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Operational Workarounds for the Space Station Beta Gimbal Anomaly

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The International Space Station (ISS) is the largest and most complex spacecraft ever assembled and operated in orbit. The first U.S. photovoltaic module, containing two solar arrays, was launched, installed, and activated in early December 2000. After the first week of continuously rotating the U.S. solar arrays, engineering personnel in the International Space Station Mission Evaluation Room observed higher than expected electrical currents on the drive motor in one of the beta gimbal assemblies, the mechanism used to maneuver a U.S. solar array. The magnitude of the motor currents continued to increase over time on both beta gimbal assemblies, creating concerns about the ability of the gimbals to continue pointing the solar arrays towards the sun, a function critical for continued assembly of the ISS. A number of engineering disciplines convened in May 2001 to address this on-orbit hardware anomaly. This paper reviews the International Space Station electrical power system analyses performed to develop viable operational workarounds that would minimize beta gimbal assembly use while maintaining sufficient solar-array power to continue assembly of the International Space Station. Additionally, electrical power system analyses performed in support of on-orbit beta gimbal assembly troubleshooting exercises are reviewed.

Nomenclature

x = axial coordinate
y = axial coordinate
z = axial coordinate
β = angle between the sun vector and orbit plane

Introduction

WHEN fully assembled, the U.S. electrical power system (EPS) will include four photovoltaic (PV) modules[1] that will be capable of producing a combined average power output of 75 kW. The arrays power not only electrical loads when the station is in the sun, but also charge batteries that supply the station's power demands in eclipse. To maximize the power available for core system electrical loads, unique International Space Station (ISS) assembly activities, and scientific experiments, the arrays need to be pointed towards the sun throughout the sunlit period of the orbit (insolation). Continuous sun pointing is accomplished via target positions supplied to the beta gimbal assemblies (BGA) by the onboard guidance, navigation, and control (GN&C) system. The BGA target positions are updated once every second by the GN&C software.

In the early ISS assembly configuration, as depicted in Fig. 1, the solar arrays on the first U.S. PV module, designated P6, can only rotate in one axis. The solar arrays, designated PV (or channel) 2B and PV 4B, are electrically isolated. The percentage of the maximum solar-array power available for electrical loads can be approximated by the cosine of the sun incidence angle. This angle is measured between the normal to the active surface of the array and the sun vector. The magnitude of the sun incidence angle is influenced by three factors: the vehicle orientation (or attitude), the array position, and the solar β angle, which is the angle measured between the sun vector and the orbit plane (see Fig. 2).

The ISS generally orbits in one of two attitudes: Xvv Znadir or XPOP. In the Xvv Znadir attitude (see Fig. 3), the ISS+X axis points in the direction of the velocity vector, while the ISS+Z axis points nadir. In this attitude, the BGAs rotate each solar array through a full 360-deg sweep about its longitudinal axis once every orbit, 16 orbits per day, to track the sun. When the ISS is flying in this Xvv Znadir attitude, the power generated from the P6 solar arrays decreases as the magnitude of the solar β angle increases. This occurs because the sun incidence angle on the arrays increases with increasing solar β angle.

In the XPOP attitude (see Fig. 4), the ISS X axis remains pointed in a direction perpendicular to the orbit plane. The XPOP attitude is more conducive for power generation because the sun incidence angle remains nearly perpendicular to the active surface (front side) of the P6 solar arrays throughout the orbit. In this attitude, the BGAs travel approximately 4.5 deg/day, which is roughly equivalent to the daily rate of change of the solar β angle.

Beta Gimbal Assembly Anomaly

The BGA provides two critical capabilities to the ISS: 1) transfer of electrical power across a rotating joint and 2) positioning of the solar arrays. The primary component of the BGA, illustrated in Fig. 5, is the bearing motor roll ring module (BMRRM). The BMRRM contains a unique bearing assembly that, before the ISS, has never been operated in space. Because of this, it is difficult to determine what constitutes an anomalous motor current signature.

Industry standards state that the system should operate below 25% of full capability for average current and below 50% of full capability for peaks. The BMRRM motor can supply a maximum output current of 1.5 A. Applying the industry standards, a BMRRM motor current of <0.38 A is considered an average or nominal value, while a BMRRM motor current of >0.75 A is considered anomalous and is often referred to in the BGA community as a motor current "spike."

During the majority of the first month of operations, the BGAs remained parked in a stationary position that was selected to optimize

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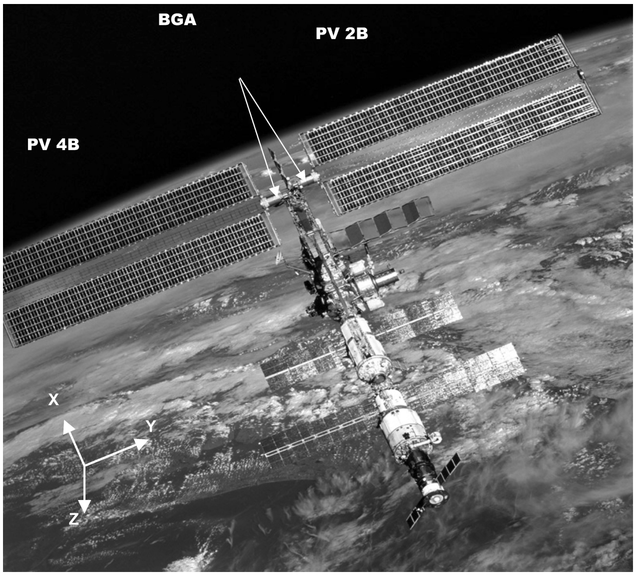

Fig. 1 Location of the gimbals that rotate the U.S. photovoltaic arrays.

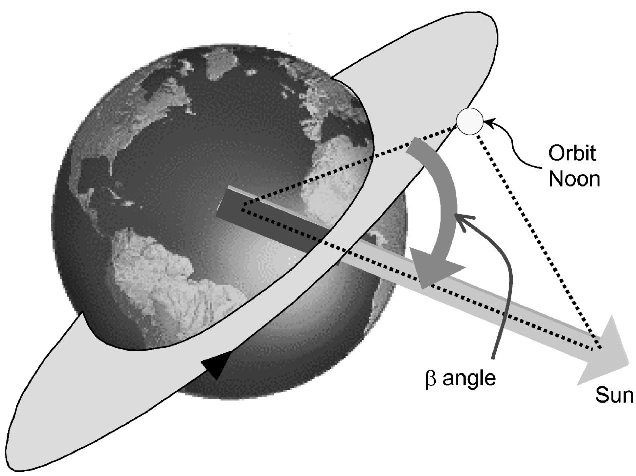

Fig. 2 Solar β angle.

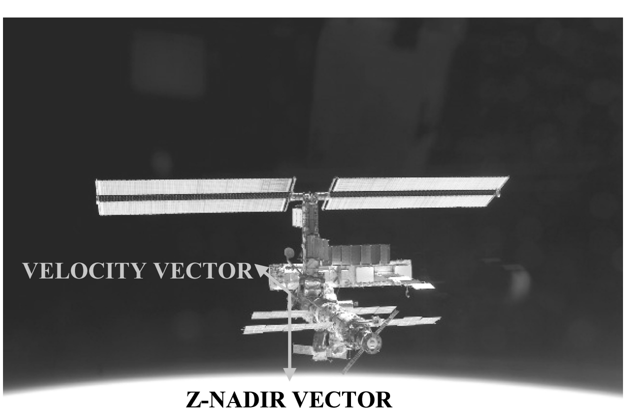

Fig. 3 Illustration of the ISS orbiting in the Xvv Znadir flight attitude.

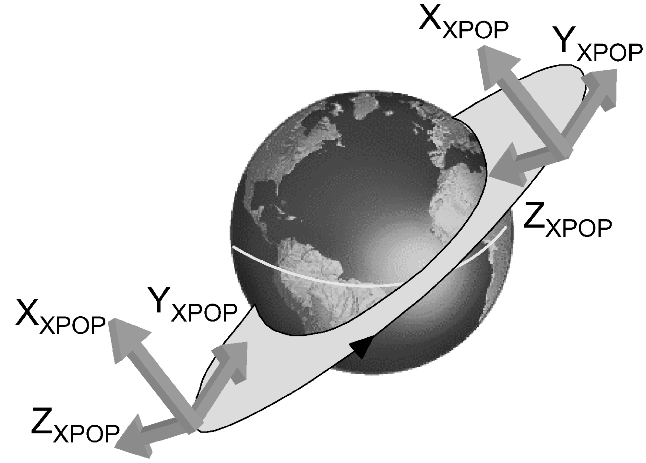

Fig. 4 XPOP flight attitude.

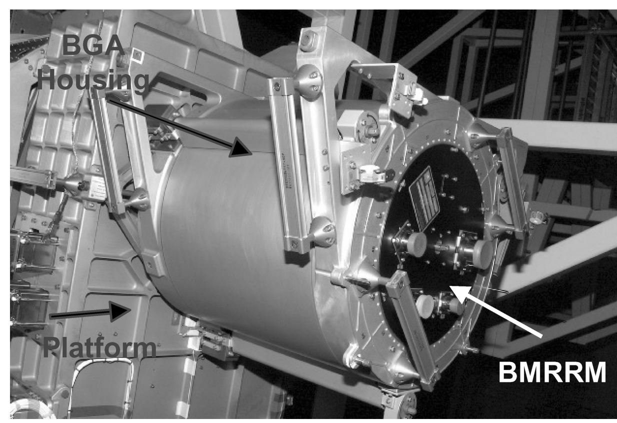

Fig. 5 Beta gimbal assembly.

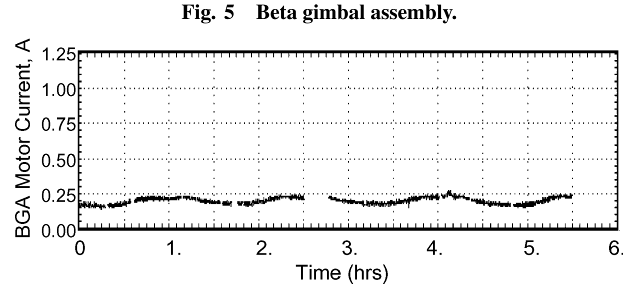

Fig. 6 Channel 4B BMRRM motor current (amps) over 5.5-h period (performance after 20 cumulative rotations).

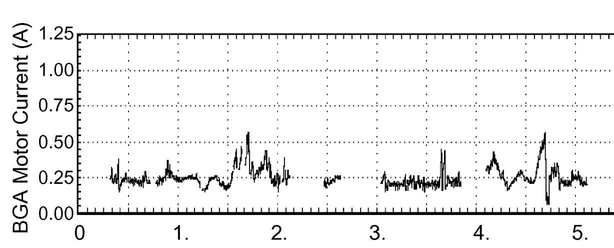

Fig. 7 Channel 4B BMRRM motor current (amps) over 5-h period (performance after 635 cumulative rotations).

power generation. The arrays were not required to rotate because the U.S. power demands were low. The primary incentive for parking the solar arrays was to reduce the drag on the vehicle. As a result, the rate of degradation of the ISS altitude was decreased, and on-orbit propellant supplies were preserved. The electrical loads increased significantly with the installation of the U.S. Laboratory module Destiny in January 2001. The power system began to rely more heavily on the BGAs to rotate when the ISS was orbiting in the Xvv Znadir attitude, allowing the P6 solar arrays to provide the power necessary to meet the increased electrical load demands.

After one week of continuous rotation, engineering support personnel in the ISS Mission Evaluation Room (MER) observed higher than expected electrical currents on the drive motor in the channel 4B BMRRM. The 4B BMRRM performance steadily decreased over the next four months, as the frequency of excursions over 0.5 A increased with time (Figs. 6 and 7).

In early May 2001, the 4B BMRRM experienced the first motor current in excess of 1.0 A. This was a significant milestone

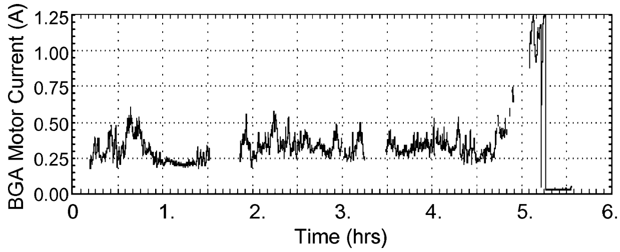

Fig. 8 Channel 4B BMRRM motor current (amperes) performance during a stall event (5.5 h).

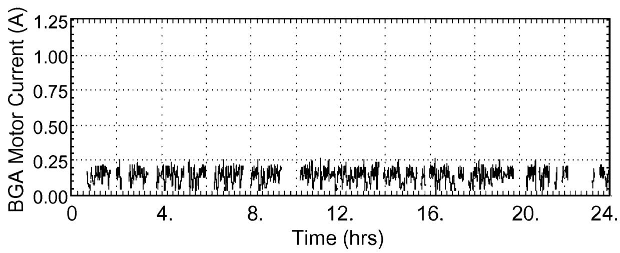

Fig. 9 Channel 4B BMRRM motor current performance in the XPOP attitude (24 h).

because it indicated the BGA motor needed two-third of its maximum capability to maintain rotation. At the same time, the channel 2B BMRRM, which had been operating nominally, began experiencing motor currents in excess of 0.5 A.

After 1200 cumulative rotations, the 4B BMRRM began to periodically stall. A stall event (Fig. 8) occurs whenever the BMRRM velocity goes to zero and the position error (error = actual position − commanded position) exceeds 10 deg for more than three minutes. The maximum current the motor is allowed to draw during a stall condition is 1.1 A.

To recover from a stall event, electrical systems flight controllers in the Mission Control Center command the BMRRM motor back on, rotate the array backwards, then continue forward motion. During the five-month period of January through May 2001, the motor current performance of both BGAs remained pristine when the ISS was orbiting in the XPOP attitude (Fig. 9).

Neither BGA has ever become stuck, unable to move in either direction with a motor current of 1.1 A applied. The ISS MER mechanisms experts believe a stuck BGA is an unlikely event because of the available 0.4-A motor current margin and the history of successful stall recoveries.

Early projections of the motor current trends indicated frequent stalls could be realized within six months. The ISS program office became concerned about the feasibility of continuing the assembly of the ISS using degraded BGAs, primarily because the majority of assembly missions occur during solar β periods that require the ISS to fly in the Xvv Znadir attitude. A BGA anomaly resolution team (ART) was formed in early May 2001 and consisted of three subteams: 1) root cause team, 2) operations team, and 3) BMRRM remove and replace (R&R) team.

The root cause team coordinated several on-orbit and ground tests in an attempt to isolate the root cause, but results were inconclusive. Meanwhile the BMRRM R&R team identified several risks associated with an on-orbit replacement of a BMRRM. The primary risks were 1) hardware survival would be threatened with nearly all of one U.S. power channel shut down during the R&R, as several unpowered components were predicted to exceed lower temperature limits within 6–10 h; 2) thermal gradients and fit tolerance issues would complicate successful installation of a new BMRRM or reinstallation of the old BMRRM; and 3) precise choreography of both intra- and extravehicular activity (EVA) as well as ground personnel activities would be required for a successful R&R. In October 2001, the ISS program decided against a BMRRM R&R, primarily because the consequences of a failed BMRRM R&R could be extremely high, possibly leaving the ISS to operate on one power channel and at reduced functionality because of potential hardware failures. The BGA ART was strongly encouraged to identify and implement viable operational techniques to reduce rotations on the BGAs to the greatest extent possible while minimizing impacts to continued ISS assembly and scientific experiments. The scope of the effort to reduce rotations extends for roughly two years, at which time both P6 solar arrays will be stowed until the PV module is relocated to an outboard position on a future ISS assembly mission.

Power Generation Analyses

The BGA ART operations team coordinated the efforts within the ISS program to identify feasible options for reducing BGA rotations while continuing to support on-orbit troubleshooting. Toward this end, a group of ISS power resource experts convened to begin determining the projected U.S. segment power demands and power-generation capabilities for a defined set of operational scenarios. The ISS EPS analysis team at NASA's Glenn Research Center (GRC) used System Power Analysis for Capability Evaluation (SPACE)[2–4] to predict the EPS power-generation capabilities for each of the proposed operational scenarios, covering a range of ISS stages, flight attitudes, array control techniques, and solar β angles. Four of the operational scenarios and one of the test conditions that were analyzed will be reviewed in this paper.

Scenario 1: PV 4B BGA Parked in Xvv Znadir

An early goal for the BGA ART operations team was to minimize rotations on the channel 4B BGA. With the ISS still in the early stages of assembly, it was hoped that the U.S. electrical loads could be managed such that the channel 4B BGA could be parked for extended periods of time when the ISS was in the Xvv Znadir attitude. GRC personnel used SPACE to generate a set of power generation capabilities as a function of parked solar-array position across the nominal Xvv Znadir solar β range (Fig. 10).

Using these data, the ISS power resource experts on the BGA ART operations team determined that by transferring a subset of channel 4B electrical loads to channel 2B, from one array to the other (see Fig. 1), only one BGA must be able to reliably rotate to successfully complete the next three assembly missions. Beyond that, two reliable BGAs would be required to continue assembly of the ISS. This was a significant finding for two reasons: 1) the channel 4B BGA could remain parked, thus reducing the risk of further degradation in the BMRRM; and 2) it provided the root cause and BMRRM R&R teams additional time to work their issues before ISS program management was scheduled to reconvene to make a decision regarding the R&R of the channel 4B BMRRM.

Scenario 2: PV 4B BGA Constant Rotation in XPOP, Test Condition

With the next ISS assembly mission just over one month away and no root cause identified, the root cause team continued to plan and execute on-orbit tests on the channel 4B BGA. Unfortunately, the solar β regime at that time required the ISS to fly in the XPOP

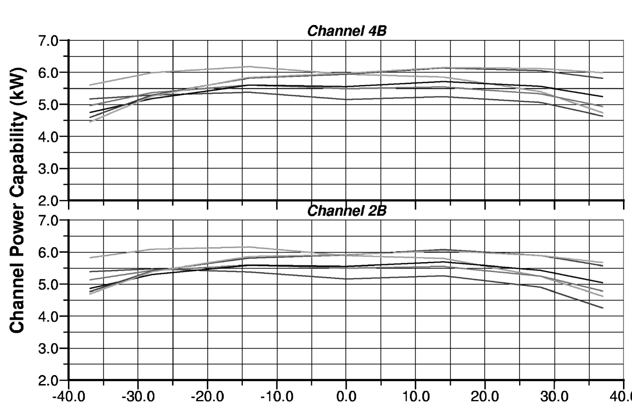

Fig. 10 Parked solar-array power generation at various solar β angles and BGA park angles.

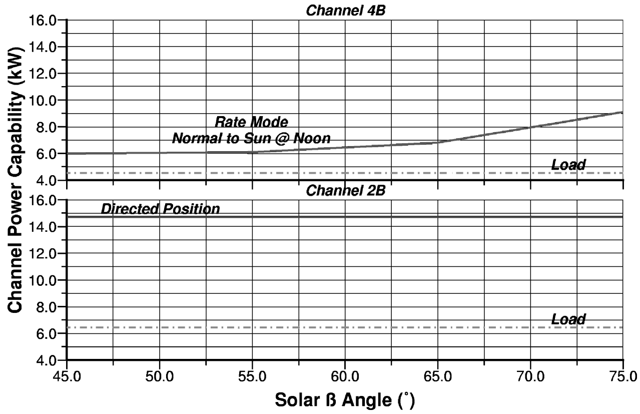

Fig. 11 Power generation and expected load demand for Channel 4B XPOP rate mode test with Channel 2B parked.

attitude to maintain positive energy balance. The BGA is not required to travel more than a few degrees in either direction when the vehicle is orbiting in the XPOP orientation. To assist the root cause team's troubleshooting efforts, the ISS power resource experts were asked to formulate a plan that would rotate the 4B BGA at a fixed orbital rate of ~4 deg/min in XPOP while maintaining positive energy balance on the ISS. A rate of ~4 deg/min was selected because the BGAs normally move at that speed when tracking the sun in the Xvv Znadir attitude. To implement this request, one of the BGA software control modes, namely Rate Mode, was utilized to control the movement of the BGA at a commanded rate. SPACE was used to determine how to optimize power-generation capabilities for Rate Mode operations in XPOP. The analyses indicated that power generation could be maximized if the solar-array rotation were synchronized such that the active face (front side) of the array pointed directly toward the sun when the vehicle arrived at orbit noon. Using this technique, the active face of the array will generate most of the available power during insolation. Power is also generated from direct solar illumination of the backside[5] and from albedo illumination on both the front and backsides[6] of the array. As a general rule of thumb, the backside of the U.S. PV arrays produces approximately $\frac{1}{3}$ the power of the front side for equivalent sun incidence angles.

The expected electrical load demand on channel 4B during the XPOP rate mode test was ~4.5 kW and on channel 2B ~6.4 kW. Figure 11 shows the results of the power balance analysis. Positive power margins were realized across the solar β range of interest for the proposed test. The data were presented to the BGA ART on 23 May 2001, and the XPOP 4B BGA rate mode test was successfully executed two days later.

Scenario 3: BGA Backdrive Prior to Thermal Blanket Installation

In July 2001, the root cause team called on the ISS passive thermal analysis team to assess the possibility of thermal gradients contributing to the apparent friction in the BMRRM bearing mechanisms. The results of the thermal analyses led the BGA ART to propose building and installing a thermal blanket around the BGAs to provide a more thermally stable operating environment for the gimbals and attempt to improve their overall motor current performance. ISS program management approved the thermal blanket proposal in late October 2001, and the blanket installation was scheduled for an EVA on the next ISS assembly mission in late November 2001.

The lead power resource officer on the electrical systems flight control team requested assistance from the BGA ART operations team in analyzing power generation capabilities for the two leading operational scenarios proposed for installing the BGA thermal blankets. The basic plan was to rotate both solar arrays backward 360 deg at 10 deg/min, then continue to rotate in the reverse direction until each BGA had reached a predetermined park position required to provide adequate clearances at the EVA worksites. At the conclusion of the 4-h EVA to install the blankets, the arrays would be further rotated backward to a new "thermal hold" park position that optimized power generation. The thermal hold would consist of one insolation pass on channel 2B and three insolation passes on channel 4B. Figure 12 illustrates the time-phased BGA position profile for case 1, in which the backward rotation is initiated at orbital sunset.

NASA GRC personnel used SPACE to generate view factors for each case. The view factors for direct solar illumination are illustrated in Fig. 13. The additional backward rotation on the channel 2B BGA, following the initial 360-deg reverse rotation, resulted in no illumination on the front side of the PV 2B array for half of the first insolation period.

Figure 14 illustrates the time-phased BGA position profile for case 2, in which the backward rotation is initiated at orbital sunrise.

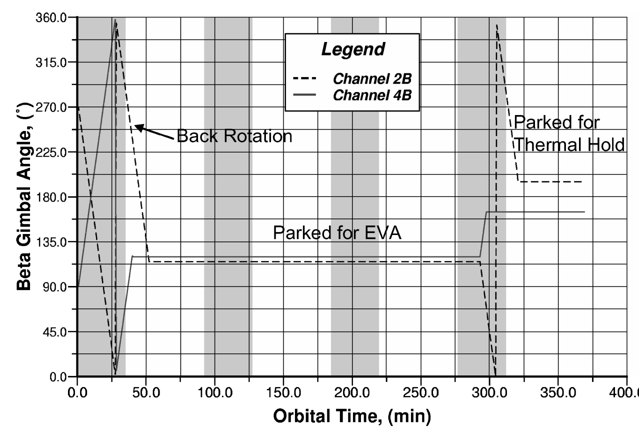

Fig. 12 BGA position for BGA blanket installation EVA case 1: begin reverse rotation at orbit sunset (gray bars denote eclipse).

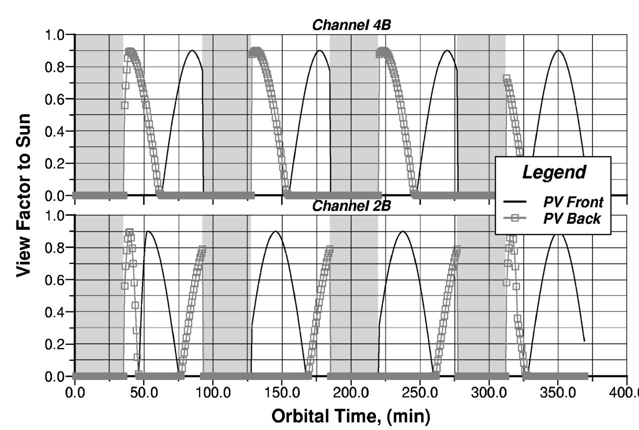

Fig. 13 Case 1 solar view factors (albedo view factors not shown; gray bars denote eclipse).

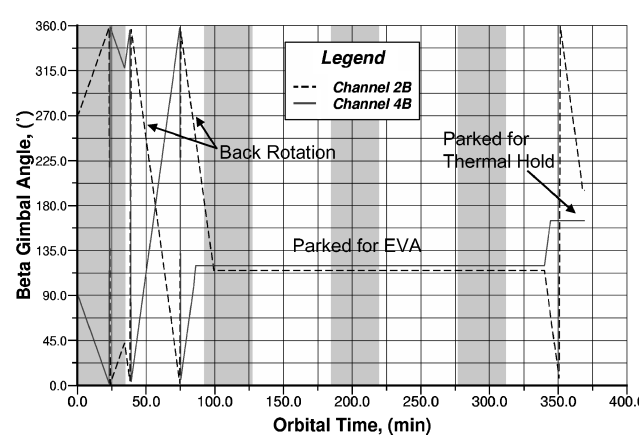

Fig. 14 BGA position BGA blanket installation EVA case 2: begin reverse rotation at beginning of insolation (gray bars denote eclipse).

Case 2 results in an additional backdrive of ~50–100 deg, further "resetting" the BGA performance before the blanket installation.

The direct solar illumination view factors for case 2 are illustrated in Fig. 15. The view factors indicate that, when compared to case 1, starting the 360-deg backward rotation at the beginning of insolation leads to significantly more cosine losses on both the front and backsides of the array.

Each P6 electrical channel is outfitted with three 76-cell nickel hydrogen batteries. The nameplate capacity of an ISS battery is

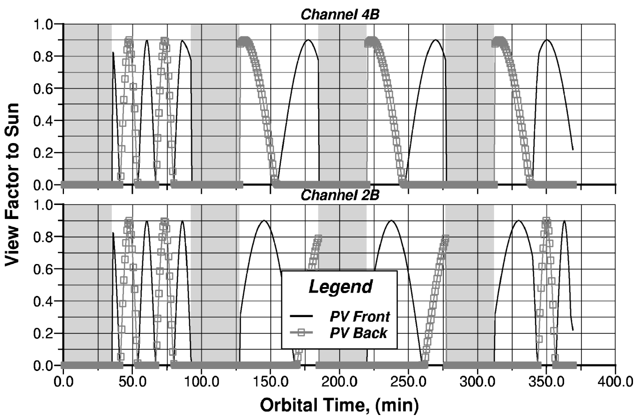

Fig. 15 Case 2 solar view factors (albedo view factors not shown; gray bars denote eclipse).

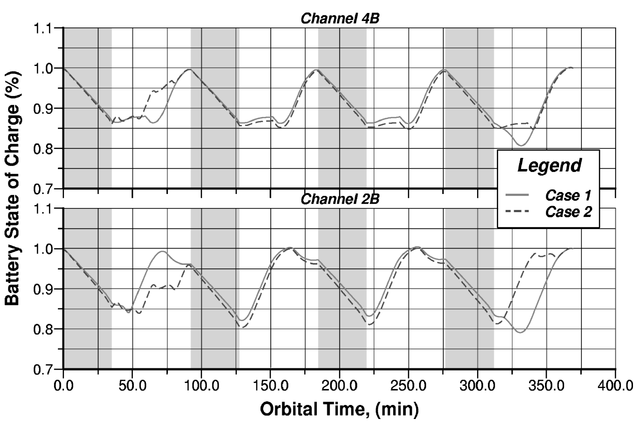

Fig. 16 Battery state of charge on channels 2B and 4B for cases 1 and 2 (gray bars denote eclipse).

81 amp-hours. The computer that controls the P6 electrical systems computes a battery state of charge (SOC) once every second for each of the three batteries. The magnitude of the SOC is an indication of the percentage of amp-hours remaining in a battery at any given time. NASA GRC personnel used SPACE to generate predicted battery SOCs during the blanket install EVA. The results are illustrated in Fig. 16. The analysis assumed electrical loads of 6 kW on channel 2B before and after the EVA and 7 kW during the 4-h EVA. Channel 4B had a constant applied load of 5.6 kW. The impact of deferring the start of the backdrive operation until insolation is evident in the Channel 2B case 2 SOC profile. The loss of power generation capability during the 360-deg reverse rotation in insolation prevented the 2B batteries from fully recharging before the ISS entered eclipse. The 2B batteries did not become fully recharged until the middle of the second insolation pass. The battery SOC profile is also impacted by the timeline of the solar-array repositioning for BGA thermal conditioning. Case 2 reorients the solar arrays during insolation, whereas case 1 completes the repositioning just after orbital dawn. The predicted battery SOC performance for case 1 is less desirable because the solar array is significantly off-pointed just after eclipse, forcing the batteries to continue to discharge to meet the ISS electrical loads.

The electrical systems flight controllers selected the case 1 operational scenario for the BGA blanket installation because of the more favorable channel 2B battery SOC performance early in the EVA. Postflight analysis showed a significant reduction in the magnitude of the thermally induced cyclic motor current signature, but the thermal blankets did not resolve the overall anomaly.

Scenario 4: Low Solar β XPOP

Electrical systems flight controllers had been able to keep the PV 4B BGA parked during the majority of the Xvv Znadir flight periods through November 2001, but the PV 2B BGA continued to sun-track as a result of the magnitude of the electrical load demands on that channel. The failure of the BGA thermal blankets to resolve the motor current performance anomalies resulted in a paradigm shift in the BGA ART from engineering solutions to operational workarounds aimed at reducing cumulative travel on both BGAs. The two leading candidates for operational workarounds were as follows: 1) expand existing flight attitudes and 2) develop new solar-array control techniques to be used in combination with electrical load management. Because the BGAs continued to perform nominally in the XPOP flight attitude, the operations teams efforts became focused on expanding the certified XPOP attitude envelope beyond $|\text{solar } \beta| > 37$ deg (Fig. 17).

As noted earlier, the XPOP attitude is the most favorable attitude for power generation from the P6 solar arrays. The initial goal was

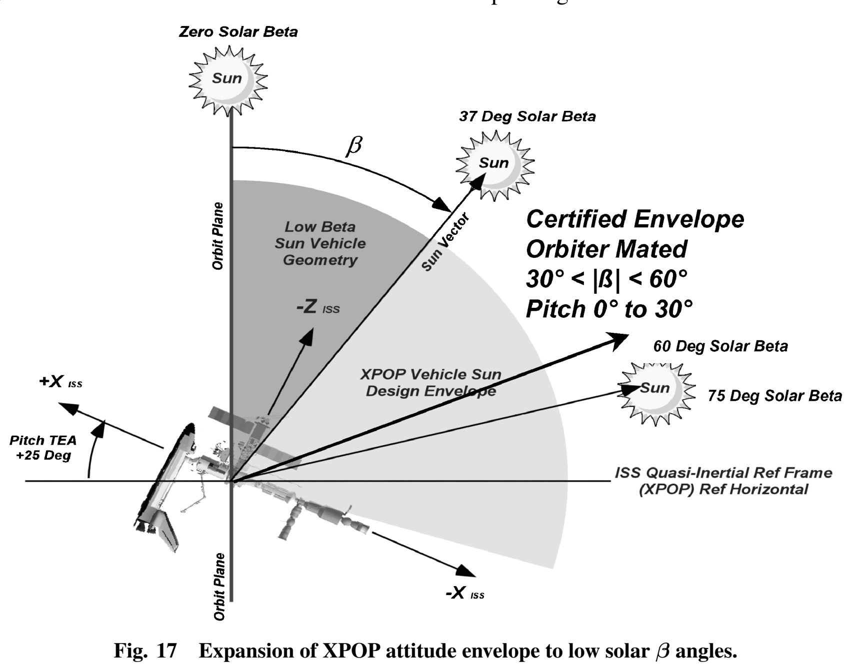

Fig. 17 Expansion of XPOP attitude envelope to low solar β angles.

to expand the envelope all the way to solar $\beta = 0$ deg. However, GN&C analysts reported that to fly XPOP below |solar β| < 10 deg long term, several hundred kilograms of ISS propellant would be expended to maintain an acceptable vehicle pitch angle. Using an expanded XPOP envelope of |solar β| > 10 deg, the operations team estimated savings of 1000 rotations on the PV 4B BGA and 2000 rotations on the PV 2B BGA. An on-orbit low solar β XPOP test was executed 9–16 November 2001, with no unacceptable core systems impacts identified for the U.S. or Russian segments of the ISS. In January 2002, ISS program management approved the BGA ART's recommendation to implement low solar β XPOP as soon as possible. Unfortunately, implementation of low solar β XPOP also created issues for scientific payloads designed specifically for the Xvv Znadir attitude. Expanding the XPOP envelope from $|\beta| > 37$ to 10 deg reduces the time spent in Xvv Znadir from ~60% of the year down to ~15% of the year, significantly reducing opportunities for experiments requiring the Xvv Znadir attitude.

Scenario 5: Development of the Dual-Angle Concept

By June 2001, the root cause team had identified two possible data trends: 1) long-duration unidirectional BGA motion appeared to exacerbate the high motor current anomaly and 2) the motor current performance appeared to return to nominal levels after reversing the direction of the BGA, commonly referred to in the BGA ART as backdriving. Taking these observations into consideration, the BGA ART developed an operational concept that would reduce cumulative BGA travel by reducing the range of travel (or sweep interval), incorporate a backdrive operation, and improve the system's robustness against a stalled or stuck BGA. This operational concept became known as the dual-angle mode. This technique is unique in that should the BGA stall or become stuck the solar-array position is guaranteed to be within a range of sun-facing positions when the vehicle is in insolation, thus minimizing the potential impacts to power generation.

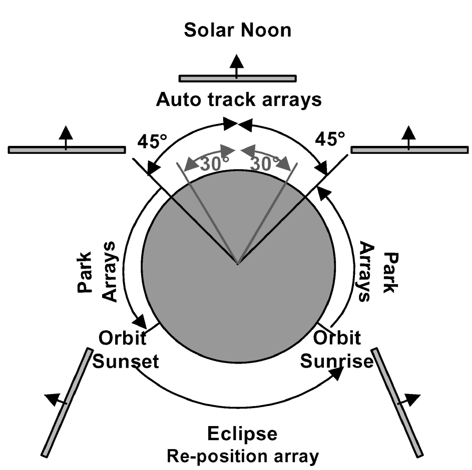

Fig. 18 Dual-angle mode operational concept (90- and 60-deg sweep) and tracking about solar noon.

To illustrate the implementation of the dual-angle mode concept, the following example is provided for a 90-deg sweep interval (Fig. 18):

1) Beginning at orbit dawn until 45 deg before orbit noon, the array is parked such that at 45 deg before orbit noon the array is normal to the sun.

2) From 45 deg before orbit noon to 45 deg after orbit noon, the array tracks the sun.

3) Then, from 45 deg after orbit noon until orbit sunset, the array is parked.

4) Finally, during orbit eclipse, the array is returned to its starting position by backdriving the BGA through the beta gimbal sweep traversed in insolation.

The percentage reduction in cumulative BGA travel is a function of the magnitude of the dual-angle mode sweep interval. For example, in comparison to a BGA operating in sun-tracking mode, total BGA travel is reduced by 50% if a 90-deg sweep is implemented and by 67% if a 60-deg sweep is implemented.

A peer review of the dual-angle mode concept indicated the technique had merit. The BGA ART operations team then had to prove that the dual-angle mode technique could provide adequate power generation capabilities in the Xvv Znadir flight attitude. GRC personnel used SPACE to determine power-generation capabilities for a 90- and a 60-deg sweep interval for |solar β| < 75 deg (see Fig. 19). The SPACE results proved that the dual-angle mode technique could generate 85–90% of the power realized from a sun-tracking solar array in the nominal ISS Xvv Znadir solar β regime (|solar β| < 37 deg).

By spring 2002, the conflicts between low solar β XPOP and ISS payloads needs for Xvv Znadir had not been resolved, and so the BGA ART turned to a second alternative for reducing BGA rotations, namely the dual-angle mode concept just described. A 16-orbit dual-angle mode test was successfully executed on the channel 4B BGA on 7–8 May 2002. The success of the initial test on the channel 4B BGA provided the incentive to pursue a longer-duration dual-angle mode test. The electrical systems flight control team in the Mission Control Center became concerned that a long-duration test would become too operator intensive, requiring the team to reset the BGA target angles in the software buffer once every 1–2 days to correct for possible solar-array off-pointing caused by target angle walk-off over time. GRC personnel used SPACE to estimate the amount of power availability that could be lost over time using a single set of BGA target angles across a solar β range of +28 to −28 deg. The results, as seen in Table 1, indicated the worst case loss would be 400 W out of a total capability of 10 kW. This analysis proved that a single set of BGA target angles could be used for dual-angle mode tests lasting as long as 11 days with only a 4% loss in total power generation capability.

More extensive dual-angle mode tests were executed successfully on the channel 2B BGA on 17–23 June and 10–15 July 2002. The BGA motor current performance observed during the initial test phase was similar to that observed during early BGA operations with an occasional excursion over 0.5 A (Fig. 20), but with time the performance degraded (Fig. 21). After reviewing the test data, ISS program management declared the BGA performance was

Table 1 Estimated power generation drop-off using a single set of BGA target angles for a long-duration dual-angle mode test (90-deg sweep) and tracking about solar noon

Solar β angle, deg	Solar β pointing used, deg	Power, kW		Power reduction due to dual-angle mode, kW	
		Channel 2B	Channel 4B	Channel 2B	Channel 4B
−28	$\beta = -28$	10.7	10.2	——	——
	$\beta = 0$	10.7	10.3	0	0
	$\beta = +28$	10.4	10	−0.3	−0.2
0	$\beta = -28$	11.7	11.7	−0.2	−0.1
	$\beta = 0$	11.9	11.8	——	——
	$\beta = +28$	11.7	11.6	−0.2	−0.2
28	$\beta = -28$	10.1	10.5	−0.4	−0.2
	$\beta = 0$	10.5	10.8	0	0.1
	$\beta = +28$	10.5	10.7	——	——

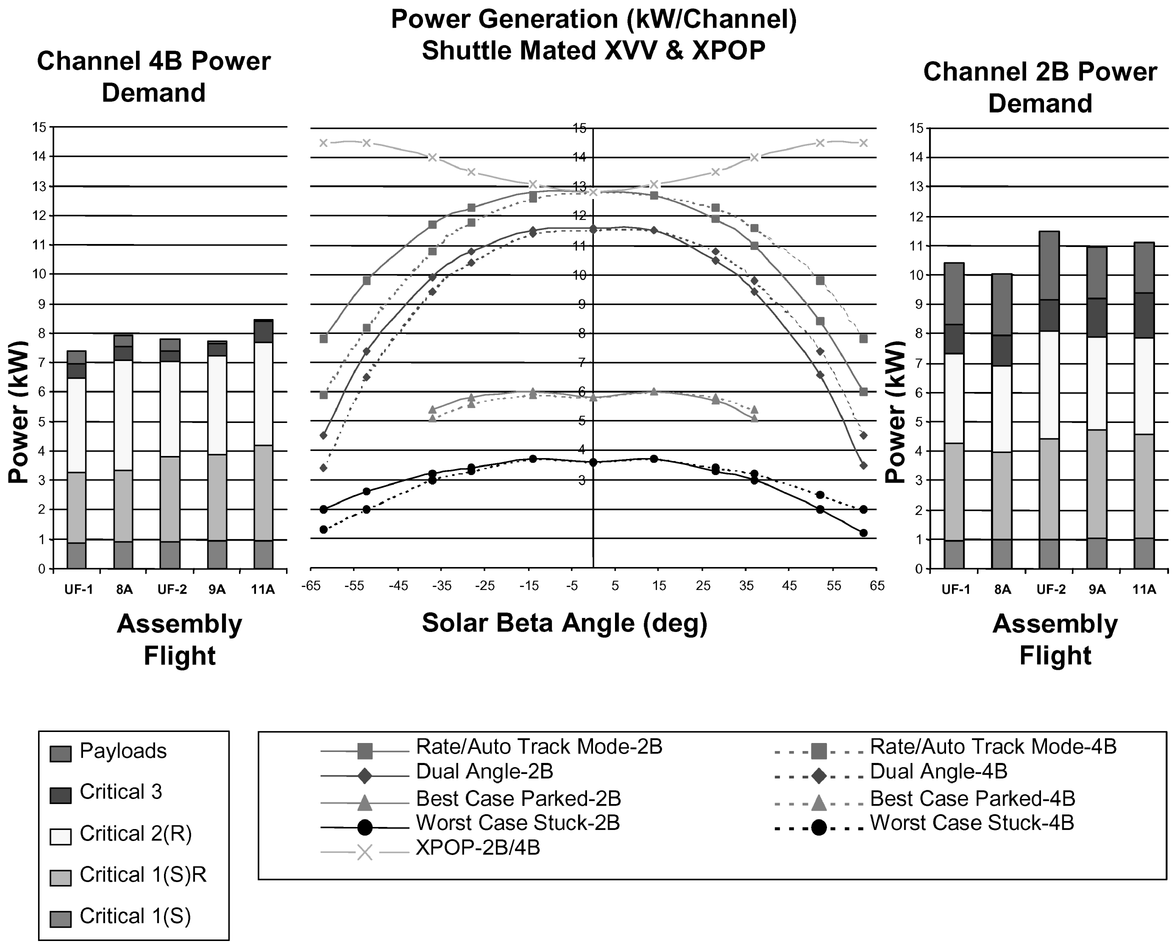

Fig. 19 Power demand per channel and power generation per channel.

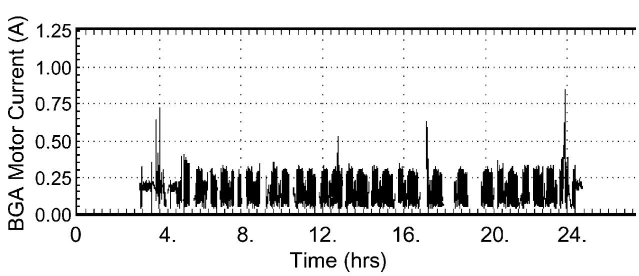

Fig. 20 Channel 4B BGA motor current performance during dual-angle mode testing (24 h, 7–8 May).

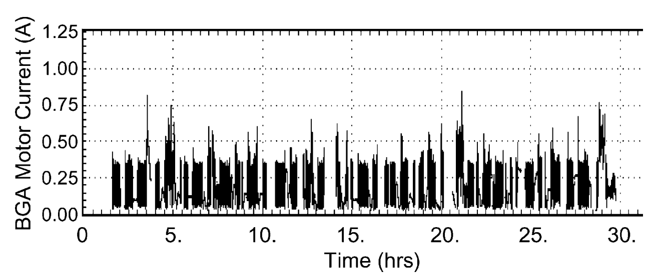

Fig. 21 Channel 2B BGA motor current performance during dual-angle mode testing (30 h, 21–23 June).

acceptable and approved the dual-angle mode technique for future on-orbit operations.

Power-Generation Comparison

Figure 19 summarizes the U.S. segment power balance for a set of five consecutive ISS assembly missions scheduled between December 2001 and December 2002. XPOP is the preferred operational flight attitude because it produces the most robust power-generation capabilities across the solar β regime and because it significantly reduces cumulative BGA travel. In Xvv Znadir, Rate Mode is able to support the electrical loads for $|\text{solar } \beta| < 37$ deg, but induces the most wear on the BGA. On the other hand, dual-angle mode provides power generation adequate to support electrical loads for $|\text{solar } \beta| < 25$ deg and reduces cumulative BGA travel by at least 50%. A solar array parked in a position optimized for power generation is able to support only those loads critical for maintaining steady-state ISS functionality, such as GN&C, thermal control, and life support systems. At this point, all payloads will be powered down. Finally, the ISS and the on-orbit crew can survive a worst-case stuck BGA, but will be significantly handicapped because of the reduced power availability.

As of October 2002, XPOP is usually flown for $|\text{solar } \beta| > 30$ deg. For $|\text{solar } \beta| < 30$ deg, the dual-angle mode is implemented in Xvv Znadir as often as energy balance and operational plans permit. Otherwise, the solar arrays track the sun throughout the orbit.

Summary

The on-orbit BGA motor current anomalies introduced a significant threat to the continued assembly of the ISS. A multifaceted team was formed to address root cause, BMRRM R&R, and operations issues. Over the course of a year, the operations team developed successful methods of managing ISS energy balance while supporting the root cause team's troubleshooting efforts and the overall team goal of minimizing cumulative BGA travel. At no time were the nominal ISS science objectives jeopardized. The operations team successfully negotiated a few short-duration periods of low solar β XPOP in the fall of 2002. And the dual-angle technique continues to be used successfully in the absence of low solar β XPOP. The BGA ART faces additional challenges to reduce BGA rotations in the future as the ISS electrical loads continue to increase with each assembly mission. However, the team is confident that those challenges can be overcome by developing and implementing innovative operational techniques such as those described in this paper.

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