

## On-orbit Performance of the ORBCOMM Spacecraft Constellation

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**Abstract.** ORBCOMM is a low cost, two-way data messaging system that uses a constellation of 36 spacecraft to provide global coverage for a wide variety of applications. Following an aggressive launch schedule, Orbital Sciences Corporation (Orbital) launched 26 spacecraft within 10 months to set up the constellation that is now providing global service to subscribers. As of August 1999, the constellation spacecraft have already accumulated over 30 spacecraft-years of on-orbit experience while demonstrating excellent in-flight performance. The ORBCOMM spacecraft design epitomizes the mass, power, and volume efficiencies of Orbital's MicroStar spacecraft platform. Unlike a single spacecraft mission, the ORBCOMM constellation provides a unique opportunity to assess the performance of multiple spacecraft at the same time. This paper presents pertinent flight data for key spacecraft subsystems with a focus on hardware performance. Beginning with the subsystem performance for a single spacecraft the analysis is then extended to the constellation level with an assessment of subsystem performance of multiple spacecraft over an extended period of time. The presented data demonstrates the successful design and operation of the MicroStar spacecraft platform, which constitute the basis for the ORBCOMM satellite constellation.

### Introduction

ORBCOMM is a two-way data messaging system that utilizes a constellation of 36 spacecraft to provide global service. Orbital Sciences Corporation (Orbital) was responsible for the design, development, integration and test, launch, and on-orbit checkout of the constellation spacecraft. Based on the low mass, low power, and low volume MicroStar spacecraft design, 26 ORBCOMM spacecraft were launched within 10 months in 1998 to set up the world's first commercial communications constellation and provide service. As of August 1999, these spacecraft have amassed over 30 spacecraft-years of on-orbit experience while demonstrating excellent in-flight performance.

Typical single spacecraft missions only provide a two-dimensional (performance versus time) analysis space for assessment of spacecraft performance. The ORBCOMM spacecraft constellation uniquely provides a three-dimensional performance analysis space (performance versus time versus spacecraft) which allows the simultaneous assessment of multiple spacecraft over time. In addition to rapidly accumulating on-orbit hours, the same hardware flying on multiple spacecraft permits quantification of both temporal and spatial effects of the space environment on hardware.

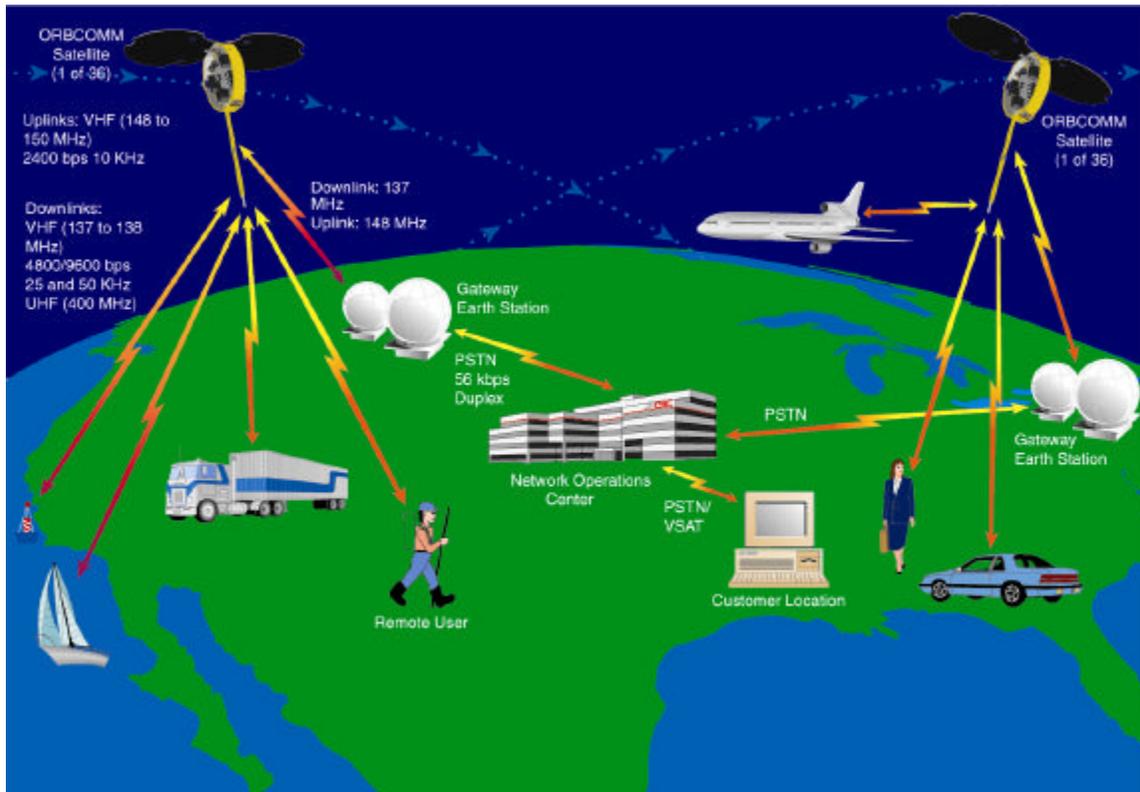
The primary objective of this paper is to present on-orbit performance data that demonstrates the successful operation of the ORBCOMM spacecraft. The paper starts off with an overview of the ORBCOMM data messaging system. A summary of the spacecraft design and key spacecraft requirements is then given to set the stage for subsequent presentation of flight performance data by subsystem. The flight data is presented by subsystem. Within each subsystem, data is first presented for a single spacecraft before correlation with performance of multiple other spacecraft.

### ORBCOMM System Overview

ORBCOMM is a low cost, two-way satellite-based global data messaging system developed and operated by ORBCOMM Global L.P. Orbital is responsible for the design, integration and test, launch, and on-orbit checkout of the constellation of 36 spacecraft.

The ORBCOMM system architecture, shown in Figure 1, supports a wide variety of applications that include subscriber messaging, positioning, and monitoring of remote assets such as truck fleets and oil pipelines. The constellation spacecraft use two separate VHF links to communicate with subscribers and gateways. Messages from remote units are uplinked to the spacecraft, which then downlinks the data to a gateway earth station for routing to the network operations center in Dulles, Virginia. The data are then routed

via land lines to the ultimate recipient. On the forward uplinked to the spacecraft for subsequent downlink to



**Figure 1 ORBCOMM System Architecture**

link, data from the network operations center is the remote terminals.

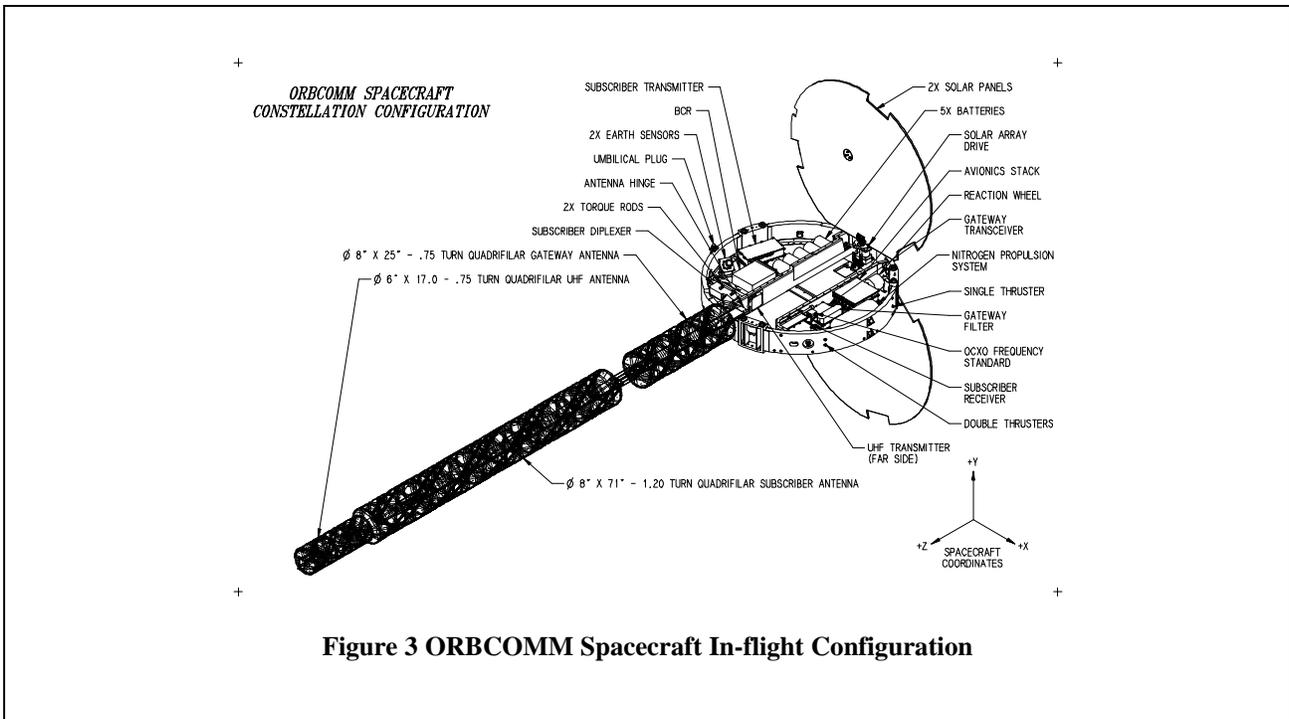
The ground segment consists of the subscribers, the network operations center, and a series of gateway earth stations. The spacecraft segment comprises a

constellation of 35 spacecraft in a variety of orbits. Designed and manufactured to be compatible for launch on Orbital's Pegasus and Taurus launch vehicles, the spacecraft are deployed in six distinct orbit planes. Utilizing novel manufacturing techniques, the ORBCOMM spacecraft were developed under a tight schedule to support the launch of 26 spacecraft within 10 months<sup>1</sup>. The status of the constellation deployment is summarized in Table 1. Although launch of the fourth plane is not scheduled until mid-1999, the current 28 spacecraft in orbit are sufficient to provide global service.

**Table 1: ORBCOMM Launch Schedule**

Satellites	Launch Vehicle	Orbit Altitude (km)	Orbit Inclination (deg)	Orbital Phasing (deg)	In-Plane Separation (deg)	Launch Date (Projected)
F1, F2	Pegasus	775	70	N/A	180	April 1995
G1, G2	Taurus	820	103	N/A	180	February 1998
A1-8	Pegasus XL	820	45	120	45	December 1997
B1-8	Pegasus XL	820	45	120	45	August 1998
C1-8	Pegasus XL	820	45	120	45	September 1998
D1-7	Pegasus XL	1000	0	N/A	~51	(Mid-1999)

### ORBCOMM Spacecraft Design Overview

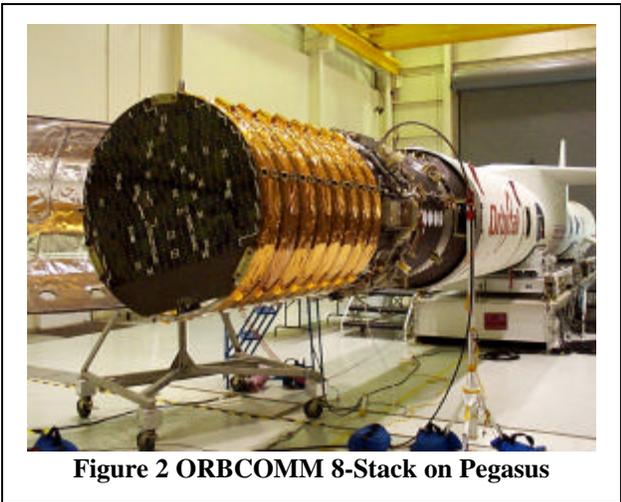


**Figure 3 ORBCOMM Spacecraft In-flight Configuration**

Figure 2 shows an 8-stack of spacecraft ready for launch on the Pegasus XL while Figure 3 illustrates the in-flight configuration of the ORBCOMM spacecraft.

The patented stackable configuration results in the ability to launch eight spacecraft in a single Pegasus XL launch. In the stowed configuration, the antennas fold into the antenna trough while the solar panels fold back

onto each side of the cylindrical bus structure, which is about 102 cm in diameter and 15 cm in height. Designed for a lifetime of 5 years, weighing under 45 kg, and providing over 200 W of power at End-of-Life (EOL), the ORBCOMM spacecraft epitomizes the high



**Figure 2 ORBCOMM 8-Stack on Pegasus**

**Table 2: ORBCOMM Spacecraft Subsystem Functions**

Unit	Function
Flight computer (FC)	Command handling and telemetry gathering, Health and maintenance, GPS receiver management
Electrical power system (EPS)	Solar array and battery charge control, power switching, deployment sequence
Attitude control system (ACS)	Control of nadir pointing and sun pointing, GPS data processing
Global Positioning System (GPS)	Provision of navigation fix data, absolute and relative time synchronization inputs
Thermal Control Subsystem (TCS)	Maintain avionics and battery at operating temperatures.
Gateway transceiver (GWT)	Spacecraft command and telemetry link with ground, exchange of subscriber message data with gateways
Subscriber receiver (SRX)	Receipt of subscriber messages
Subscriber transmitter (STX)	Transmission of subscriber messages

mass, power, and volume efficiencies of Orbital’s MicroStar spacecraft. Seven Motorola M68302 microprocessors form the core of the distributed spacecraft system that runs the VxWorks operating system.

In the nominal flight configuration, the VHF antennas point towards nadir while the spacecraft yaws to face

**Table 3: Key Subsystem Requirements**

Unit	Key Requirements
Electrical power system (EPS)	<ul style="list-style-type: none"> <li>- Fully recharge batteries every orbit</li> <li>- Control solar array input to maximize power available</li> </ul>
Attitude control system (ACS)	<ul style="list-style-type: none"> <li>- Maintains nadir pointing &lt; 5° CEP and &lt; 10° 90 % of time</li> <li>- Generate 95% of available power</li> </ul>
Global Positioning System (GPS)	<ul style="list-style-type: none"> <li>- Fix accuracy of 100m 2d RMS with SA enabled</li> <li>- Fix availability of 90%</li> </ul>
Thermal Control Subsystem (TCS)	<ul style="list-style-type: none"> <li>- Maintain battery temperature within -5C to 10C</li> </ul>
Gateway transceiver (GWT)	<ul style="list-style-type: none"> <li>- EIRP consistent with expected value</li> </ul>
Subscriber receiver (SRX)	<ul style="list-style-type: none"> <li>- Measured signal level consistent with expected value</li> </ul>
Subscriber transmitter (STX)	<ul style="list-style-type: none"> <li>- EIRP consistent with expected value</li> </ul>

the sun. In addition, the solar arrays are articulated about the y-axis to maximize power generation capability. This low cost spacecraft is also designed for maximum onboard autonomy so as to minimize constellation operations via ground control<sup>2</sup>. Furthermore, onboard autonomy is enhanced with the implementation of a layered health and maintenance scheme that encompasses all hardware and software. Table 2 summarizes the key functions of each subsystem on the spacecraft.

The STX, SRX, and GWT make up the spacecraft payload although the GWT also provides the spacecraft command and telemetry link. Table 3 shows the key applicable requirements for the subsystems analyzed. The following sections provide a brief description of each subsystem.

### Flight Computer (FC)

The flight computer consists of a master/slave configuration of the Motorola 68302 with EDAC memory. The primary functions of the flight computer are command handling and telemetry gathering. The FC also serves as the interface between the spacecraft bus and the payload. Subscriber messages are stored in memory and routed to the appropriate payload units as required. The FC also serves the important function of autonomous fault detection and correction through the use of a flexible health & maintenance scheme and a layered reset strategy scheme. Additionally, the FC manages the GPS receiver and executes the time management scheme onboard the spacecraft.

### Electrical Power Subsystem (EPS)

The EPS consists of the Battery Charge Regulator (BCR), solar arrays, battery, and sensors. EPS control is maintained by the microprocessor in the BCR. The Gallium Arsenide solar panels, which are capable of generating 210W at EOL, are controlled with the use of peak power tracking algorithms. The 10 Ahr Nickel Hydrogen battery is charged using a sophisticated charge control algorithm. Power to the spacecraft is provided by a 5 V regulated and a 14 V unregulated power bus with power switching to all boxes provided by the BCR. The UHF beacon transmitter is controlled by the BCR which also controls the spacecraft deployment sequence after separation from the launch vehicle. Heater control for the thermal control system is done in the BCR. A key feature of the ORBCOMM EPS is the ability to autonomously recover from complete power loss or extremely low power conditions.

### Attitude Control Subsystem (ACS)

The ACS is responsible for ensuring the pointing performance of the spacecraft in terms of nadir pointing of the antenna and sun pointing of the solar arrays. On-orbit station keeping is accomplished by flaring or feathering of the solar arrays. The ACS system is gravity gradient-based with a single serial-interface reaction wheel and three magnetic torquers as actuators. Two Earth sensors, a magnetometer, and six cosine sensors complete the ACS sensor suite. This low-cost attitude control implementation results in nadir-pointing accuracy of under 5 degrees. The ACS also processes GPS fix data from the GPS receiver to provide spacecraft navigation data. Navigation data are required for magnetometer-based attitude determination and transmission of ORBCOMM spacecraft ephemerides to subscribers for subscriber positioning.

### Global Positioning System (GPS)

Utilizing a low-cost lightweight GPS receiver, the GPS subsystem provides navigation and time synchronization functions on the spacecraft<sup>3</sup>. The Rockwell MPE-I 5 channel GPS receiver, controlled by the spacecraft FC, provides navigation fixes to the ACS. It also provides absolute and relative time synchronization inputs to the spacecraft time control loops in the form of a time transfer message and pulse per second signal respectively. The zenith-facing side of the spacecraft structure accommodates an active GPS antenna that has near-ideal  $2\pi$  steradian coverage. GPS data are also used on the ground for orbit determination and constellation maintenance activities.

### Thermal Control Subsystem (TCS)

The TCS is an essentially passive system that primarily uses radiators to maintain the spacecraft temperature within acceptable limits. Software-controlled heaters turn on when the battery temperature drops below  $-5^{\circ}\text{C}$  and thus aid in maintaining the battery temperature within acceptable ranges.

### Gateway Transceiver (GWT)

The GWT is part of the payload suite but also serves the function of command and telemetry link provision. It consists of a receiver and transmitter that operate in the VHF frequency band. Commands uplinked to the spacecraft are received by the GWT and forwarded to the FC. Spacecraft telemetry is routed by the FC to the GWT for downlink. Subscriber messages for downlink are also routed to the GWT for downlink to a gateway earth station. Additionally, the GWT controls the oven-controlled crystal oscillator that provides the most stable short term onboard frequency reference.

### Subscriber Receiver (SRX)

The function of the SRX is to receive subscriber messages from remote units. Using a patented Dynamic Channel Activity Assignment Scheme (DCAAS), the SRX utilizes DSP technology to detect

and demodulate messages from the remote units. It also scans the assigned VHF frequency band to search for low activity channels that can be used by the ORBCOMM system.

### Subscriber Transmitter (STX)

The STX transmits subscriber messages directly to the remote terminals using a high power transmitter at VHF frequencies. It also periodically transmits ORBCOMM spacecraft ephemerides to users to support the subscriber positioning mission.

### Flight Performance Data Analysis

This section of the paper presents flight performance data by subsystem. As of August 1999, the ORBCOMM spacecraft constellation, not including F1 and F2 launched in 1995, will already have accumulated over 30 spacecraft-years of operation. The focus of the data analysis is hardware performance and software performance is not considered in this paper.

Unlike a single spacecraft mission that only provides performance of one spacecraft over time, a constellation like ORBCOMM adds a further dimension by providing the capability to assess the

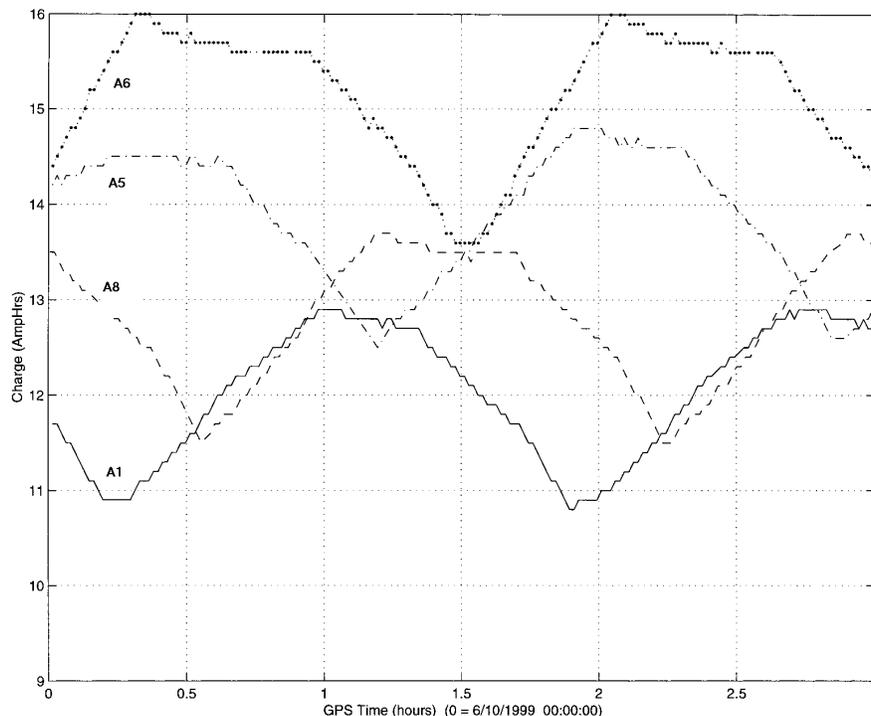


Figure 4 Battery Charge for Four Spacecraft in A Plane (A1, A5, A6, A8)

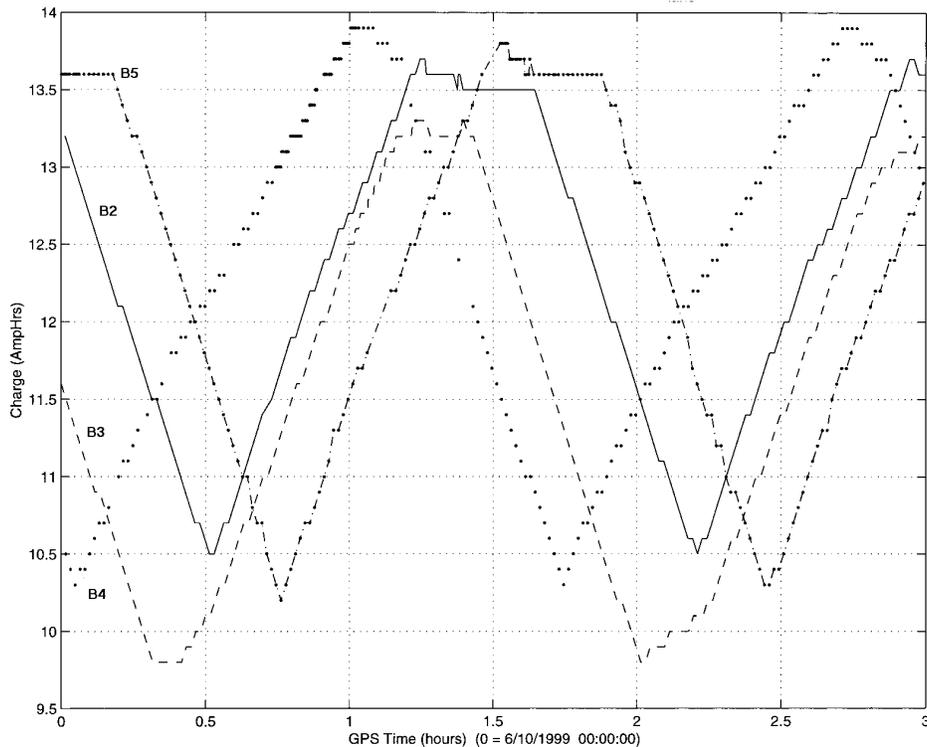
performance of multiple spacecraft at the same time. This section attempts to present both these dimensions.

For each subsystem, one or two parameters are used to demonstrate on-orbit performance. The performance of one spacecraft is explained before correlating it with the performance of multiple other spacecraft. Such a bottoms-up approach is ideal to assess not only the joint performance of the hardware and software elements, but also the performance of a given spacecraft over an extended period of time in relation to other spacecraft in the constellation. Furthermore, the performance of hardware components is truly

the large number of ORBCOMM spacecraft and the long timeframe they have been operating over.

### Electrical Power Subsystem (EPS)

Two hardware items of interest in this subsystem are the solar array and the battery. Figures 4 through 6 show battery charge of four spacecraft from each of three planes over the course of about two orbits. Although the nameplate capacity of the battery is 10 AHr at 10°C, the actual capacity at Beginning-of-Life (BOL) is significantly higher even when the actual battery temperature is taken into consideration. This is generally true for all spacecraft in the ORBCOMM



**Figure 5 Battery Charge for Four Spacecraft in B Plane (B2, B3, B4, B5)**

represented by the relatively large sample of 26 spacecraft in orbit.

Before examining the flight performance itself, it is important to make note of a few things. The amount of telemetry accumulated for each of the 6 subsystems of the 26 spacecraft over 1.5 years is large. This in itself is a problem due to the difficulty of presenting all that data in a paper of this kind. In order to alleviate this, an attempt is made to show different combinations of spacecraft and timeframes. It is hoped that this method of data presentation maximizes the coverage of both

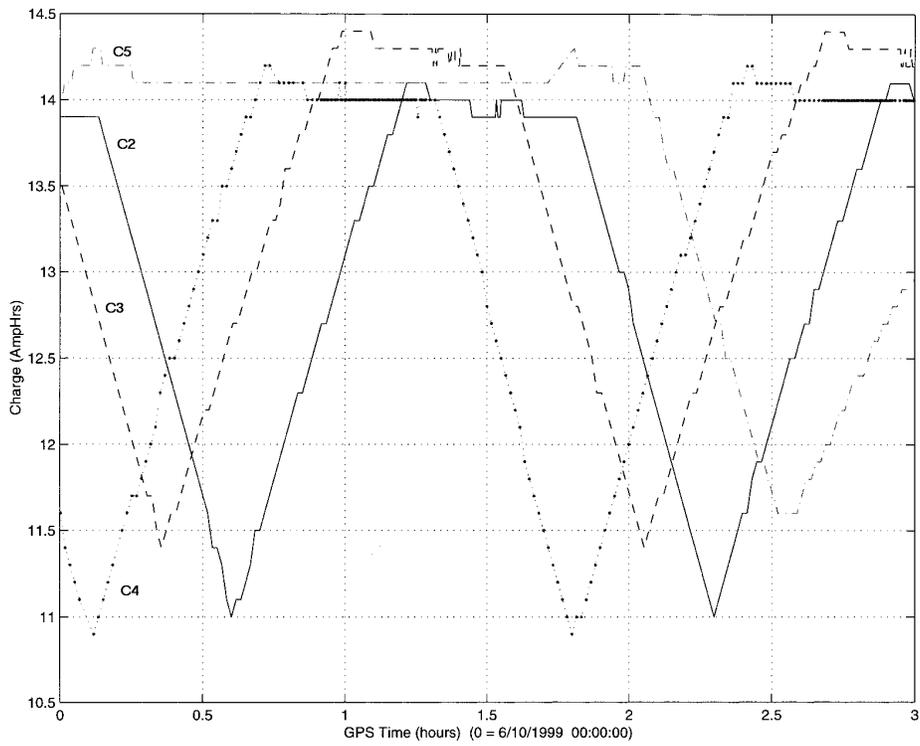
constellation.

Considering the profile for just a single spacecraft first, the battery is seen to discharge during maximum eclipse periods of about 35 minutes and charges back up to full capacity in about 45 minutes. When more spacecraft in the plane and across planes are taken into consideration, three things are of note. First, the depths-of-discharge are not the same, since the total spacecraft power load is different based on the service loading, and hence transmitter duty cycle, of individual spacecraft. Second, the charge/discharge curves of the spacecraft are generally shifted in time. This is

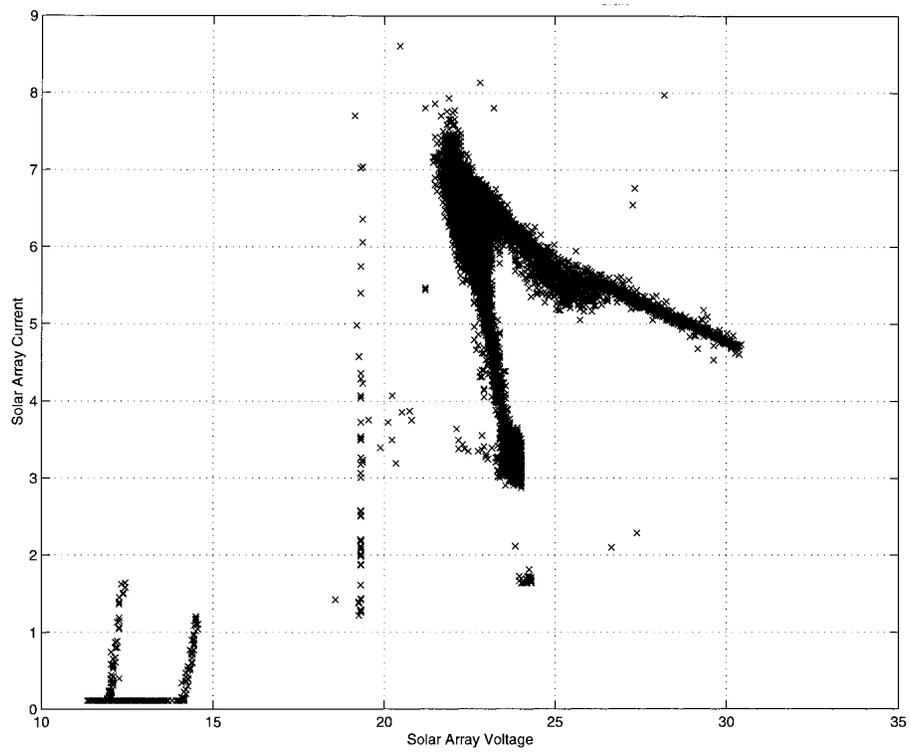
because each spacecraft enters and exits eclipse based on its orbit and each spacecraft in the constellation has a relative separation in terms of orbit plane, inclination, and mean anomaly. Third the level of the curves indicates a variability in the battery capacity on the order of 25%. Even with this variability, battery capacities are still above the nameplate capacity of 10 Ahr.

Figure 7 characterizes the solar array performance of one spacecraft in terms of its current-voltage curve. The ORBCOMM EPS solar array power control

algorithm tailors the solar array operating point to provide the power required by the spacecraft loads. The algorithm sets either the solar array voltage or current operating point in order to provide the finest control. The plot shows individual data points on the current-voltage curve, displaying the classic inverse relationship of solar array voltage and current. The different curves are due to changes in solar panel temperature. Additional spacecraft plots are not shown for the sake of clarity, but all spacecraft display similar current-voltage characterization curves.



**Figure 6 Battery Charge for Four Spacecraft in C Plane (C2, C3, C4, C5)**

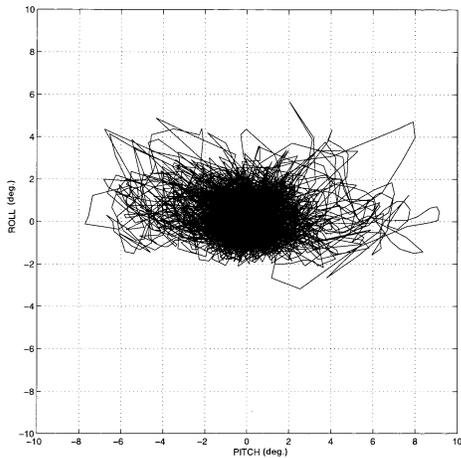


**Figure 7 Solar Array I-V Curve for Spacecraft in C Plane (C4)**

**Attitude Control Subsystem (ACS)**

### Attitude Control Subsystem (ACS)

The ACS has two main pointing requirements, namely nadir pointing of the antenna to within 5 degrees CEP and within 10 degrees 90% of the time. Sun pointing of the solar arrays has to be such as to generate 95% of the available power. While nadir pointing, the spacecraft yaws to point the arrays at the sun, so yaw error is a good measure of the spacecraft's sun-pointing performance. Considering nadir pointing

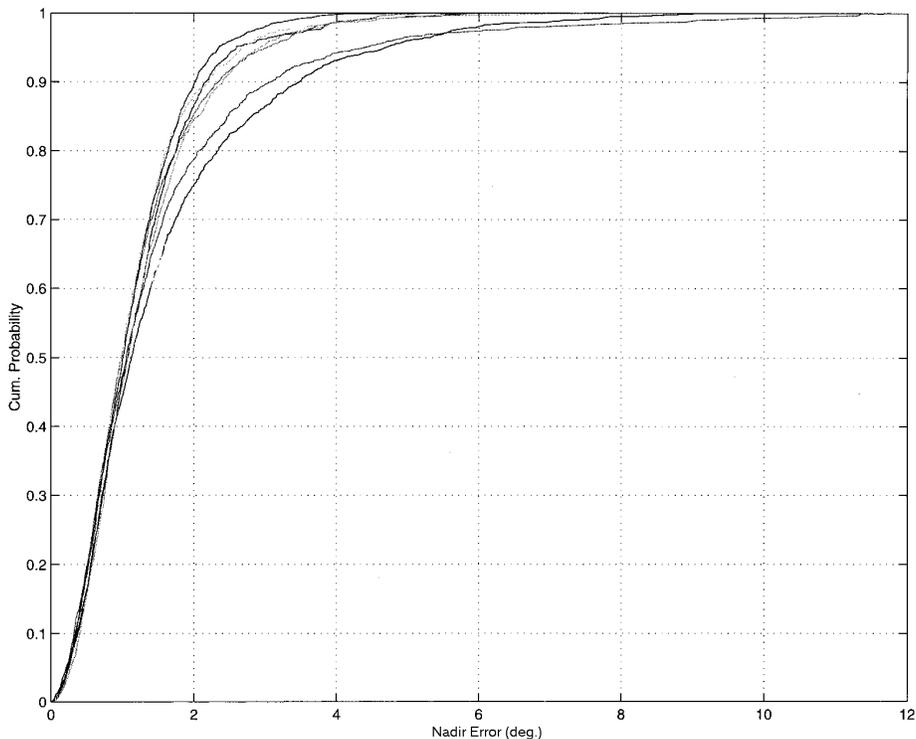


**Figure 8 Nadir Pointing Trajectory for Spacecraft in C Plane (C5)**

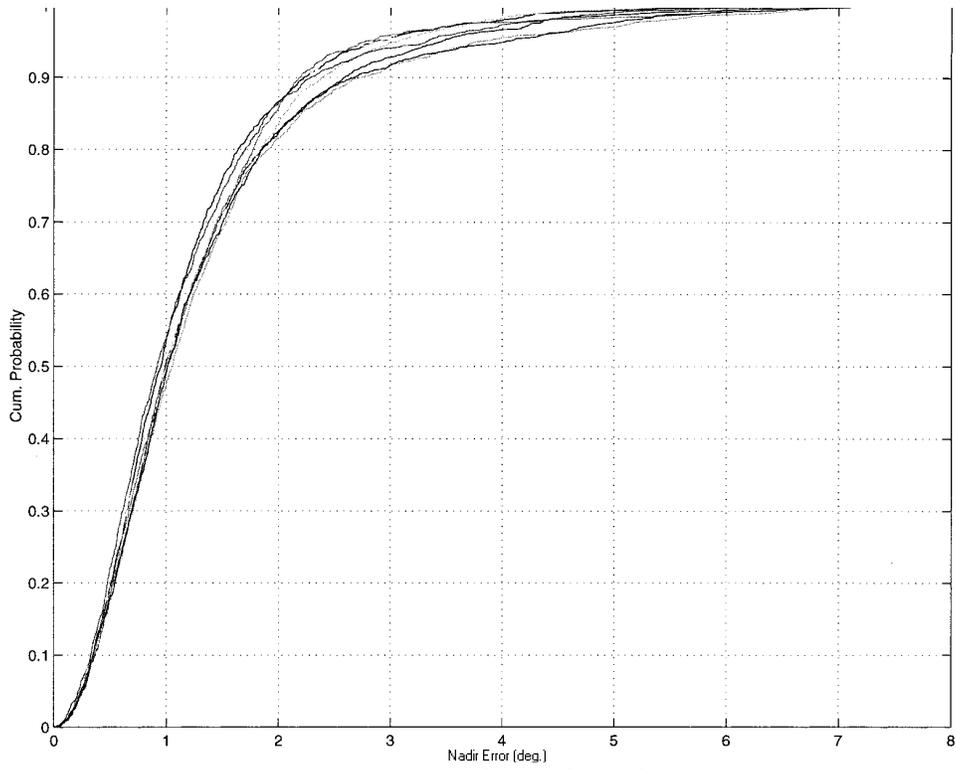
performance first, Figure 8 plots the nadir pointing trajectory (pitch versus roll) for a single spacecraft. Typical of all constellation spacecraft, the nadir error is less than 5 degrees 90% of the time.

Taking nadir performance from the viewpoint of multiple spacecraft, Figures 9 through 11 show nadir pointing performance of all spacecraft in A,B,C planes respectively in terms of their cumulative probability functions. All spacecraft show performance that exceeds requirements, with pointing within 5 degrees for over 90% of the time, and better than 10 degree pointing all the time. The CEP (circular error probable) performance of the spacecraft is about 1 degree compared to the 5 degree requirement.

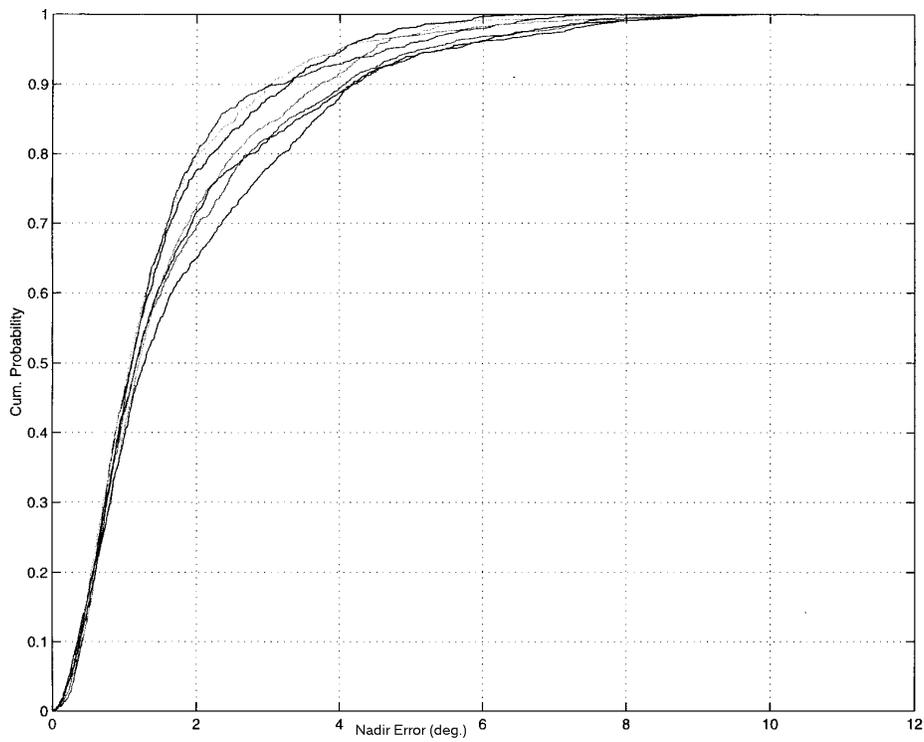
The ACS has to provide yaw performance commensurate to the needs of the EPS for solar array power generation. Figures 12 through 14 show the cumulative probability function for yaw error for all spacecraft in plane A,B and C over a period of almost a month. The yaw error remains below 5 degrees 90% of the time for all spacecraft in plane A and B. This is significantly below the required 18 degrees to meet the 95% power generation requirement. The requirement is met even during the rare excursion to larger yaw errors.



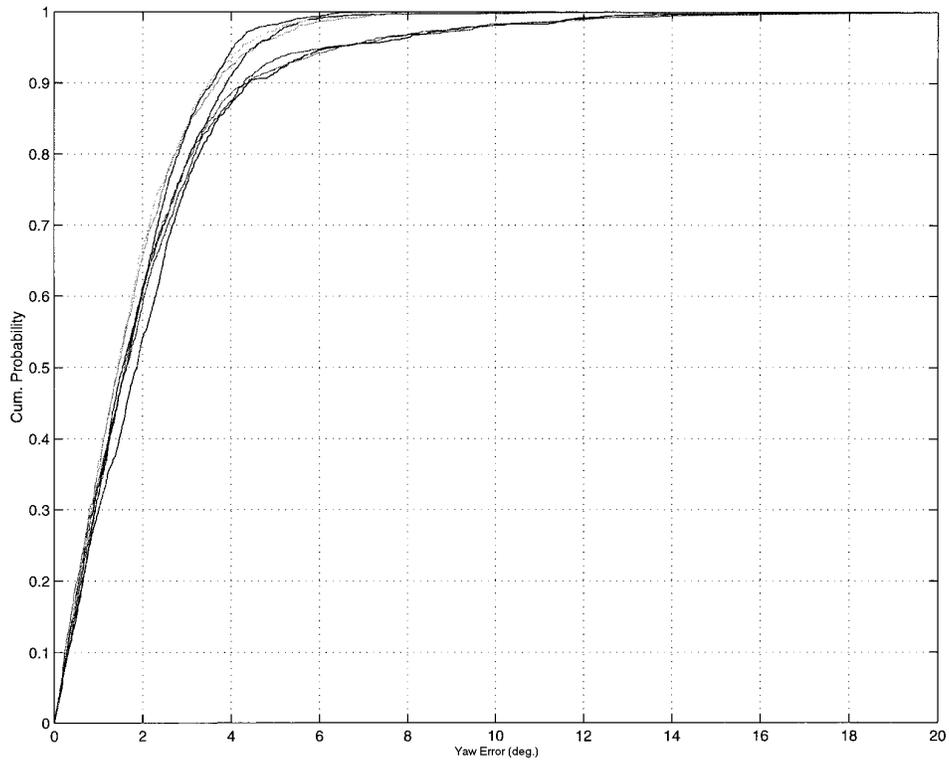
**Figure 9 Nadir Error CDF for Plane A Spacecraft**



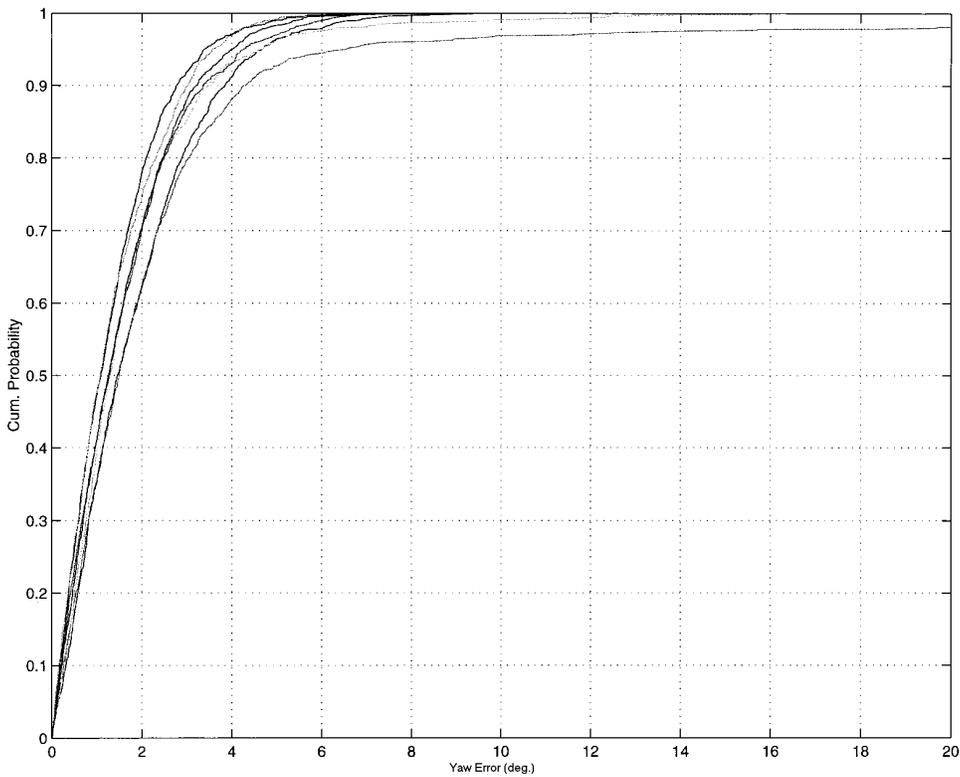
**Figure 10 Nadir Error CDF for Plane B Spacecraft**



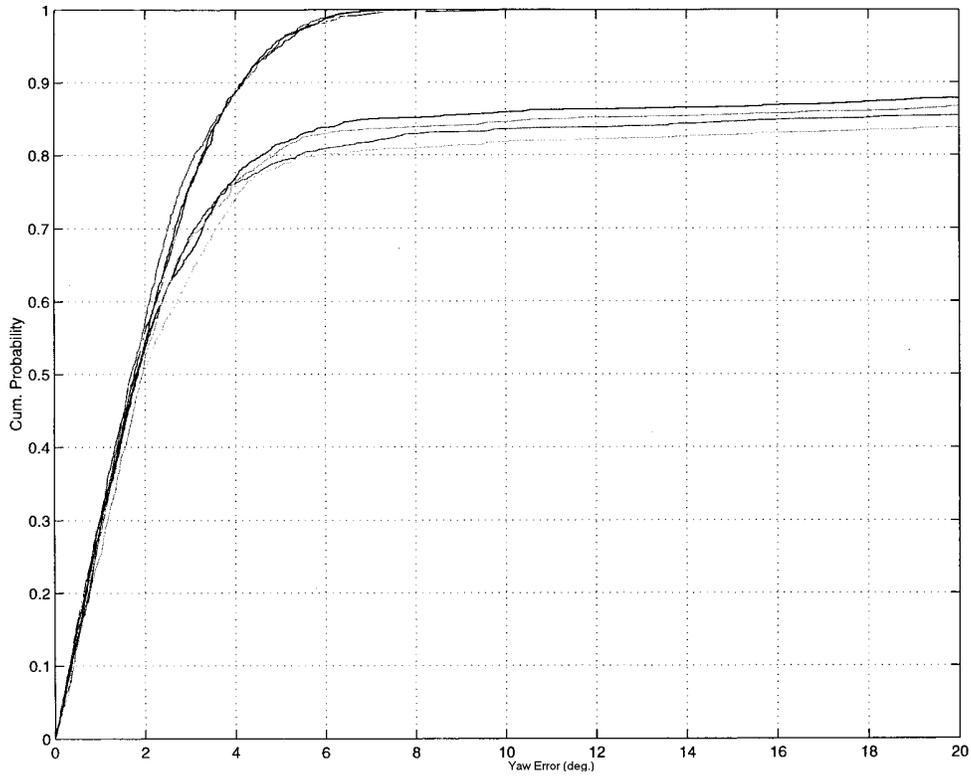
**Figure 11 Nadir Error CDF for Plane C Spacecraft**



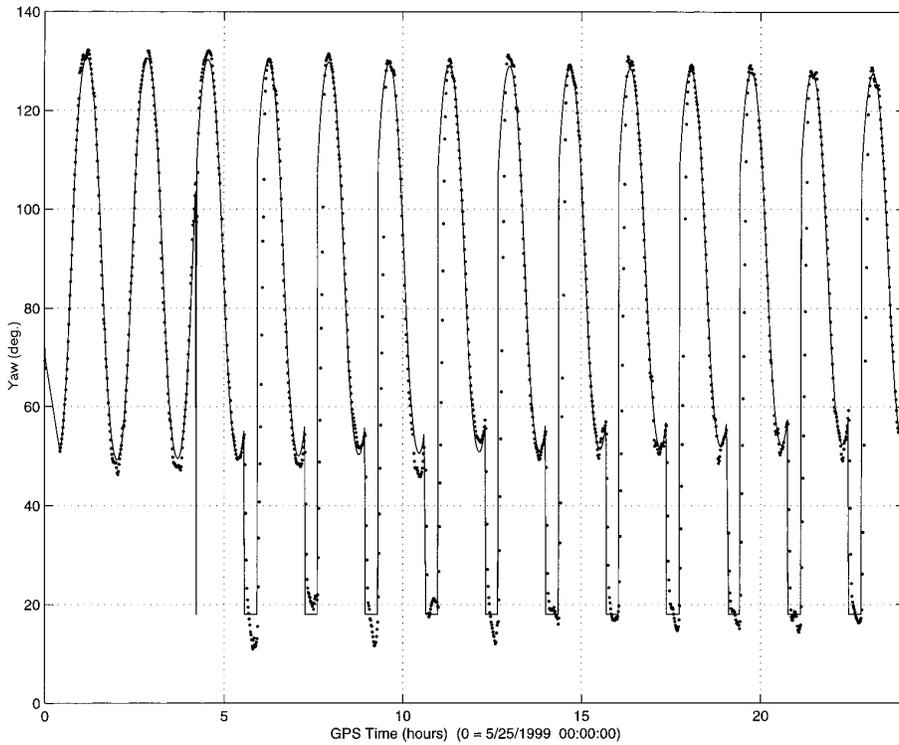
**Figure 12 Yaw Error CDF for Plane A Spacecraft**



**Figure 13 Yaw Error CDF for Plane B Spacecraft**



**Figure 14 Yaw Error CDF for Plane C Spacecraft**



**Figure 15 Commanded Yaw versus Actual Yaw for Spacecraft in C Plane (C3)**

This level of ACS performance is consistent across all constellation spacecraft. Four of the spacecraft in plane C show higher than expected yaw errors. The explanation for this is shown for a select spacecraft in Figure 15. During the time period these four spacecraft were commanded to certain yaw angles in order to perform scheduled flare/feather maneuvers.

### Global Positioning System (GPS)

Performance of the GPS subsystem can be characterized in terms of the tracking performance, percentage of time the receiver provides fixes, and the accuracy of the fixes<sup>3</sup>. Figure 16 presents the tracking

might be expected from the CA code-capable GPS receiver, the accuracy for all spacecraft are in the 75-125 m range. The ACS filters out large errors when processing GPS navigation data.

A good statistic that summarizes GPS performance is the percentage of time the GPS receiver remains converged and provides navigation fixes. Figure 17 is a bar chart, which shows the daily fix percentage of spacecraft C2 over the course of over 2 months. Averaging the daily fix percentage over this time period results in C2's average daily fix percentage to be 98%. Averaging this statistic across all the

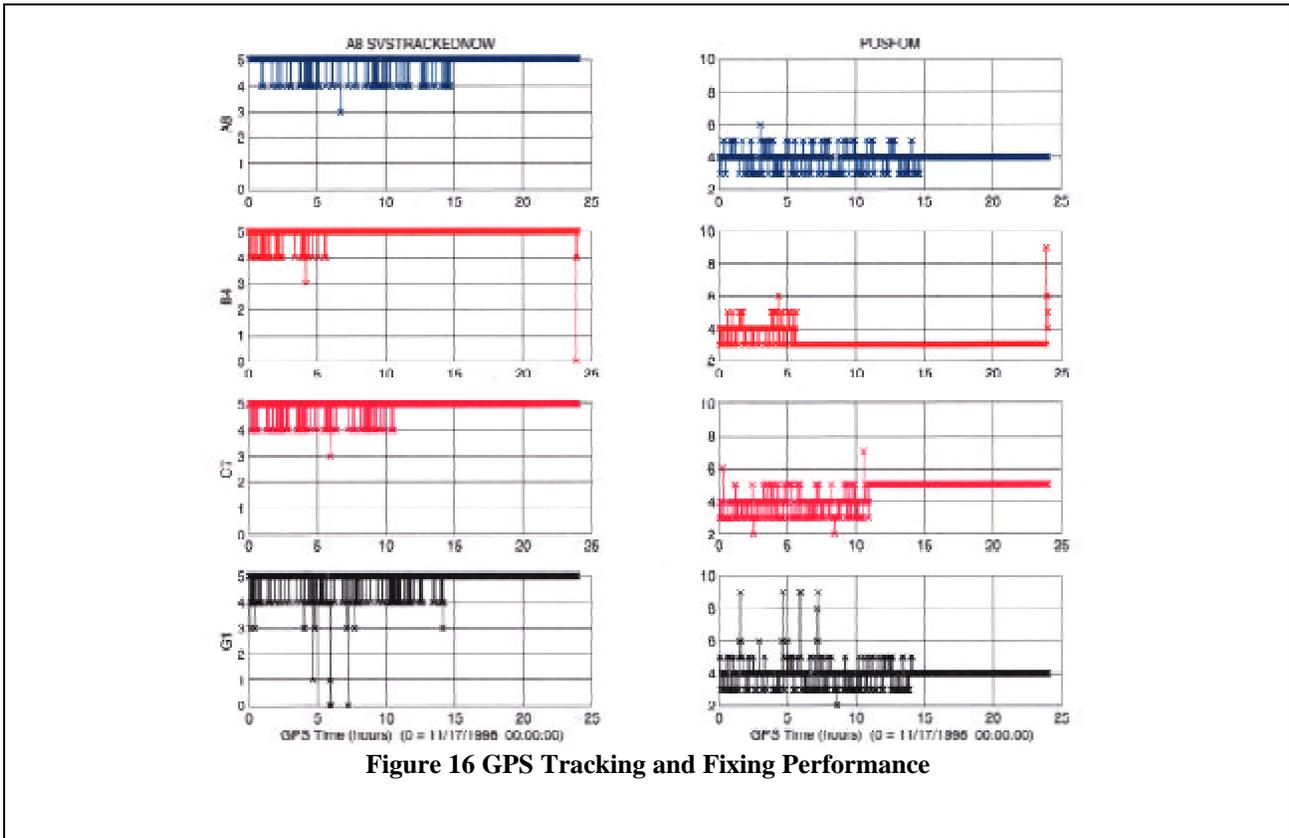


Figure 16 GPS Tracking and Fixing Performance

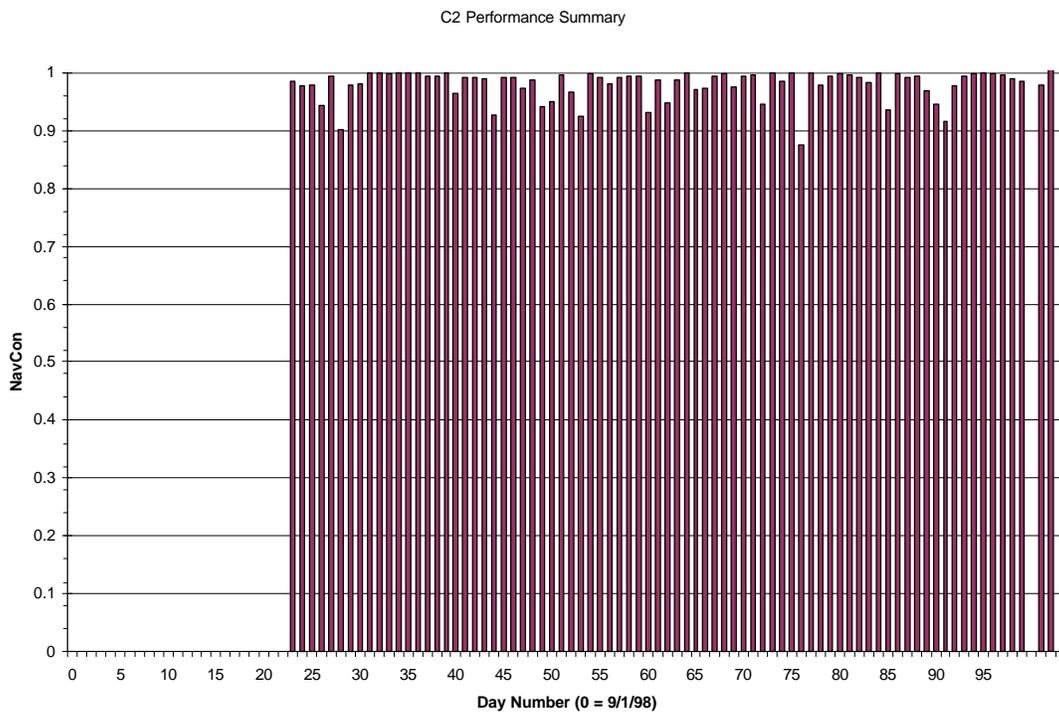
and fix accuracy performance of 4 spacecraft over the course of a day. As shown by the plots on the left, the 5 channel receivers on all spacecraft track 4 or 5 GPS spacecraft for the most part. Although G1 has more loss-of-track events, it nevertheless provides navigation fixes for over 99% of the time like the other spacecraft.

The plots on the right in Figure 16 plot the Position Figure of Merit (PFOM) for all spacecraft. The PFOM is a quantifiable measure of the quality and accuracy of the navigation fix provided by the GPS receiver. For example a PFOM of 4 corresponds to 100m accuracy while a PFOM of 3 corresponds to 75 m accuracy. As

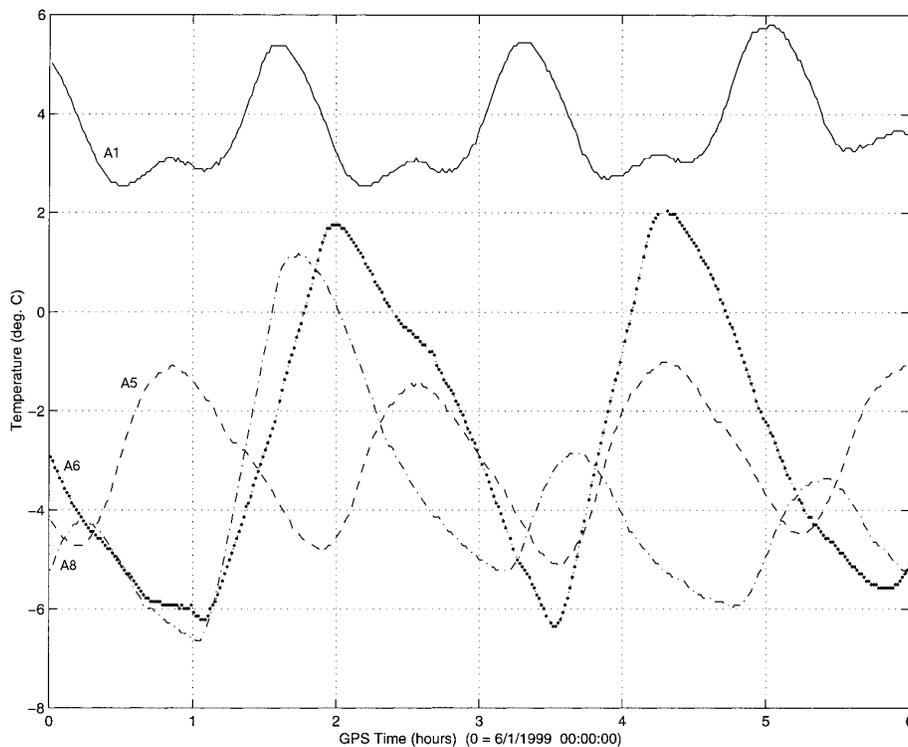
constellation spacecraft for the same timeframe results in a constellation average of 90% fix percentage. Ground-based orbit determination using the same GPS data results in navigation accuracy in the range of 40-70m.

### Thermal Control Subsystem (TCS)

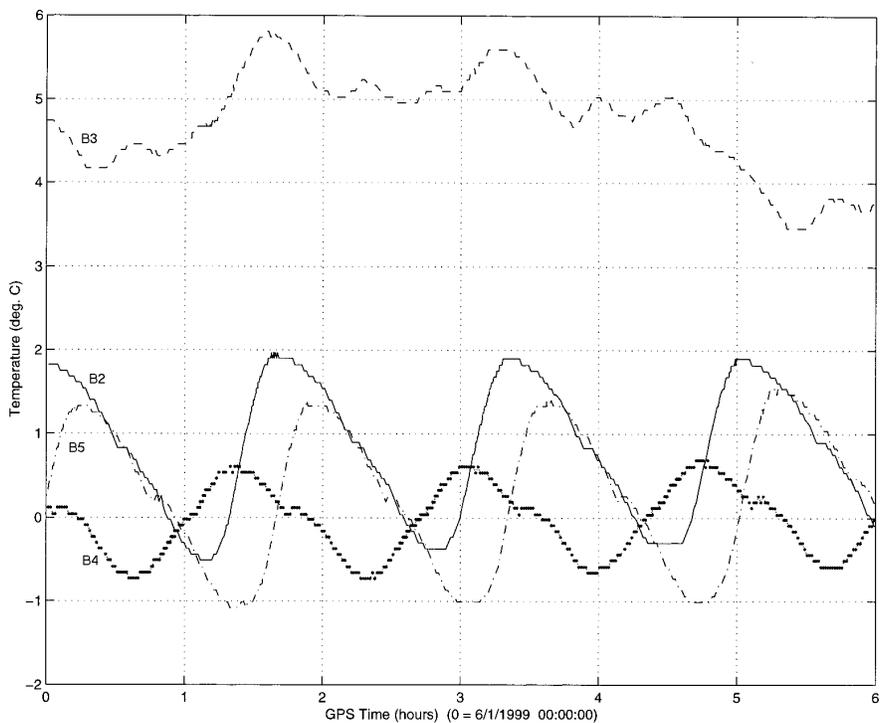
TCS performance is demonstrated here in terms of maintaining the temperature of one of the most critical components on the spacecraft, the battery. The requirement is to maintain the battery in the range of -5 to 10 degrees C. Figures 18 through 20 show the battery temperature for four spacecraft in each of three



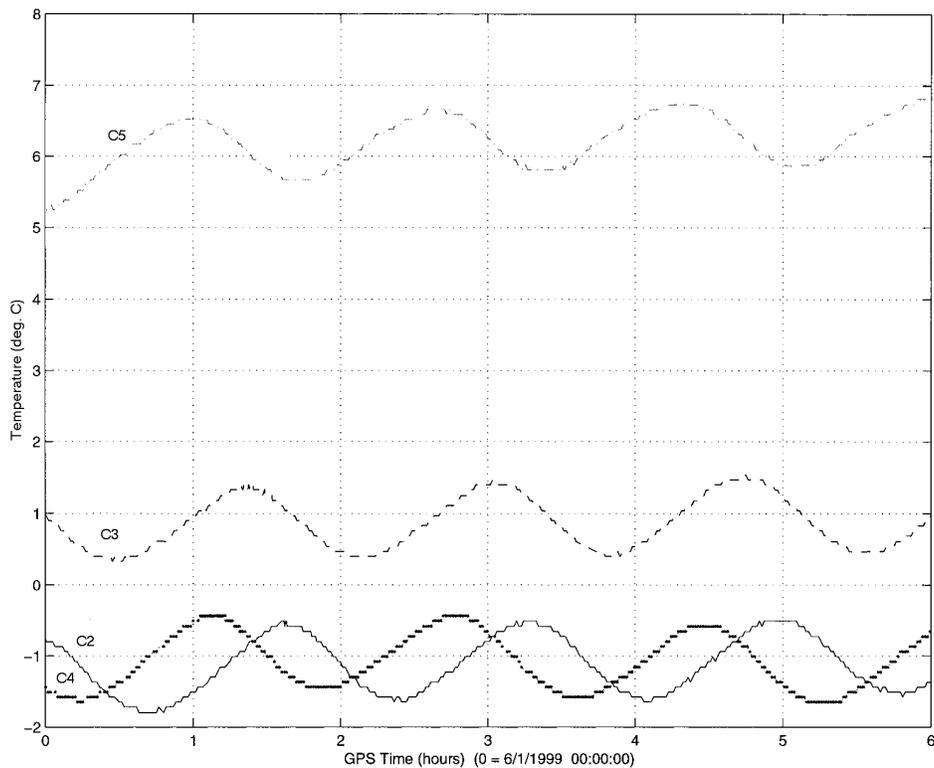
**Figure 17 C2 GPS Fix Availability**



**Figure 18 Battery Temperature for Four Spacecraft in A Plane (A1, A5, A6, A8)**



**Figure 19 Battery Temperature for Four Spacecraft in B Plane (B2, B3, B4, B5)**



**Figure 20 Battery Temperature for Four Spacecraft in C Plane (C2, C3, C4, C5)**

planes. Battery temperature is maintained in the range of -2 to 7 degrees C for the spacecraft in plane B and C thereby complying with the requirement. The plane A spacecraft were commanded to various yaw angles during the time period displayed and thus do not display as tightly controlled temperature ranges. Also evident in the plots of battery temperature for multiple spacecraft is the variability in nominal temperature and the time lag due to the relative phasing of the orbit position which results in different eclipse entry and exit conditions.

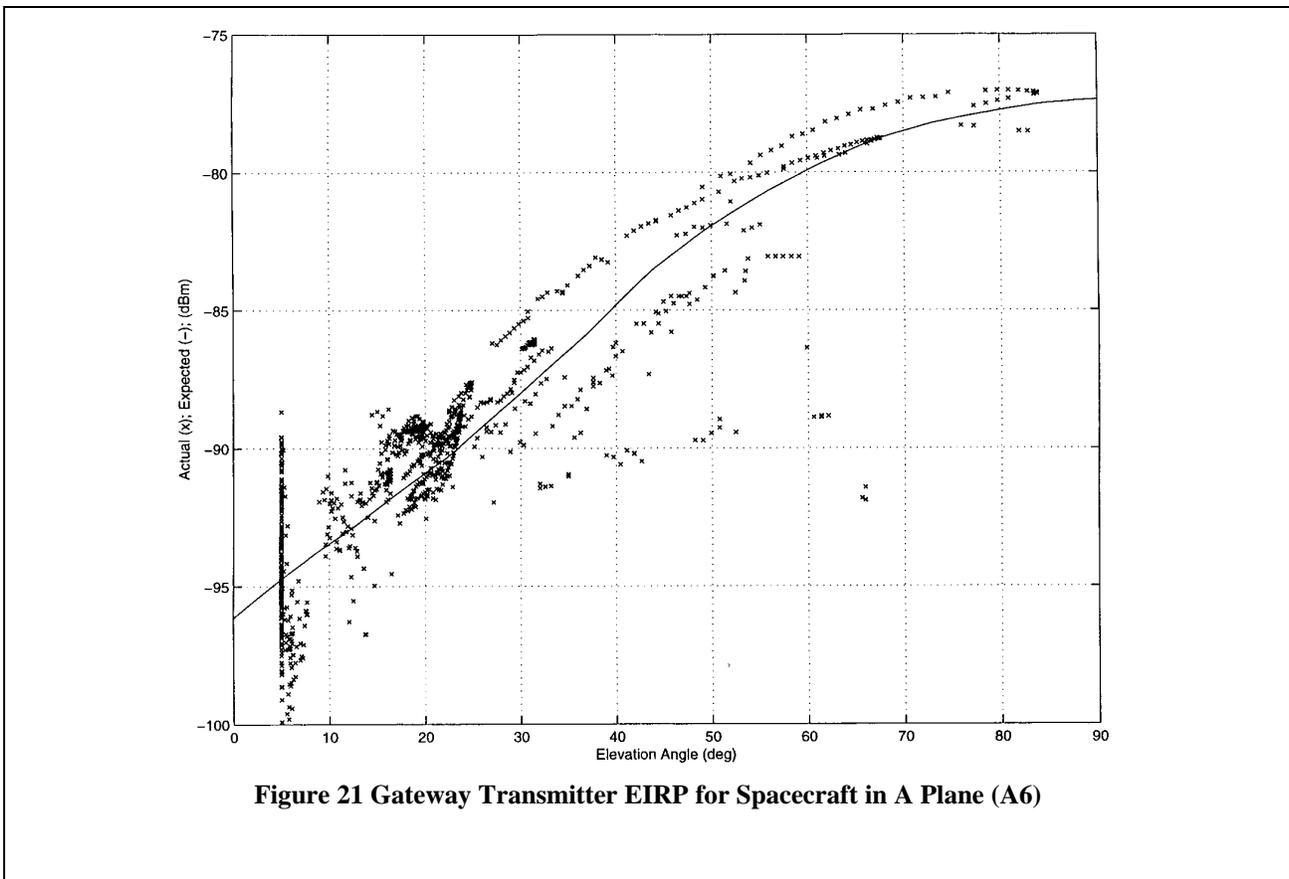
**Gateway Transceiver (GWT)**

The primary performance parameter of interest for the GWT is the received power at the gateway earth station

effect adding even greater measurement variance at low elevation angles.

**Subscriber Receiver (SRX)**

A pertinent performance parameter for the SRX is a scan of the received power level across the receiver VHF frequency band. Figures 25 and 26 show such scans for a plane B and C spacecraft. The spike evident in the center channel is expected and due to the local oscillator residing in the SRX. Figure 25 shows the power level for a specific channel, which was used for transmission for a brief period of time. The performance of the selected spacecraft is typical of the performance seen on the other constellation spacecraft.



**Figure 21 Gateway Transmitter EIRP for Spacecraft in A Plane (A6)**

antenna. This is a measure of the GWT’s transmit capability. Figures 21 through 23 plot received power as a function of elevation angle for a single spacecraft in planes A,B and C.

As expected, this shows received power to increase with elevation angle and leveling off as elevation angle reaches 90 degrees. Scatter is expected due to the constant variations in the atmosphere with multi-path

**Subscriber Transmitter (STX)**

One of the primary performance parameters for the STX is the power received by the communicator units. Figures 27 through 29 show received power as a function of elevation angle, displaying characteristics similar to those shown in the GWT figures. The data for plane A has not been filtered for spacecraft antenna pointing errors nor instances where the gateway earth elevation angle is out of limits. This results in data points, which are well below expected levels.

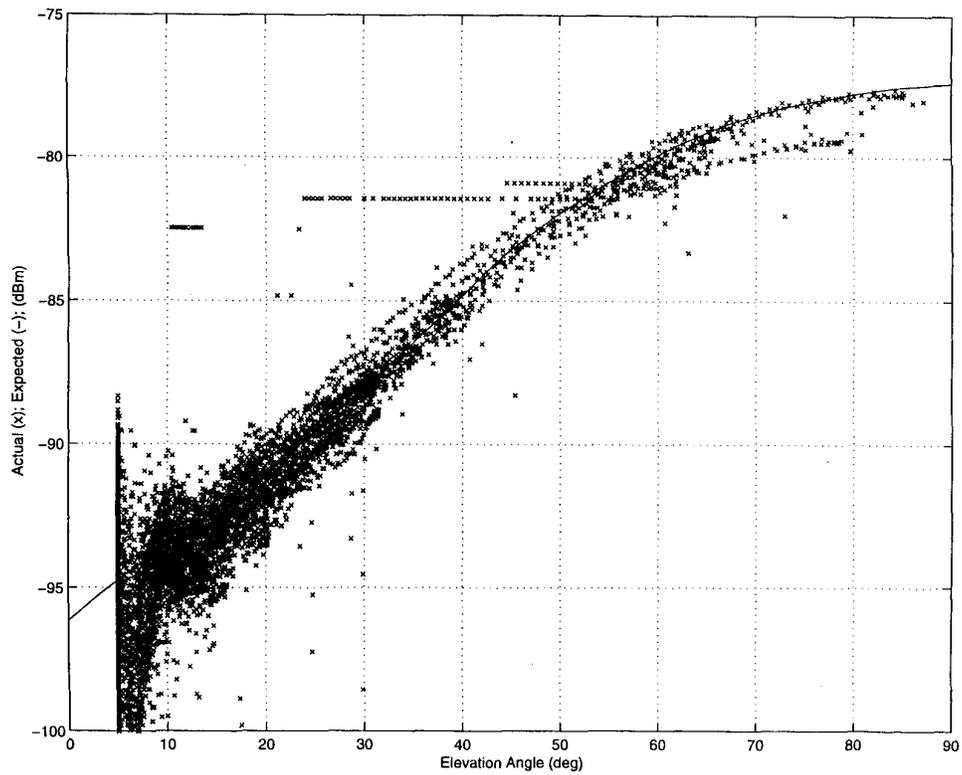


Figure 22 Gateway Transmitter EIRP for Spacecraft in B Plane (B4)

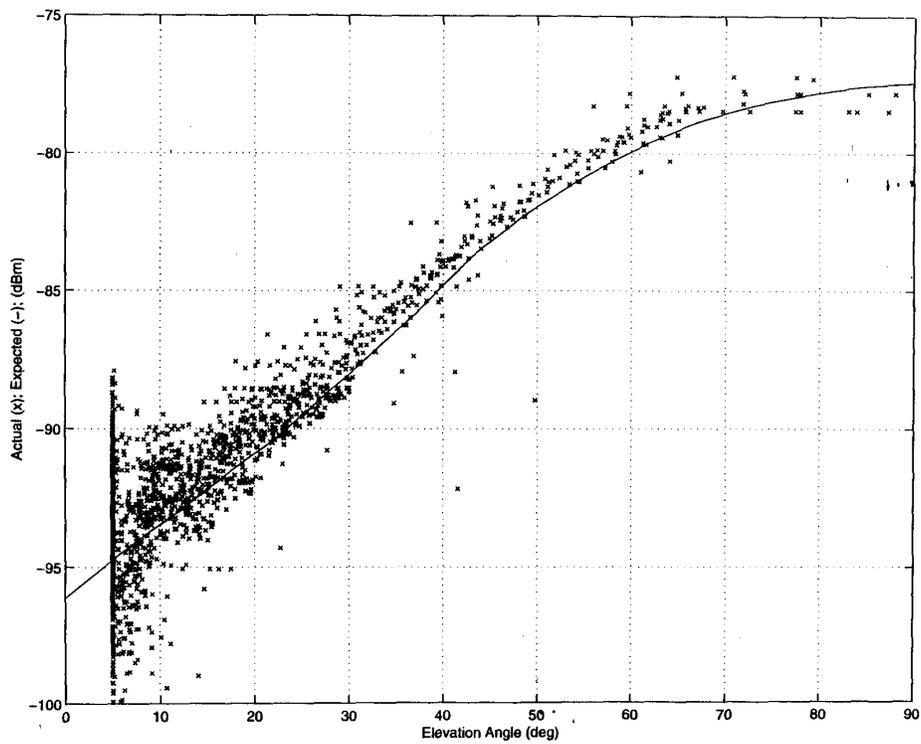
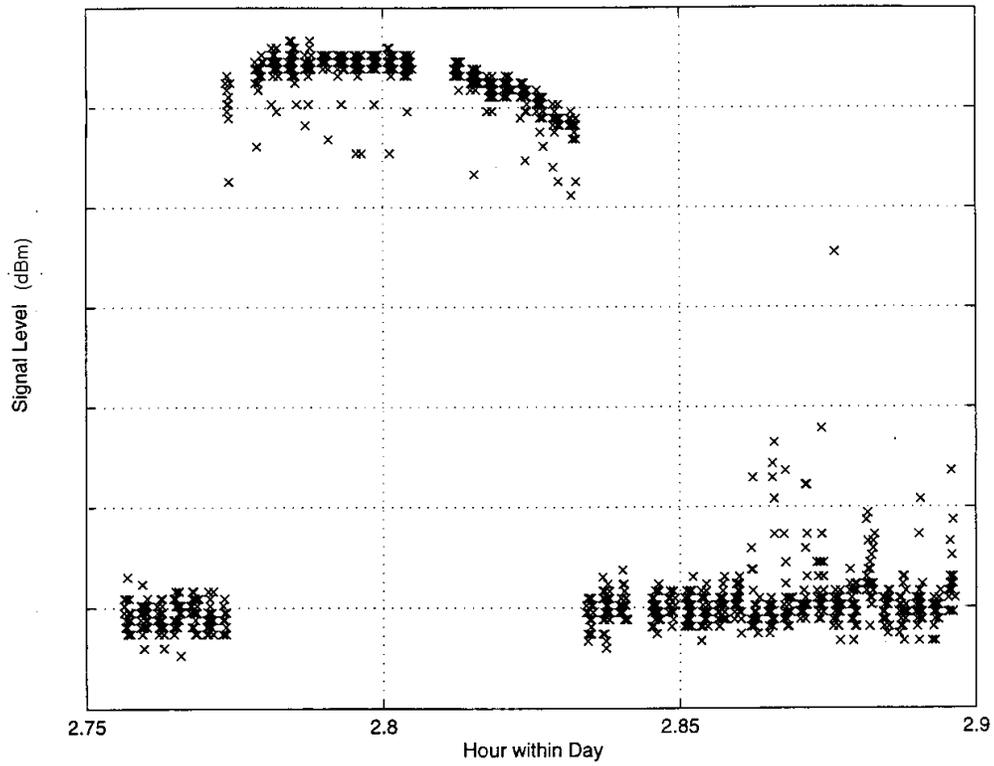
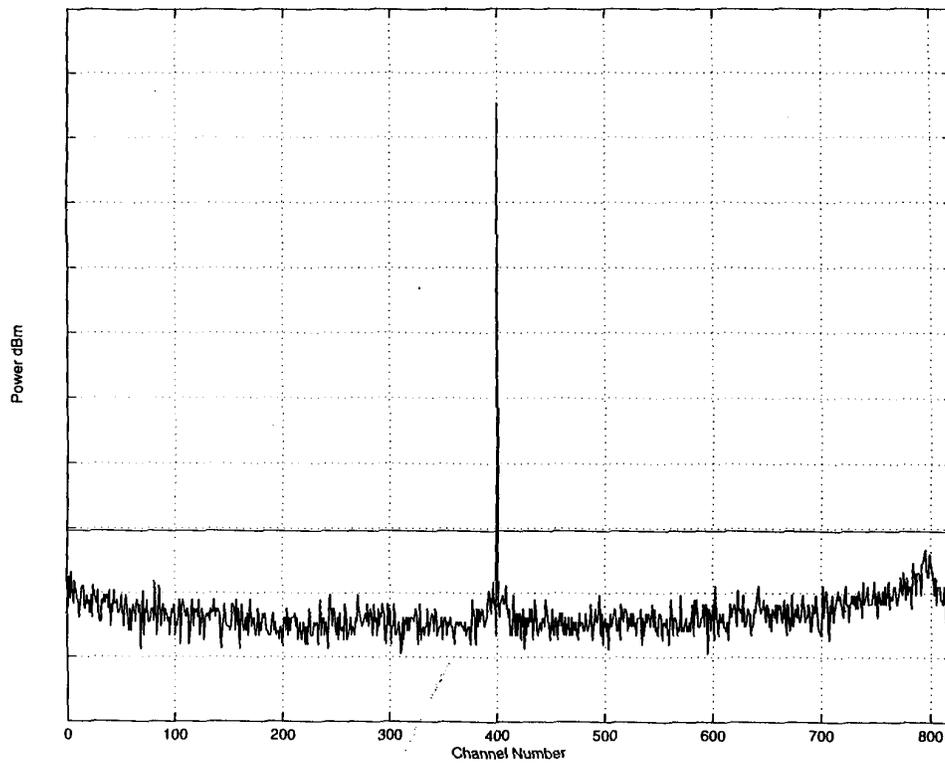


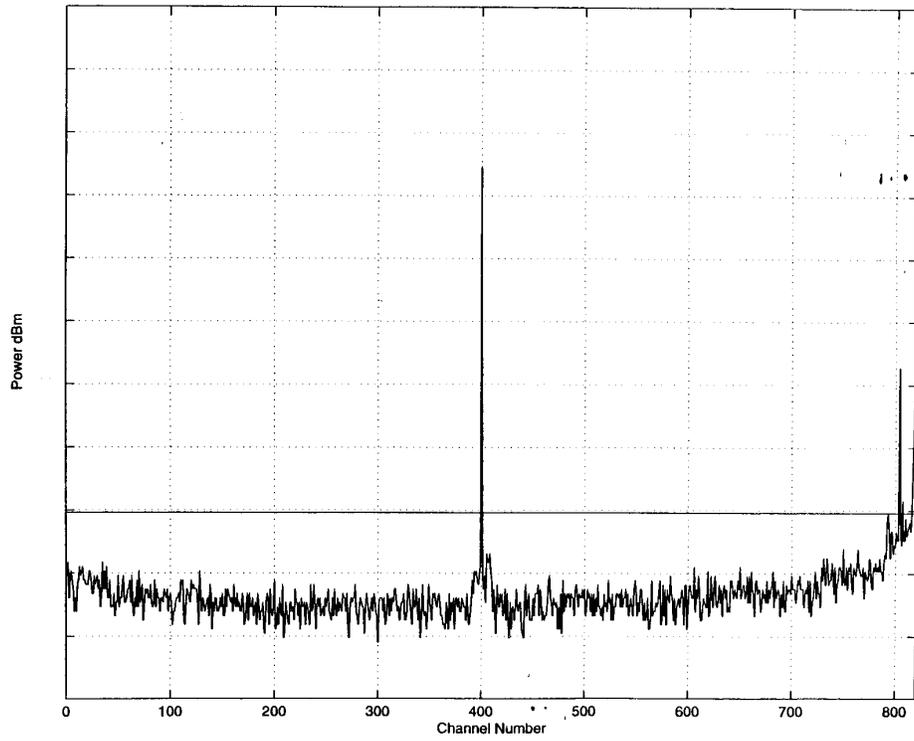
Figure 23 Gateway Transmitter EIRP for Spacecraft in C Plane (C3)



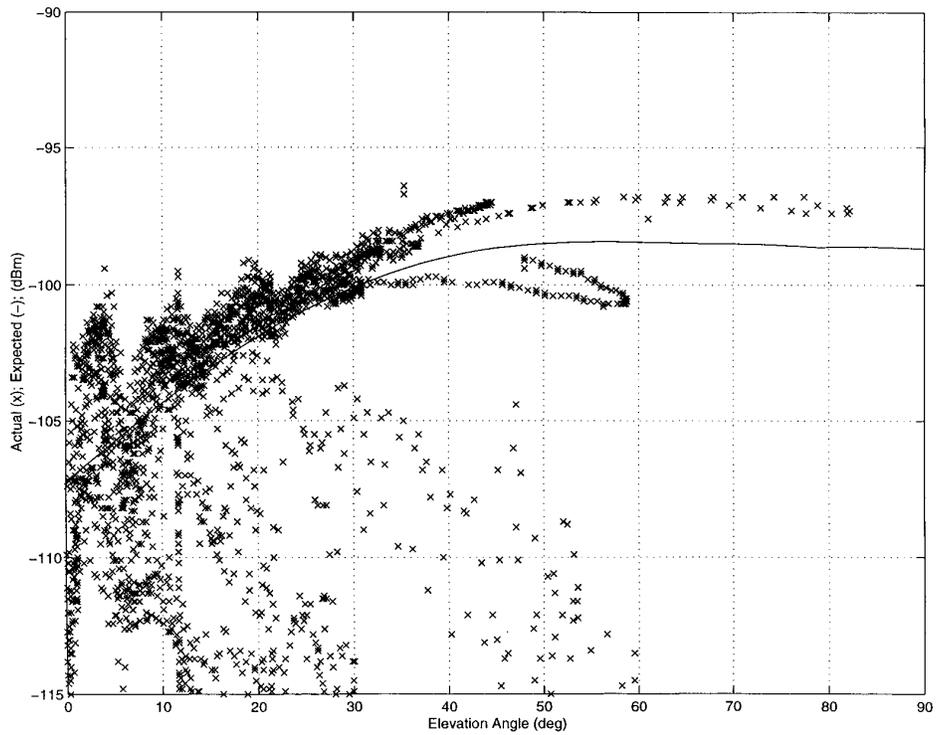
**Figure 24 Scan Data for Channel 524 for Spacecraft in A Plane (A6)**



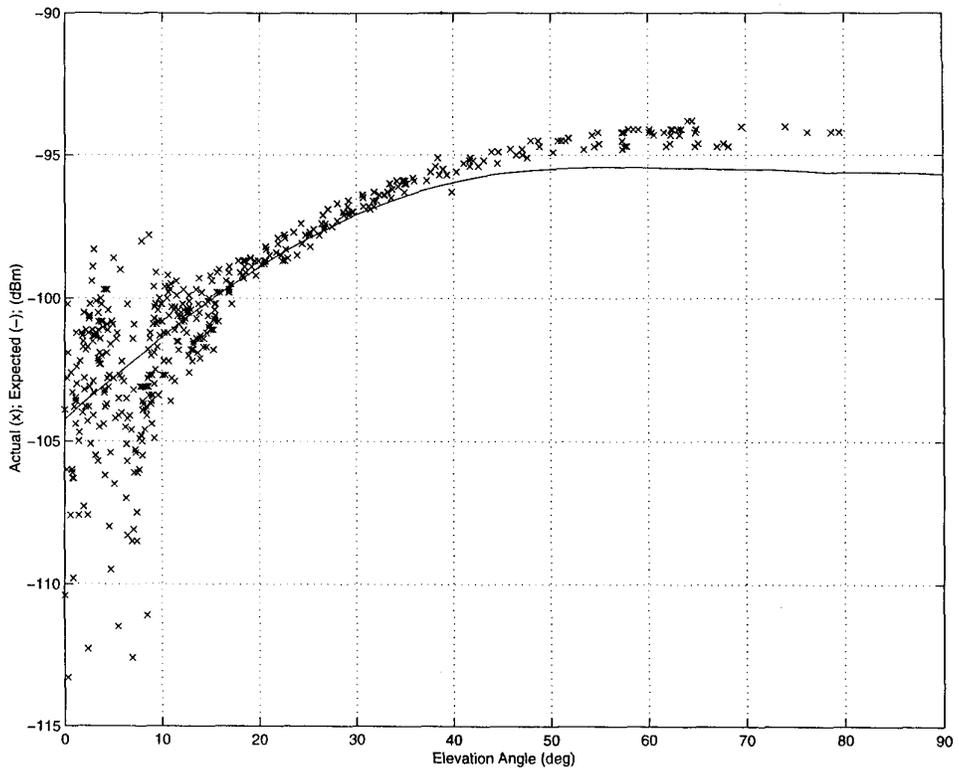
**Figure 25 Subscriber Receiver Scan for Spacecraft in B Plane (B4)**



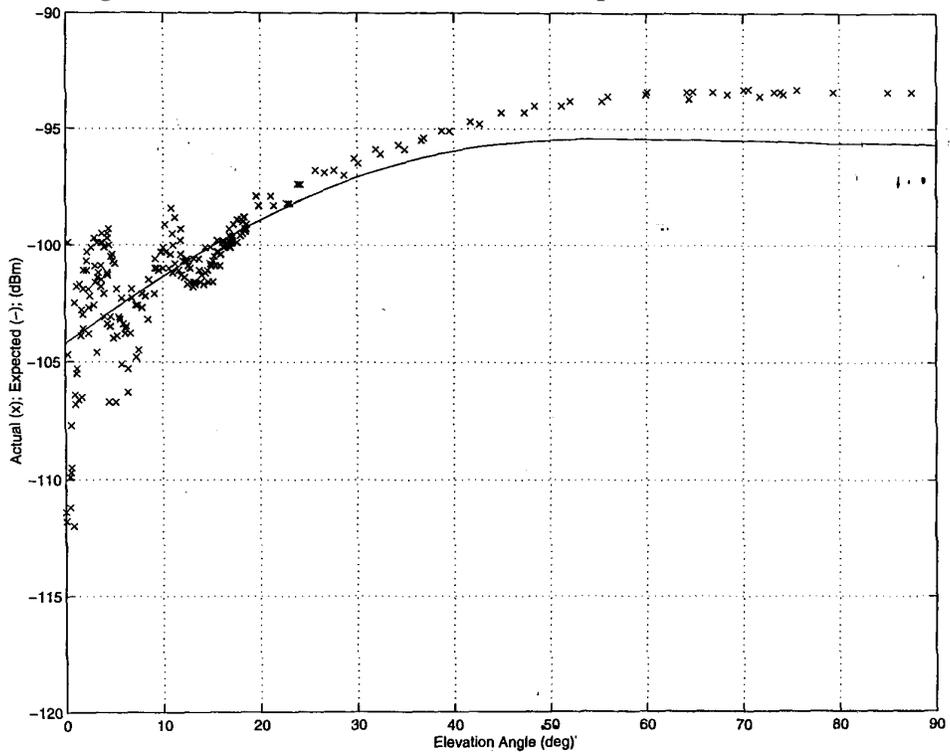
**Figure 26 Subscriber Receiver Scan for Spacecraft in C Plane (C3)**



**Figure 27 Subscriber Transmitter EIRP for Spacecraft in A Plane (A6)**



**Figure 28 Subscriber Transmitter EIRP for Spacecraft in B Plane (B4)**



**Figure 29 Subscriber Transmitter EIRP for Spacecraft in C Plane (C3)**

## **Conclusion**

With 26 spacecraft launched in 10 months in 1998, the ORBCOMM spacecraft constellation is the world's first commercial LEO data constellation in service. The spacecraft design forms the basis for the Orbital's Microstar platform. The constellation has already amassed over 30 spacecraft-years of on-orbit experience that shows the spacecraft to be meeting and in many areas exceeding performance requirements.

Unlike a single spacecraft mission, the ORBCOMM constellation provides the unique opportunity to assess the performance of various hardware components across numerous spacecraft simultaneously and over longer periods of time. This paper has attempted to provide a sampling of the large amount of performance data accumulated for each of the 6 subsystems of the 26 spacecraft that have been in operation for over 1.5 years.

It is evident from the sampling of data presented in this paper that the performance of the constellation spacecraft is very consistent across spacecraft and over time. The variability that is apparent is generally due to one or more of three factors, those being hardware peculiarities, orbital position/attitude and atmospheric variations. The hardware peculiarities particularly manifest themselves in the plots of battery capacity. The variability seen due to the orbital location is expected and only verifies that the spacecraft behave as intended. The atmospheric variations are obviously uncontrollable, but the presented data shown that adequate margins were adopted in the communication subsystems such that the spacecraft meet all requirements within the specified elevation ranges.

The presented data demonstrates that Orbital's high mass-power-volume efficiency spacecraft also provides consistent high performance across many spacecraft over long time. The high level of heritage, accumulated on-orbit experience, and demonstrated on-orbit performance substantiates the utility of this low cost spacecraft bus for future commercial communications or remote sensing constellation applications.

## **Acknowledgments**

This paper is dedicated to the ORBCOMM spacecraft program team. The authors would also like to thank the following people for assistance: John Stolte and John Tandler for reviewing the paper; Bill Peterson and Kellie Deane for assisting with the preparation of this paper.

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