge and discharge cycles. Battery longevity can be contributed to several factors: maintaining battery temperature between 0 and 25 °C, maintaining maximum cell divergence or voltage spread between battery pack cells to less than 100 mV, maintaining the depth-of-discharge (DOD) ratio to less than 50 percent, and maintaining the charge-to-discharge (C/D) ratio between 1.0 and 1.1.

Battery temperatures must be maintained between 0 and 25 °C over the life of the mission in spite of seasonal changes in spacecraft environment. The narrow operating temperature range is necessary to satisfy the battery requirements for long life and high depth of discharge performance. Temperature control of the spacecraft structure and battery subsystem is achieved by conventional passive design techniques augmented by heaters and careful placement of components within the thermal subsystem.

Heaters are used to compensate for the wide range of internal heat dissipations due to eclipse season, the state of the power subsystem, and the variable number of transponder channels in operation. Each battery pack contains separate primary and backup heaters that contain resistor strip heaters that are mounted alternately between battery cells and connected in series with a heater control module. The heater control module has redundant circuitry to control heating operations for a primary heater and a backup heater. The heater control module turns heaters on when battery temperatures are below 2.0 °C and are turned off when temperatures are above 2.0 °C. Battery primary and backup heaters can be turned on and off from ground commands.

Since 1999, maximum battery temperature would exceed 25 °C during the 8-week period centered on the winter solstice each year if left unchecked. The potential rise in battery temperature above 25 °C has been noticed since 1999 due to the deterioration of the optical solar reflectors located within the thermal subsystem. The optical solar reflectors serve to remove excess heat within the spacecraft and radiate it into space. If left unchecked, the rise in battery temperature above 25 °C during storage, discharging, or charging causes the separator and seals to weaken and accelerates changes to the plate material. It is desired to delay or interrupt battery charging so that the daily peak temperature of the battery due to spacecraft heating does not coincide with the exothermic portion of the battery charge in order to reduce the average battery charge temperature. Since 1999, the spacecraft controllers have disconnected the C/60-Ah battery chargers during portions of the 8-week period centered on the winter solstice to keep battery temperatures below 25 °C The batteries are neither charging nor discharging when disconnected from the battery.

Battery cell divergence is caused by a decrease in cell and battery capacity resulting from chemical changes within the cell that reduce the active surface area of the cell plate. Divergence or voltage spread greater than 100 mV between the highest cell voltage and the lowest cell voltage in a battery pack cell indicates the need for reconditioning. Battery cell divergence takes place when the capacity within the battery and cell after each charge starts to decrease with the tendency for the battery not to provide the original power capacity after charging. If necessary, each battery cell is reconditioned by a deep discharge to 0.2 V and rapid recharge on each cell in a battery shortly before each eclipse season. The voltage spread between the highest and lowest cells measured during peak eclipse time on day 080 and day 266 (day 264 in 1994 and 1995) each year from 1994 through 2003 and is illustrated in tables I and II. The batteries have been working so well over the past 10 years that battery reconditioning used to reduce maximum cell divergence or voltage spread between battery pack cells is considered unnecessary by spacecraft engineers from Lockheed Martin. Battery cell divergence has not been observed during the past 10 years resulting in the decision by spacecraft controllers not to recondition the batteries.

DOD is the ratio in percent of the amount of electrical power removed from the battery compared to BOL battery name plate capacity before launch. The BOL name plate battery capacity prior to launch measured 19 Ah. The DOD in percent for each battery is defined by the equation

$$\mathrm{DOD} = 100\left(\frac{Ah_d}{19\ \mathrm{Ah}}\right)$$

where Ah_d is ampere-hours of discharge current removed from battery. The term Ah_d can be calculated by the equation

$$Ah_d = A_d \cdot T_d$$

TABLE I.—ACTS BATTERY PERFORMANCE, AUTUMNAL EQUINOX ECLIPSE SEASON[a]

Day (year)	Depth of discharge, DOD, percent	Maximum cell divergence, V	Charge to discharge ratio, C/D
264 (1994)[b]	30.6	0.031	1.06
264 (1995)[b]	30.7	.031	1.09
266 (1996)	30.3	.039	1.04
266 (1997)	29.9	.047	1.04
266 (1998)	30.2	.039	1.06
266 (1999)	29.6	.039	1.06
266 (2000)	38.6	.047	1.00
266 (2001)	36.4	.047	1.04
266 (2002)	38.1	.047	1.03
266 (2003)	32.3	.039	1.03

[a]Battery temperature maintained between 0 and 25 °C.
[b]Battery telemetry unavailable on day 265 or 266 in years 1994 and 1995.

TABLE II.—ACTS BATTERY PERFORMANCE, SPRING EQUINOX ECLIPSE SEASON[a]

Day (year)	Depth of discharge, DOD, percent	Maximum cell divergence, V	Charge to discharge ratio, C/D
080 (1994)	38.4	0.031	1.04
080 (1995)	38.2	.031	1.04
080 (1996)	37.0	.039	1.05
080 (1997)	37.1	.047	1.05
080 (1998)	37.1	.039	1.06
080 (1999)	37.8	.039	1.04
080 (2000)	32.7	.047	1.04
080 (2001)	36.8	.047	1.03
080 (2002)	34.8	.047	1.05
080 (2003)	32.6	.039	1.01
080 (2004)	29.2	.039	1.02

[a]Battery temperature maintained between 0 and 25 °C.

where A_d is battery current measured in amperes during battery discharge and T_d is the time in hours during battery discharge. The term 19 Ah is the BOL name plate battery capacity prior to launch.

A DOD of 30 percent indicates a battery has been discharged by 30 percent of its total electrical power capacity and has a 70 percent state of charge or electrical power capacity remaining. The ACTS batteries were designed to operate with DOD less than 50 percent per discharge cycle. As DOD is increased over 50 percent per discharge cycle, there is a decrease in the total number of charge and discharge cycles available in a lifetime, a decrease in the available electrical power retention, and an increase in the degradation of the battery.

The C/D ratio is the measure of electrical power supplied to the battery during charging compared to electrical power removed from the battery during discharge and is defined by the equation

$$\mathrm{C/D} = Ah_c/Ah_d$$

where

$$Ah_c = A_c \cdot T_c \cdot 0.85$$

The term Ah_c is ampere-hours of charge current during battery charging, A_c is amperes during battery charging, and T_c is time in hours during battery charging. The number 0.85 represents the efficiency of the ACTS battery charging.

C/D ratios less than or equal to 1.0 indicated that the battery might not be fully charged and the state of charge of the battery is unknown. This unknown state of charge is not damaging to the battery, although it is not a desired or recommended operating procedure. C/D ratios greater than 1.1 indicate that the battery is overcharged, and the excess energy from the battery charging current cannot provide more chemical energy. This excess energy due to overcharging generates heat as well as possibly splitting water in the battery electrolyte into hydrogen and oxygen gas allowing the pressure to build up and potentially rupturing the battery case, draining the electrolyte, and causing explosion. The spacecraft engineers from Lockheed Martin have successfully ensured that the ACTS battery is charged without overcharging by maintaining the C/D ratio between 1.0 and 1.1 as illustrated in tables I and II.

Performance Conclusion

The primary purpose of the ACTS batteries is to provide electrical power to the six satellite electrical subsystems during solar eclipse periods. The two eclipse seasons each year are 44 days long and centered on spring equinox and autumnal equinox. During the two eclipse seasons, the spacecraft experiences eclipses each day that range from a few to 70 min. As of April 28, 2004, ACTS batteries have successfully supported the ACTS experiment program for over 10 years and operated in excess of 900 charge and discharge cycles through 21 eclipse seasons. It is noteworthy that ACTS battery life surpassed the spacecraft design life of 4 years by over 2.5 times. Battery longevity can be contributed to several factors and is documented in tables I and II: maintaining battery temperature between 0 and 25 °C, maintaining maximum cell divergence or voltage spread between battery pack cells to less than 100 mV, maintaining the DOD ratio to less than 50 percent, and maintaining the C/D ratio between 1.0 and 1.1. NASA considers the 10-year history of ACTS on-orbit battery performance successful with adequate design margins.

Conclusions

This report has described the Advanced Communications Technology Satellite (ACTS) power subsystem and the solar array and battery assemblies located within the power subsystem and documented on-orbit measured performance from launch on September 12, 1993, to mission end on April 28, 2004. The ACTS power subsystem, solar array data, and battery performance data have been presented in this report.

The ACTS contractor, Lockheed Martin Commercial Space Systems, performed beginning-of-life (BOL) worst case telemetry system analysis and documented the accuracy results in DRD 113, ACTS Flight System, CR&T and Data Handling Analysis (1988, General Electric Company, Astro-Space Division, Princeton, NJ, internal document). Analog voltage and current accuracy was calculated to be ±3 percent, and temperature sensor accuracy was calculated to be ±6.0 °C BOL. Lockheed Martin did not provide end-of-life worst case telemetry accuracy, and the accuracy of the data in this report is unknown.

For 277 days out of each year, ACTS is illuminated by the Sun throughout each daily orbit, with the load power requirements supplied entirely by the solar array. Solar array failure is defined as solar array output power available to spacecraft being less than the 1113 W required to operate ACTS on-orbit experiments and provide sufficient power to operate the six ACTS subsystems. The measured solar arrays are providing approximately 1508 W of output power available to the spacecraft as illustrated in figure 2. This translates into an excess solar array output power margin of 395 W after 10 years of successful on-orbit operation.

The solar array output power and solar array north and south approximate short circuit current sensor telemetry cell percent change with life represent three separate telemetry measurements of solar array cell degradation over the operational life of ACTS. This report illustrates that the approximate solar array output power available to the spacecraft, the percent change with life, and the solar array north and south approximate short circuit current sensor telemetry cell percent change with life track each other to within less than 4 percent. Telemetry circuits tracking to within 4 percent indicates that the spacecraft telemetry electronics, the solar array solar cells that generate electrical power to the spacecraft, and the north and south short circuit current sensor telemetry cells are degrading at the same rate with no significant damage observed in the power subsystem or CR&T subsystem.

ACTS batteries provided electrical power to the six satellite electrical subsystems during the two 44-day eclipse seasons each year centered on the spring and autumnal equinoxes. During the two eclipse seasons, the spacecraft experienced eclipses that range from a few to 70 min each day. Because of budget and weight constraints in the late 1980s, ACTS was not designed to support experiment operations through the daily eclipse period and all nonessential circuitry was turned off during this period.

The two batteries were name plate rated at 19 Ah each for a total of 38 Ah capacity, and they supply the essential payload and housekeeping energy path through the discharge diodes during solar eclipse periods. The ACTS batteries have successfully provided electrical power for 21 eclipse seasons over 10 years and have gone through approximately 900 charge and discharge cycles. Battery longevity can be contributed to several factors: maintaining battery temperature between 0 and 25 °C, maintaining maximum cell divergence or voltage spread between battery pack cells to less than 100 mV, maintaining the depth-of-discharge (DOD) ratio to less than 50 percent, and maintaining the charge-to-discharge (C/D) ratio between 1.0 and 1.1.

The ACTS was launched into geostationary orbit in September 12, 1993, and has accumulated over 10 years of trouble-free operation and met all program objectives. The original spacecraft hardware design was for 4 years of on-orbit experiment operation, but because of a robust design, and successful program management, the experiment demonstrations were extended to mission end on April 28, 2004. The successful electrical performance characteristics and measured data of the battery and solar array assemblies operating in geosynchronous orbit onboard the ACTS spacecraft have been presented in this report. The ACTS is a NASA experimental communications satellite system that demonstrated on-orbit

Ka-band communications and switching technologies that are currently used by NASA and the commercial sector. NASA considers the 10-year history of ACTS on-orbit solar array and battery performance successful with adequate design margins.

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13. ABSTRACT ***(Maximum 200 words)***

The Advanced Communications Technology Satellite (ACTS) is a NASA experimental communications satellite system designed to demonstrate on-orbit Ka-band communications and switching technologies that will be used by NASA and the commercial sector in the 21st century. The ACTS was launched on September 12, 1993, and has performed over 10 years of successful experimental operations. The purpose of this report is to describe the ACTS power subsystem and the ACTS solar array and battery assemblies located within the power subsystem and then to document on-orbit measured performance from launch to mission end on April 28, 2004. Solar array and battery performance data is presented, and respective conclusions are drawn. The total solar array power available to the spacecraft was measured each year at the same time, and battery voltage performance was measured twice per year at the same times during peak solar eclipse. At the highest spacecraft power demand, the ACTS uses approximately 1113 W of electrical power during the low-burst-rate experiment to operate all six satellite subsystems. After 10 years of on-orbit operation, solar array available output power normal to the Sun measured 1508 W, which represents 395 W of excess margin. The ACTS batteries have successfully supported the ACTS experiment program for over 10 years and operated in excess of 900 charge and discharge cycles through 21 eclipse seasons.

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