OPERATING A LIGHTWEIGHT, EXPENSIVE LOW EARTH ORBITING SATELLITE

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ABSTRACT

An increasing number of satellite users and manufacturers are looking to lightweight, inexpensive satellites as substitutes to traditional large, expensive satellites with multiple payloads. Neither the Department of Defense nor the commercial sector can bear the financial or reputational consequences associated with massive program failures. With the low cost and weight of these new satellites, users can achieve mission success without great risk. One example of this new class of inexpensive spacecraft is the RADCAL (RADar CALibration) satellite. Detachment 2, Space & Missile Systems Center at Sunnyvale, CA operates the satellite. RADCAL is a 200-pound polar orbiting satellite with an average altitude of 450 miles. It is primarily used by 77 worldwide radars to calibrate their systems to within five meter accuracy. Also flying on board RADCAL is a communication payload for remote field users with small radios. The RADCAL program has satisfied all mission requirements. However, with the limited size and cost come certain challenges, both in the satellite and on the ground. Pre-launch testing was not as comprehensive as with more expensive programs; anomalies have arisen that require extensive workarounds. Data management is not a straightforward task, and it is sometimes difficult and inexact to track satellite performance. These challenges are presented with their solutions in the following discussion; this paper addresses the functional, operational, and testing aspects associated with the RADCAL satellite.

KEYWORDS

RADCAL, radar calibration, small satellite operations, GPS, UHF-band satellites, inexpensive satellites.

INTRODUCTION

NASA and DOD use many of their radars to track newly launched missiles and spacecraft in the first critical minutes of flight. During this vulnerable period, the Range Safety Officer (RSO) carefully watches the flight path. If the rocket veers outside its previously established corridor, the RSO must destroy the stray object before it inadvertently causes property damage or personal injury. The accuracy of the radars is crucial to this process, and a rigorous calibration program ensures this accuracy. A most reliable method of calibrating these radars is for them to track a space object, usually one specifically designed for this purpose. After March 1990, when GEOSAT's secondary radar calibration mission ceased, the 77 worldwide C-band radars belonging to NASA and DOD were without a common, definitive, space-based calibration target. Granted that some of the larger radars were able to use existing low-earth orbiting satellites (such as the giant Russian Mir space station) for coarse cross-referencing, smaller radars were completely reliant on second-generation data from the large radars. Standardizing the calibration data source for all radars had eventually become a critical need.

Meanwhile, certain US Army units had a critical requirement of their own. Tactical users were requesting an inexpensive improvement to their communication capability that would help them during their remote training exercises. Often being preempted by higher priority missions, it was becoming increasingly difficult for the smaller field units to schedule time on the busy geosynchronous communication satellites. In any case, those satellites could not fulfill the requirements for the deployments at higher latitudes, and they usually required bulky ground equipment. The Army wanted a satellite over which they could exert more of their own control--a system more tailored to their specific requirements .

On June 25, 1993, the RADCAL satellite was launched atop a Scout rocket, providing an effective answer to both the radar and communication challenges. One year from proposal to launch, RADCAL cost $10 million (including launch services and one year of operations). RADCAL is a light-weight, inexpensive satellite orbiting the earth at an average altitude of 450 nautical miles. Each revolution of RADCAL's polar orbit takes 100 minutes to complete, bringing the satellite around the world just over 14 times a day. Every spot on the earth's surface is covered at least four times a day.

RADCAL's primary mission is to provide a space-based target for C-band radars. The satellite's secondary mission is to provide both delayed and real-time communication capability. RADCAL also accommodates two experiments: a set of economical GPS navigation receivers, and a special solar array enhancement device known as the Peak Power Tracker (PPT).

THE RADAR CALIBRATION MISSION

The calibration of NASA and DOD radars, is made possible by careful comparison of two types of position data: data generated by radars as they track the satellite's C-band transponder, and data generated from on-board 150- and 400-MHZ beacons.

The 30th Space Wing (30 SPW) at Vandenberg AFB, CA, is the administrator of the C-band radar calibration effort. In this capacity, 30 SPW serves as the scheduling authority for RADCAL's C-band transponder requests. Radar range supervisors around the world send their requests to 30 SPW, where administrators consolidate and deconflict the requests into one weekly list. This request list is passed on to the RADCAL flight controllers in Sunnyvale, CA, and the flight controllers program RADCAL to respond at the appropriate times. As RADCAL passes over an applicable radar, the satellite's C-band transponder switches on. When a radar user transmits "interrogation" pulses up to RADCAL, the satellite's transponder returns pulses back down to the radar. The time delay is translated into ranging data.

Also key to the radar calibration process is a set of beacons on-board RADCAL transmitting at 150 and 400 MHZ. A dozen beacon receivers distributed around the northern hemisphere detect these beacon transmissions. The doppler system generates position data of RADCAL within two to three meter accuracy, one order of magnitude better than the accuracy obtained before RADCAL was launched. Administrators at 30 SPW can compare this doppler-generated position data to the radar transponder data. They can then direct the radar personnel to calibrate their equipment as necessary.

THE COMMUNICATION MISSION

When necessary, Army Special Forces units make requests to the RADCAL Support Center (RSC) for communication payload use. They request specific times for the satellite to uplink or downlink digital data to or from given mailboxes on board. The requests will specify various parameters of the communication events (such as data rate, modulation, and which antenna system to use). The requests also specify the timing of the operations, which correlates to the location on the globe where these events are to take place. Users can upload messages from one geographic location, and download them to another. The data can be either encrypted or clear text. Users can also request RADCAL's real-time voice or data communication capability (also known as "bent-pipe" mode): Two users can communicate in real time within the footprint of the satellite (approximately 1500 nautical mile radius).

THE EXPERIMENTS

The satellite also has the capability to generate its position through use of an experimental package -- a pair of Global Positioning System (GPS) receivers. The two Trimble Advanced Navigation Sensor receivers represent one of the first times that a commercial course acquisition GPS receiver has been used on a satellite. As requested by the experimenter, a GPS receiver is turned on for a specified period of time (usually between five and ten hours). Positioning information is collected and recorded in a three-megabyte memory on board. After the collection period is complete, the RSC flight controllers can program the satellite to download the position data to the telemetry and commanding computer. This position data is currently experimental, but experimenters propose the use of this data in lieu of the beacon-generated position data for the radar calibration mission. The GPS methodology has also been used successfully to determine spacecraft attitude to within one degree. Two technical papers have been published (Stanford University and the Aerospace Corporation) on the use of GPS for orbit and attitude determination, particularly on the RADCAL satellite.

RADCAL's second experiment, the Peak Power Tracker, uses a combination of known technologies in a highly creative way to enhance the satellite's power management capability. A series of three integrated circuits is used to track the maximum solar array voltage-current, placing the bias point at the optimum position. This power is used to more efficiently charge RADCAL's two NiCd batteries, significantly outperforming the satellite's traditional charge regulators. This experiment has been declared a success, and has been proposed for a more permanent role in power management, particularly when the solar arrays begin to degrade at RADCAL's end of life. Derivatives of this experiment are slated for future satellite designs .

THE RADCAL SATELLITE

The heart of the satellite is its on-board computer. The computer's Central Processing Unit (CPU) is an 80C86 chip; a flight-certified version of its 8086 cousin from the early days of personal computing. The computer has four megabytes of Random Access Memory (RAM). Three megabytes are reserved for the GPS experiment. The remaining megabyte contains telemetry samples, "mailboxes" for the communication payload, and the satellite schedule.

The satellite communicates to the outside world through 15 antenna elements (see Figure 1 for details). These elements are used for telemetry and commanding (T &C), mailbox communication, GPS data collection, tracking beacons, and C-band

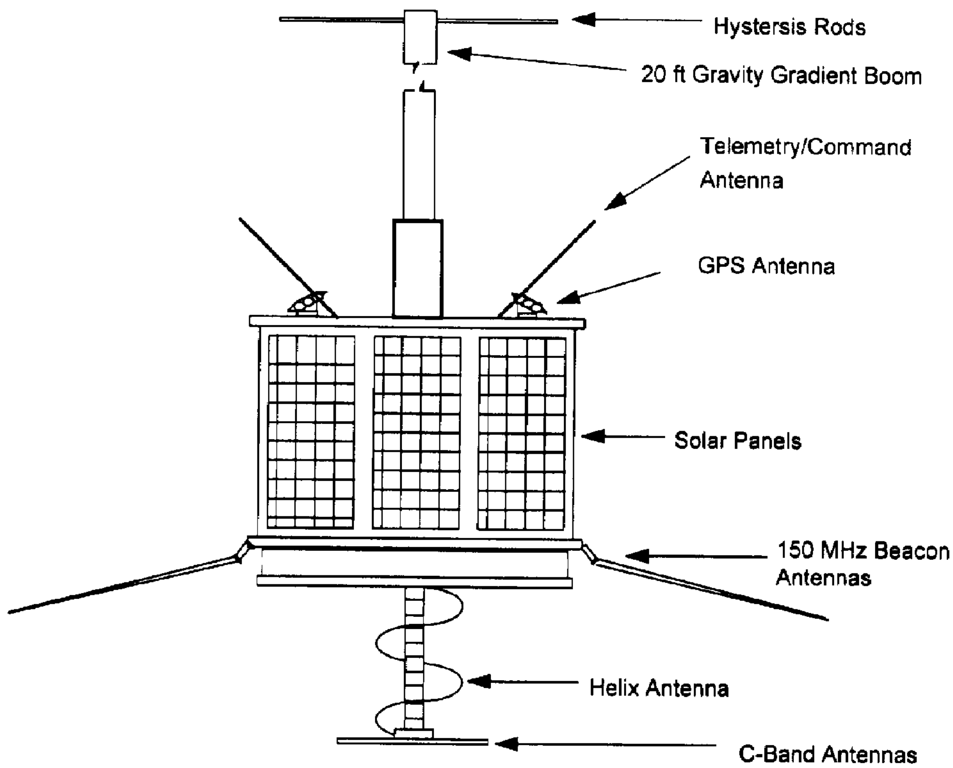

Figure 1: The RADCAL Satellite

turnaround tones. There are four omni-directional blade antennas for telemetry and commanding, generating a 400 MHZ beacon and communicating with a mailbox; there are four whip antennas for a 100 MHZ beacon. Four GPS receiving antennas are cross-connected to two GPS receivers. Two transponder antennas are used for C-band turnaround tones, and there is one helix antenna is for telemetry and commanding.

The satellite derives its electrical power from an array of solar panels that cover 75% of the outer structure, and the solar arrays also keep a pair of nickel-cadmium (NiCd) batteries fully charged in preparation for uninterrupted eclipse operations. Eclipse seasons occur twice per year for three months; the longest eclipses in each season lasts about 37 minutes of every 100-minute revolution.

Position and attitude control on RADCAL is a passive operation. RADCAL has no thrusters, and therefore cannot change position. For the vast majority of its mission, the spacecraft uses a passive attitude stabilization solution. Stabilization of the longitudinal axis is achieved by using a 20-foot long gravity gradient boom with a five-pound tip mass. This scheme provides a sufficient mass placement differential to keep the satellite pointed toward the earth. At the same time, a set of hysteresis rods use the earth's magnetic field to dampen rotation and libration to negligible levels.

Coarse attitude data is derived from a navigation magnetometer package on board that measures electromagnetic flux in the earth's magnetic field. In the event that the satellite becomes inverted, a large electromagnet known as the "Z-wire" can be used to re-invert the satellite to its nominal attitude.

OPERATING RADCAL

The RADCAL satellite is controlled from the RADCAL Support Complex (RSC) in Sunnyvale, California. The RSC is a small room in an office building, equipped with two personal computers, a UHF -band transceiver, an antenna control unit, and an UHF antenna. The complex is run by Detachment 2, Space and Missile Systems Center, with a crew of four flight controllers from Loral Space and Range Systems.

All operational telemetry and command processing is accomplished on a standard IBM-based PC (with a 386 chip), known as the T&C computer. Data moves to and from the T&C computer through a transceiver attached to a helix antenna on the roof. The system is operated using software provided by the satellite manufacturer, CTA Space Systems (formerly Defense Systems, Incorporated). Tracking operations are performed using another PC attached to an Antenna Control Unit (ACU) which controls the azimuth and elevation of the antenna. See Figure 2.

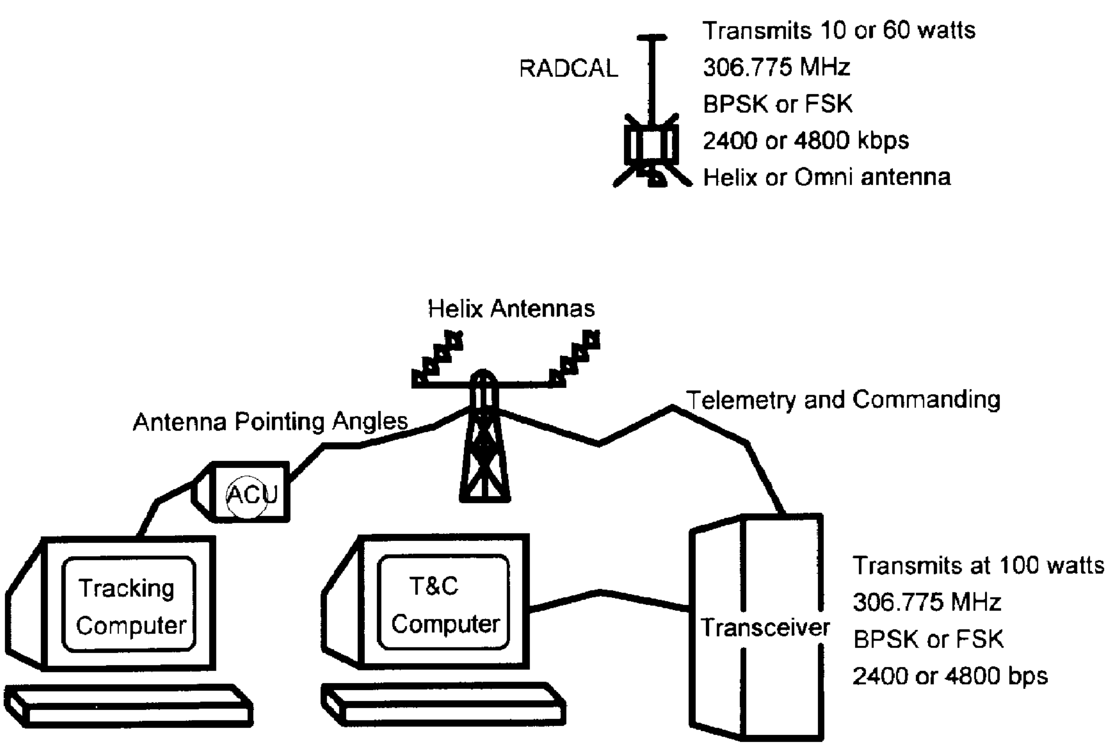

Figure 2: The RADCAL Support Complex

Operations at the RSC are centered around short contacts with the satellite conducted during a period of visibility lasting about 15 minutes. These visibilities take place at least twice every 12 hours, separated by 100 minutes (one orbital revolution).

The RSC receives schedule requests through a computer bulletin board, fax machine, or telephone. In response to these requests, an uplink file is prepared before a given satellite contact. This file contains commands that will be placed in the satellite's schedule. Placing a request into the on-board queue with a date and time of execution is the only way to command the satellite. This date and time can be the moment of the satellite contact if an immediate execution is required.

A contact usually lasts less than one minute. The satellite is configured for half-duplex communication; it transmits then receives in quick succession. The satellite begins these bi-directional conversations by "sounding" a short beep at a previously scheduled time. The one-second beep contains synchronizing frames and satellite identification. The RSC's transceiver "hears" the beep and automatically returns a like beep, containing synchronizing frames, ground station identification, and a password. Once this handshake has been established between these two similar pieces of equipment, the satellite will transmit a previously requested burst of telemetry. This usually includes state-of-health (SOH) information in two different formats, as well as a complete copy of the satellite's scheduling queue. This takes about 15 seconds. The ground station then automatically sends up a burst of commands, as necessary, to supplement the scheduling queue. This takes another 15 seconds. This action concludes a single contact. See Figure 3.

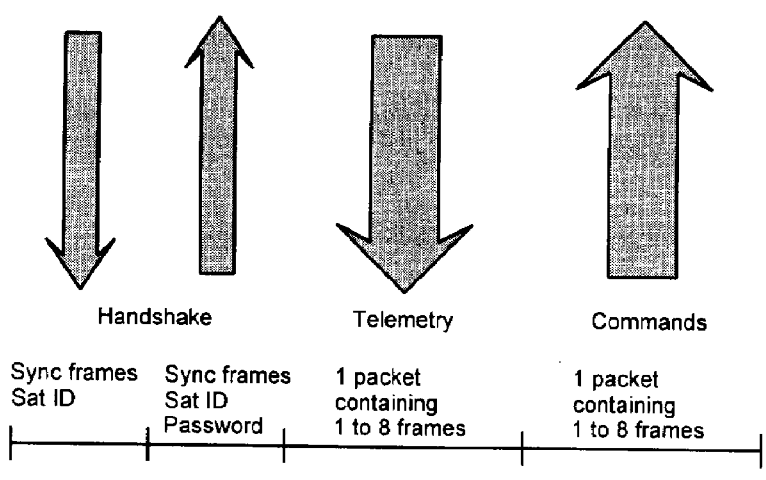

Figure 3: A Typical RADCAL Bi-Directional Communication Event

Both the ground station and satellite are capable of operating at either 2400 or 4800 bps data rates, using the Manchester encoding scheme. In addition, either Frequency Shift Key (FSK) or Bi-Phase Shift Key (BPSK) modulation types can be used. On the satellite, either of two antenna systems are available for telemetry and commanding activities: the helix antenna or the set of four omni-directional blade antennas. When using the helix antenna, the satellite can be configured to transmit at either 10 or 60 watts.

During a bi-directional contact, telemetry is received into a RAM buffer in the ground transceiver. When the contact is complete, all RAM is then transferred to a subdirectory in the T &C computer. Then the telemetry is processed by the ground station software: each frame is identified, then regrouped into telemetry files. Based on its type, the data is then transferred to an appropriate subdirectory. Because of the delay after the real-time contact, it is difficult to respond to the telemetry during a given pass, or to react quickly to satellite anomalies. The best that can be done is "virtual" real-tim:. A command is sent up to the spacecraft during a first contact, requesting the satellite to contact the ground again about three or four minutes later. After the first contact's telemetry is analyzed by the flight controller, commands can be prepared for uplink during the second contact. This second contact can therefore be used as an anomaly response tool.

THE CHALLENGES

RADCAL is an example of the space industry's attempts to minimize satellite program cost, both in terms of money and time. There are consequences of building a satellite with such downsized scope. The cause of many of RADCAL's difficulties can be traced to the lack of comprehensive testing that integrated all subsystems.

Some of RADCAL's problems center on RF interference: The beacons interfere with both the satellite's helix and GPS receive capability, and the transmission on the helix antenna which interferes with beacon transmissions. Flight controllers have had to creatively work around these problems by consistently turning on and off interfering systems at various times during RADCAL communication contacts.

In addition to the RF interference issues, RADCAL's electrical power subsystem has some unexpected limitations. One of the constraints made itself evident in the first eclipse season: Battery voltages were dropping dangerously low when the satellite was in shadow for more than 3 0 minutes. Flight controllers were able to supplement the insufficient power only by turning the satellite beacons off in lowest reaches of the southern hemisphere, where there are no beacon receivers.

Another problem in power management was also discovered: When the 60-watt transmitter was used in conjunction with the GPS receiver, it would detect an overcurrent status and shut itself off. This problem could have been averted, had bus assignments been planned more judiciously.

One of RADCAL's more obscure problems is that its helix and omni transmissions occasionally fade in and out during communication events. It has been proposed that near field multipath interference with the gravity gradient boom causes an irregular antenna pattern.

The satellite has also experienced occasional single-event upset (SEU) incidents. These SEUs have not only resulted in spurious data, but have also caused untimely satellite CPU resets (i.e., "reboots"). Fortunately, the CPU's primary operating software is stored on hardened EPROMs, which have thus far demonstrated adequate resistance to these SEUs.

The RADCAL operation is PC-based, and all telemetry is stored on 3 ½-inch floppy disks. Telemetry can be restored at any time and viewed through the manufacturer's software. Unfortunately, telemetry trend analysis had been a painstaking process, because the manufacturer's software was not compatible with any other software that facilitates telemetry analysis. However, by purchasing off-the-shelf spooling software, the telemetry data could be spooled to an ASCII format output file. This file can then be imported into spreadsheet software and analyzed in many different formats. It can also be broadcast to the RADCAL community via the TECNET bulletin board.

Operating RADCAL's GPS experiment represents a considerable challenge. Since the on-board GPS receivers are "course-acquisition" (C/A) type, precise data is not directly available. The data accuracy is intentionally corrupted with a cryptographic "selective availability" (S/A) mask. After flight controllers have downloaded position data, this data must undergo significant processing: The S/A mask must be removed to reveal the precise data required for adequate orbit determination, and then the data must be smoothed to remove noise. This processing takes place at the Test Data Analysis Center, at Onizuka Air Station, which is authorized to handle the cryptographic S/A mask.

CONCLUSION

As with any endeavor, operating a lightweight, inexpensive low earth orbiting satellite like RADCAL has its advantages and disadvantages. An advantage of the RADCAL program is its stark simplicity, but this simplicity has a price. Prudent balancing of cost and benefit are difficult to achieve in a satellite program, where there is no opportunity to "recall" the satellites. The RADCAL satellite was designed largely using off-the-shelf hardware and firmware; the ground station is manned with an operational staff of four. In spite of these factors, RADCAL has been a highly effective program significantly improving radar accuracy and providing inexpensive communication capability. The program has successfully proven GPS capability for orbit and attitude determination, and has confirmed the Peak Power Tracker solar power enhancement experiment. Just as important, the lessons learned will permit further improvements on future low-cost programs. In the absence of robust integrated pre-launch testing, the program achieved its primary objectives. Therefore, if an organization can bear the inconveniences RADCAL's challenges pose, it is highly recommended that future programs be modeled after RADCAL.

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