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GFO: Disposal of a Power-Challenged Satellite with an Attitude (Control) Problem

Angela L. Monheim[1]
Naval Satellite Operations Center, Point Mugu, California, 93042

Lance Pritikin[2], Greg Mayer[2], Gerardo San Juan[2], Ryan Palmer[2], and Kevin Miller[2]
General Dynamics C4 Systems, Point Mugu, California, 93042

And

Scott Mitchell[3], Michael Weiss[4], and Brian Pieper[4]
Ball Aerospace and Technologies Corporation, Boulder, Colorado, 80301

GEOSAT Follow-On (GFO), a low earth-orbiting satellite launched in 1998, was scheduled for a planned shutdown and disposal process to commence on 31 December 2008. However, upon entering the full-sun season at the end of September 2008, additional stresses from constant sun exposure began to exacerbate GFO's already degraded attitude control and power systems, triggering fault responses which repeatedly sent the satellite into survival mode and threatened to strand it on orbit. In order to prevent the satellite from becoming another piece of long-term space debris and a potential hazard to current and future international space missions, the decision was made to move it from its operational orbit to a disposal orbit as soon as control could be regained. The ensuing disposal process proved to be a very challenging exercise in thermal, power, time and resource management as the engineering team raced to complete the disposal before the approaching eclipse season could seriously hinder or preclude its completion. This paper highlights the unique challenges encountered and the creative engineering solutions implemented during the month-long emergency disposal and shutdown operation.

Nomenclature

Delta-V	=	Maneuver to change the velocity of the satellite
UV3	=	Under Voltage Condition 3, sheds all non-essential power loads on the satellite
UV2	=	Under Voltage Condition 2, sheds payload and other power loads on the satellite
Eclipse	=	Period when the satellite is shadowed by the Earth during part of each orbital revolution
Full-sun	=	Period when the satellite is in complete sun during the entire orbit
SCPV	=	Spare Common Pressure Vessel, two spare battery cells which can be enabled/disabled
DSU	=	Data Storage Unit, onboard memory that stores payload and health data for download
OD	=	Orbital Determination, conducted after a maneuver to accurately predict the position of the satellite
SP1	=	Spacecraft fault response in which the Central Processing Unit (CPU) is reset
CSM	=	Command Storage Memory, allows a finite number of commands to be stored for later execution
Wheel 3	=	Reaction Wheel 3, the degraded attitude control component which was thermally unstable
RF	=	Radio Frequency, the signal received from the spacecraft during commanding passes
PCU	=	Power Control Unit, controls power distribution and load shedding functions for the satellite

[1] Satellite Engineering and Orbital Dynamics Division Officer, N33/34, Naval Satellite Operations Center, Point Mugu, CA 93042, AIAA Member
[2] Satellite Engineer, GD On-Orbit Engineering Support, Naval Satellite Operations Center, Point Mugu, CA 93042
[3] Staff Consultant, Ball Aerospace and Technologies Corporation, Boulder, CO 80301
[4] Senior Project Engineer, Ball Aerospace and Technologies Corporation, Boulder, CO 80301

I. Introduction

The GEOSAT Follow-On (GFO) satellite was launched in February 1998 with a US Navy mission of measuring the topographic height of the ocean surface for use in modeling the meso-scale circulation patterns of the Earth's oceans. GFO was very important to the Navy, as no other satellite then or now provided exactly the same oceanographic measurements. TOPEX, JASON 1, and JASON 2 provide similar data, but not at the same resolution or frequency as GFO. It was built with a 5 year mean mission life, but as with many space assets, there was no planned termination date for the satellite. In fact, the satellite did not even have disposal abilities built into the design. It was designed with many backups and fail-safes in order to survive and recover from almost anything. Throughout its on-orbit mission, these recovery abilities enabled the satellite to continue its mission despite some particularly adverse conditions. This ability was due to a distributed, multi-layer fault protection system with adjustable fault thresholds.

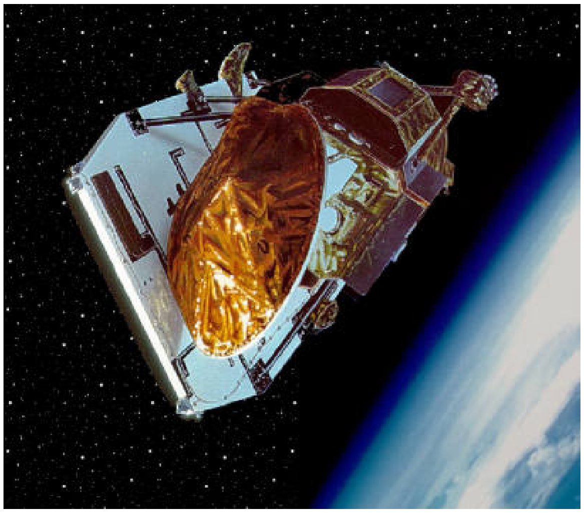

Figure 1: GFO Satellite

GFO encountered multiple issues toward the end of its lifetime. By January 2008, GFO was almost 10 years old (twice its mission life) and operating with significant degradations. At this point in time, the battery on GFO was degraded and near the end of its useful life (the 20 amp-hr capacity had degraded to less than 5 amp-hr capacity), two Reaction Wheels were very temperature sensitive, the Water Vapor Radiometer (WVR) had been turned off for thermal management, the Radar Altimeter (RA) was only operating outside of eclipses (in order to conserve stored power during eclipses), and engineers spent considerable time fine-tuning the spacecraft's yaw angle with respect to the sun in order to keep Reaction Wheel 3 (Wheel 3) thermally stable while still keeping other components warm enough to prevent survival heaters from turning on. The ground system at the Naval Satellite Operations Center (NAVSOC) was obsolete, having no planned refurbishment due to the original "five year mission life." Now at the 10 year mark, the GFO VAX computers were creating an accreditation problem for the Satellite Operations Center (SOC) which was trying to gain network accreditation for the new Mobile User Objective System (MUOS) satellite constellation. The Navy called a meeting of all the stakeholders and determined that GFO would continue its mission until the end of the year, and then retired 31 December 2008. However, GFO had other plans.

GFO was in an Exact Repeat Orbit (ERO) (800 km altitude, 108 degree inclination, 0.0008 eccentricity), with a groundtrack that repeated every 244 orbits or 17 days. Eclipses lasted up to 35 minutes and occurred every orbit, except during the full-sun periods. Full-sun is usually a good thing with respect to power, since the solar array has continuous access to the sun. However, for a heat-sensitive component, the full-sun period can cause problems as the spacecraft never gets a chance to cool down in the shade of eclipse. In order to make it to 31 December, GFO would have to survive one last full-sun period. During GFO's first six years on orbit (1998-2004), it experienced two full-sun periods each year. The next full-sun period would occur in September/October of 2008. In 2004, only Reaction Wheel 1 was acting up. With only three of the four reaction wheels being essential for attitude control, the 2004 full-sun period was not particularly threatening. However, with only two reliable wheels remaining, the 2008 full-sun period presented serious concerns.

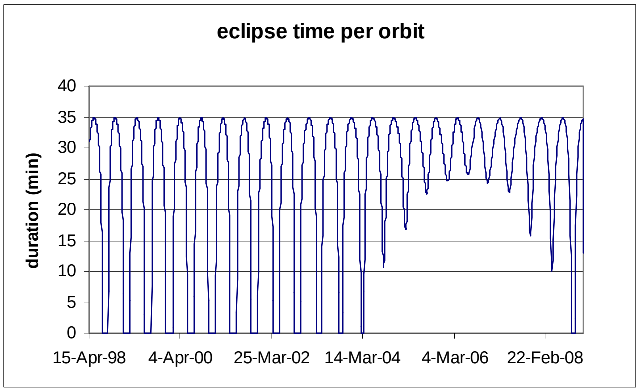

Figure 2: Eclipse Time per Orbit over GFO's Life

II. 2008 Full-Sun

The full-sun period for GFO spanned from 24 September to 16 October 2008. During that period, GFO would have no opportunity to cool Wheel 3 by traveling through orbital shadow for a portion of each orbit. Instead, the accumulation of heat had to be minimized using other methods. In preparation for the full-sun period, spacecraft engineers devised a plan to minimize heat conduction to the reaction wheel. Beginning about 10 days before the start of full-sun, the payload was turned off, eliminating a significant source of generated heat. However, this also made it necessary to take steps to insure the automatic battery heaters did not turn on during eclipse. The spacecraft yaw bias was adjusted to reduce its cross-section, as viewed by the sun, as much as possible while still maintaining enough sun on the solar array to satisfy minimum power requirements. Changing the yaw to control Wheel 3 temperatures had become a standard procedure for GFO over the last several years, with regular adjustments made to fit the length of eclipse. The day before the start of full-sun, the temperature of Wheel 3 was still increasing despite the prescribed yaw adjustment. In response, engineers significantly increased the yaw beyond previous levels to try to cool Wheel 3, but even maximum yaw was not enough to reverse the trend. During the last eclipse before full-sun was to commence, the increased yaw combined with the lowering of the Voltage-Temperature (VT) charge level, caused the battery to become too cold prompting a battery survival heater to turn on during the eclipse. This brought the bus voltage below acceptable levels and triggered an Under Voltage Condition 3 (UV3) fault. A UV3 sheds several systems (See Table 1) including the Non-Essential Bus (NEB) and the Attitude Control Bus (ACB), and the Emergency Mode Controller places the spacecraft in a random power-safe tumble using thrusters. It also erases any data stored in the Data Storage Unit (DSU).

UV Condition	Resultant Systems Shed
UV1	Payload Bus
UV2	Non-Essential Bus, Hazard Bus, Payload Bus
UV3	Attitude Control Bus, Non-Essential Bus, Hazard Bus, Payload Bus

Table 1: UV Fault Levels and their Resultant Systems Shed for Survival

Following the UV3, Engineers conducted initial recovery efforts, placing GFO in a stable 2-wheel Acquire Sun state. (For background, the as-designed Acquire Sun mode required at least three of the four reaction wheels to maintain 3-axis stability for sun-pointing. The 2-wheel Acquire Sun state was developed as a temporary configuration which maintained 2-axis stability by only allowing rotation around the sun vector.) This 2-wheel Acquire Sun state was used as a last ditch attempt to maintain spacecraft attitude control when it became obvious Wheel 3 was likely to exceed the critical temperature, rendering the wheel uncontrollable. However, over the next few days, the two functioning wheels eventually reached saturation (maximum allowed speed) and, as a result, were unable to maintain stable sun-pointing within prescribed limits. This resulted in an attitude fault response (SP1 fault) which triggered a Central Processing Unit (CPU) reset that precipitated into a second UV3. The spacecraft was left in Survival Mode in a random tumble with all reaction wheels powered off and the omni antenna configuration selected. The SP1 fault response was subsequently disabled in Random Access Memory (RAM) to prevent another CPU reset, in order to buy time to process and analyze telemetry. Engineers used that telemetry to determine how to predict when the two functioning wheels would become saturated during 2-wheel Acquire Sun state.

Over the next two weeks, the spacecraft experienced several more UV2, SP1 (CPU reset) and UV3 faults as engineers tried to gather enough data to determine a course of action that would keep the spacecraft stable. By 09 October, the random tumble had caused the battery temperature to rise to 40 degrees C, a level that, if sustained, would further harm the already weak battery. GFO was again placed into 2-wheel Acquire Sun so the batteries could be shielded from the sun and allowed to cool. The Ball Aerospace engineers knew the spacecraft could not stay in 2-wheel Acquire Sun indefinitely because although keeping all three magnetic torque rods active effectively reduces spacecraft momentum in 3-wheel mode, this configuration is antagonistic in the 2-wheel Acquire Sun mode. This is one reason why the spacecraft is not normally left in 2-wheel Acquire Sun for extended periods of time. After reviewing data confirming this antagonistic behavior, Ball recommended disabling Torque Rod 2 when the spacecraft travels through orbital shadow. According to their calculations, this configuration would prevent excessive momentum buildup while continuing to dump most of the momentum accumulated in Wheels 2 and 4, thereby allowing the spacecraft to hold 2-wheel Acquire Sun for a greater length of time.

This new torque rod management scheme worked well, and engineers turned their focus back to trying to understand the cause of the original UV3 fault that occurred at the beginning of the full-sun period. Drawing on the Data Storage Unit (DSU) data from well before and well after the event (the data immediately surrounding the event was not available because the UV3 fault responses erased all stored data), engineers determined that two battery cells had essentially failed (voltage did not increase while charging). This meant there would be less power available during future eclipses. However, GFO had been designed with a Spare Common Pressure Vessel (SCPV) which is essentially two battery cells in a unit that can be connected or disconnected via ground commands. The spacecraft was designed to operate with one failed cell, connect the SCPV for two failed cells, and still tolerate a third failed cell as long as the SCPV was connected. So, after charging the SCPV for a full day, it was connected to the battery on 15 October. The battery voltage and pressure were reading slightly higher than expected, but since this was the first time the SCPV had ever been connected on-orbit, it was entirely possible this was normal.

Confident that the spacecraft now had plenty of battery power, it was left to be monitored through the next 24 hours while we began planning for the end of the full-sun period. But less than 24 hours later on 17 October as the spacecraft emerged from the 8-hour communication black-out window, there was no RF. Engineers quickly ran through their contingency plans and discovered that GFO had experienced a UV2. One orbit later, the UV2 was followed by a UV3. The data collected from the time leading up to the UV2 indicated a combination of non-essential battery heaters turning on and an insufficient battery charge level were causing the UV conditions. Engineers increased the charge level and uploaded commands into the Command Storage Memory (CSM) that would change the charge level automatically around eclipse. But the question of why there was not enough battery capacity to handle the additional heater still remained. With the SCPV connected, there should have been plenty of battery capacity to handle the additional load. Not only did the SCPV fail to fix the power problem, but it seemed to actually make it worse. Analysis of the data showed the two failed cells had partially recovered but in a way that was detrimental. They were now increasing the voltage but not increasing the capacity. With the SCPV connected and these weak cells adding to the voltage, the charge cut-off voltage was reached before the battery was fully recharged.

At this point, it became clear that returning to a normal operating state after the full-sun period was not an option. In addition to the thermal instability of Wheel 3, which was creating attitude control problems, GFO's power problem had gotten much worse. With eclipses returning in just a few days and rapidly getting longer, the power situation was expected to deteriorate further. After careful consideration, NAVSOC decided to recommend disposal as soon as possible vice trying to hang on until the end of the year. On 24 October, NAVSOC recommended to Navy Leaders that disposal of GFO commence as soon as attitude control could be regained after the full-sun period.

Disposal was not an easy prospect. GFO was not designed with any thought of disposal. Quite the opposite, GFO was designed to survive and recover under almost any circumstance. Sometime after the GFO launch, the idea of minimizing space debris by requiring satellites to be built with disposal and debris-limiting criteria had become mandatory for all U.S. missions. Proper disposal is a very serious issue, according to Nicholas L. Johnson, Chief Scientist for Orbital Debris at NASA's Johnson Space Center:

"These spacecraft disposal measures are necessary to prevent accidental explosions of derelict spacecraft and to reduce the chance of their being involved in collisions with other resident space objects, which would add to the orbital debris population. The vast majority of debris now in Earth orbit originated from abandoned spacecraft and launch vehicle orbital stages whose propulsion and electrical power systems had not been safed. In the future, the principal source of new debris in low Earth orbit (LEO) is expected to be from random collisions. Hence, the accelerated decay and reentry of large objects from LEO is of paramount interest."

At the time, there was no doubt in our minds that we needed to attempt disposal, and we were determined to be successful. (A few months after the GFO disposal was completed, the importance of space debris mitigation was further punctuated by the collision of Iridium 33 with the inactive Cosmos 2251, adding thousands of pieces of debris to threaten satellites in LEO orbits. With no disposal efforts, GFO would remain on orbit for over 100 years, essentially becoming a hazard to active satellites, similar to Cosmos 2251.)

III. Disposal Planning

The satellite was on course to leave full-sun and enter eclipse season beginning 16 October. By 26 October, the eclipses would be long enough to provide sufficient cooling for Wheel 3 to allow other components to be turned on. Disposal burns could potentially begin anytime after 26 October assuming stable control had been regained. However, NAVSOC had never performed a disposal on a LEO satellite before. There was a graceful shutdown plan designed for use post 31 December which assumed power was not an issue and Wheel 3 was relatively stable. Neither condition was true anymore. We needed to revise our plan.

On 28 October, engineers from Ball Aerospace and NAVSOC met for a one day planning session at NAVSOC Headquarters (HQ), Point Mugu, CA to lay out a preliminary disposal plan that took into account the power and attitude control problems. The requirements* for disposal dictated that the satellite must be placed in an orbit meeting the following criteria:

- Natural decay occurs in 25 years or less using conservative assumptions of solar activity and other perturbations
- All pressurized vessels that are able must be depressurized
- All propellant expended
- Electrical sources drained and disabled if possible

These requirements did not become standard practice until after the GFO launch, so the spacecraft was not designed to meet them. But as a military satellite with sufficient fuel still onboard, GFO was still being held to these requirements. In order to start disposal, several decisions had to be made, including what the entry criteria for starting disposal burns should be, where apogee would be, how long and how often the disposal burns would occur, the date to target for a first disposal burn attempt, Go/No-Go criteria for each burn, and how the crew members would be utilized.

A. Entry Criteria:

Before we started asking external agencies to provide support for disposal burns, we needed to first establish some criteria to tell us the disposal cycle had a reasonable assurance of success. Success depended on having a reasonably controlled platform from which to conduct the burns and the ability to command and recover the spacecraft. Three criteria for entry into the disposal cycle were chosen:

- Regain 3-axis stabilization and the ability to point the spacecraft
- Determine the most power-advantageous apogee given our ground site locations and the spacecraft degradations
- Determine battery charge state, wheel temperatures, and the minimum loading regime which must be met prior to commencing a burn (Go/No-Go criteria)

These criteria focused on the physical ability of the spacecraft and ground system to successfully conduct the disposal operation. They did not address the planning and coordination efforts required of the team, nor the logistics of progressing from burn to burn until shutdown.

B. Choosing Apogee:

GFO did not have enough fuel on board to completely de-orbit the spacecraft in the near term, nor to lower the orbit in a circular fashion. To assure the 25 year requirement was met, it would be necessary to lower perigee from 800 km to below 500 km. This would allow the atmospheric drag to gradually pull the satellite down so that it reentered within the prescribed time span. The position of apogee was a critical decision. After the first disposal burn, apogee would be locked in and all burns thereafter would have to take place very close to the same place in the orbit. So the biggest question that had to be answered was "Where do we place Apogee?" There were two primary considerations: power and contact opportunities.

1. Power:

The first consideration was power, dictated by where eclipse occurred versus where the disposal burn would take place. Conditions at the time dictated that using the existing design, GFO must perform a 180 degree yaw maneuver in order to point the thrusters in the proper direction (see Figure 3). This maneuver pointed the solar array away

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* **Requirements.** Spacecraft decommissioning is governed by several documents:
  - Strategic Command Instruction 505-4, Satellite Disposal Procedures (Apr 21, 2006)
  - United States Space Command Policy Directive 10-39, Satellite Disposal Procedures (Feb 1, 2001)
  - NASA Procedural Requirements for Limiting Orbital Debris – NPR 8715.6A (Feb 18, 2008)
  - IADC (Inter-Agency Space Debris Coordinating Committee) Space Debris Mitigation Guidelines (Oct 15, 2002) and Support to the IADC Space Debris Mitigation Guidelines (Oct 5, 2004) (IADC is an international forum)

from the sun, meaning the disposal burn would have to be powered by the battery. It also exposed the temperature sensitive Wheel 3 to the sun. Once the burn was complete and the spacecraft was returned to its normal orientation, GFO would need time to recharge before entering eclipse again. With each orbit being approximately 100 minutes long and eclipse taking up a quarter or more of that 100 minutes, there might not be sufficient time to recharge the battery if the burn took place in the sun. Eclipses were getting longer now and would continue to grow throughout November as shown in Figure 4. There were three proposed options:

1. Conduct burns in eclipse – this would limit the time spent rotating to the Delta-V orientation, conducting the burn, and rotating back to point to approximately the duration of the eclipse. This would allow maximum charging time in the sun, but would also add a bigger drain to the already weakened battery during eclipse. It used the existing, pre-programmed Delta-V maneuver sequence.
2. Conduct burns in sun – this effectively lengthens eclipse because the solar array is pointed away from the sun when in the Delta-V orientation. Every minute spent in the Delta-V orientation is a minute less the spacecraft has to charge its weakened battery before the next eclipse. It also used the existing, pre-programmed Delta-V maneuver sequence.
3. Custom Delta-V maneuver – Instead of yawing 180 degrees, a custom maneuver would pitch the spacecraft 180 degrees. By using this approach, the solar array would be pointed at the sun throughout the maneuver and subsequent Delta-V, while simultaneously shielding Wheel 3 from the sun. This meant we would not be losing power during the burn and Wheel 3 would not get as hot as it would if the existing, pre-programmed Delta-V maneuver sequence were used.

The custom Delta-V maneuver was the best solution but would require additional time to study and develop. Given the recent rash of under-voltage events and the increasing length of eclipses, beginning disposal operations as soon as possible was considered the priority. The weakened battery was believed to be too much of a risk to permit burns during eclipse, so conducting the burns in the sun was the only option remaining. The existing "Yaw" Delta-V maneuver could be executed immediately, so we chose to implement Option 2 while having Ball Aerospace continue to develop a custom maneuver.

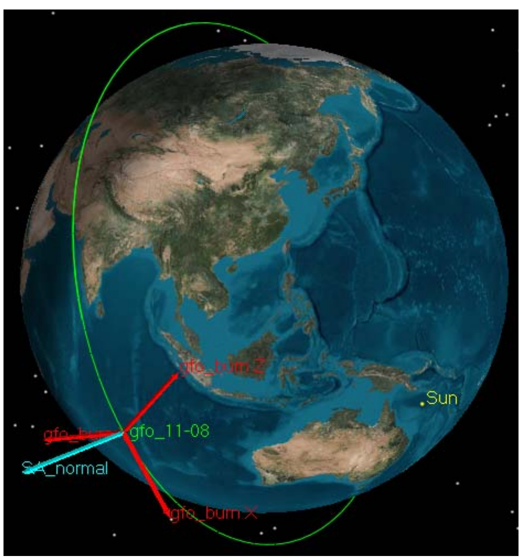

Figure 3: GFO Burn Orientation versus Sun on 01 November

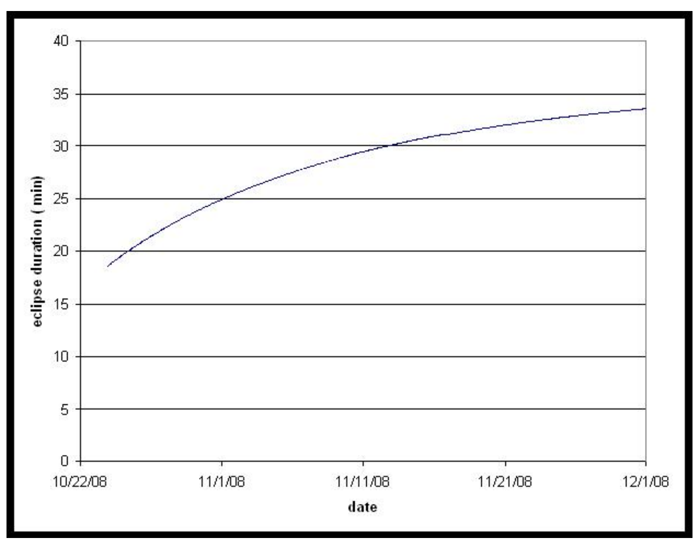

Figure 4: GFO Eclipse Durations over Time

2. Contact Opportunities:

The second consideration was the availability of ground station contacts or commanding opportunities. GFO had only three remote tracking sites located in Maine, California, and Guam as shown in Figure 5. The position of perigee would be chosen to optimize the commanding opportunities for each burn. Satellite contacts could only occur while in the sun due to the degraded battery condition. This further reduced our flexibility by eliminating half of the potential contact windows. (In Figure 5, yellow tracks are in sun and green tracks are in eclipse.) There were two proposed options. The first placed apogee at the beginning of the longest commanding window so we could conduct the burns in real-time and abort in real-time should Wheel 3 start to behave erratically. Commanding windows ranged from 8 to 14 minutes in duration, so longer burns could not be conducted entirely within that window and the commanding time available to recover from an anomalous condition would be minimal. The second option would rely on the existing fault protection to detect and abort the Delta-V maneuver and then optimize the station contacts for recovery operations. With this option, apogee would be placed about 20 minutes prior to the first usable commanding window at Maine, giving engineers three to four full commanding windows over the next six hours. Burns would be conducted via CSM uploaded approximately 8 hours prior. The engineers would not be able to stop a burn, but they would have maximum opportunities to recover should an anomaly be caused by the burn. We chose to trust the fault protection system and conduct burns out of view and maximize recovery opportunities because burning during a pass limited the length of the burn to the commanding window and reduced our ability to recover quickly from an anomaly.

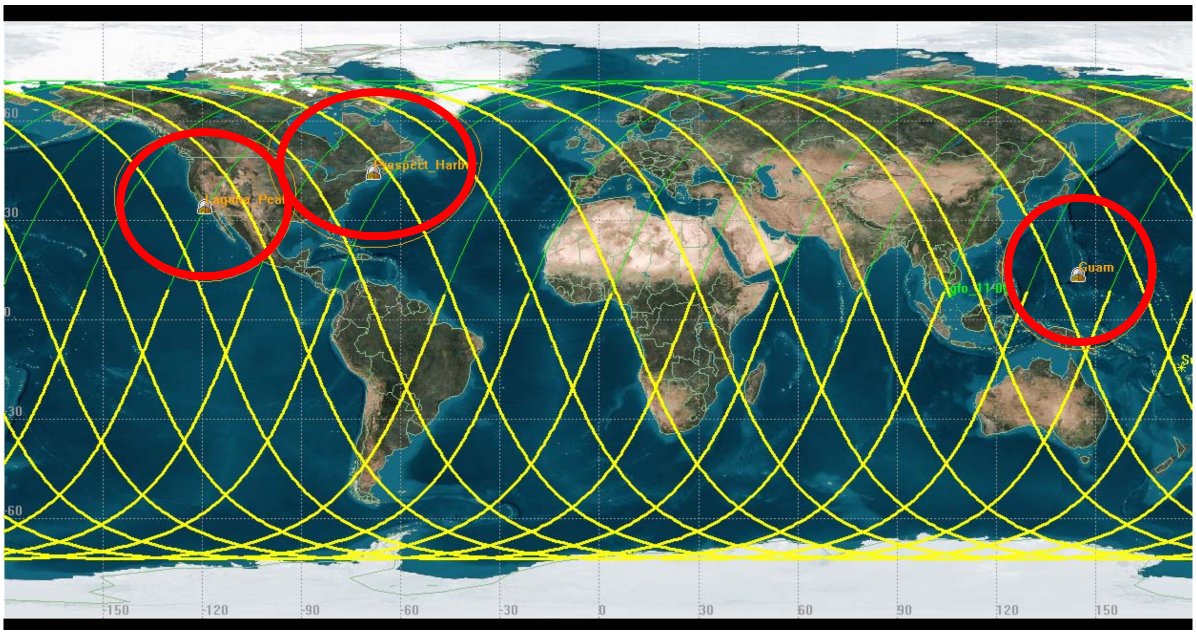

Figure 5: GFO Commanding Antenna Locations and Coverage Areas vs. GFO Ground Tracks

Based on the power situation and the commanding windows, apogee was chosen so burns would occur prior to a sunlit contact at Maine, allowing engineers to evaluate the state of the spacecraft as soon as possible after each burn. This would also position apogee to be most advantageous should the custom Delta-V maneuver become available.

C. Burn Durations:

The next item for discussion was the plan for conducting disposal burns. GFO had sufficient propellant remaining to fire the four Delta-V thrusters for approximately 55 minutes. Spacecraft design engineers recommended disposal burns no longer than 10 minutes in duration due to heat soak-back concerns. So, at a minimum, GFO would require 6 disposal burns to deplete the remaining fuel. In addition, longer burns would be less efficient since the burn would be over an arc vice instantaneous burns and would reduce the overall lowering of perigee. Initial fuel estimates and Delta-V models showed that GFO could descend below the target perigee altitude using 10 minute finite burns, but not with much margin. Further, the soak-back concern was for a healthy spacecraft, not for one with a thermally sensitive reaction wheel. No one had any idea how Wheel 3 would react to the added heat from the propulsion deck for a short burn much less a burn 10 minutes long. Everyone agreed it would be best to take a conservative approach, starting with a short duration and gradually increasing the time to find out just how much GFO could tolerate. This would also help with post-maneuver orbit prediction since a shorter burn meant a slower position change and easier tracking if the Wheel 3 fault caused a transition to Survival Mode (random tumble with transmitter powered off). No one wanted to literally lose the spacecraft and have to implement a search. Balancing the environmental need to progress quickly versus the risk of inducing a loss of control, we chose to start with a 2 minute burn and gradually increase to 10 minutes assuming GFO continued to respond well.

D. Timeline between Disposal Burns:

The next decision was how much time to allot between burns for orbit determination, planning and table uploading for the next burn. GFO used a Doppler Beacon system for orbit determination. After a maneuver, the system needed a minimum of 9 revolutions or 15 hours of Doppler data to converge on a solution. Once the orbit determination was complete, a new predicted orbit for the next burn could be generated. Each prediction needed to be screened by the Joint Space Operations Center (JSpOC) Conjunction Assessment Team to ensure the proposed burn would not create a close approach with another object. Concurrent with these events, the new command uploads would be generated and the data from the previous post-burn DSU dumps would be analyzed to ensure Go/No-Go criteria would be met. Finally, there needed to be a commanding window remaining between the time the results from the conjunction assessment were returned and the time the burn was to take place so the correct command sequences could be uploaded. In order to account for all these details and the individual decisions that could introduce a delay, a flowchart decision matrix (Figure 6) was designed to illustrate the process.

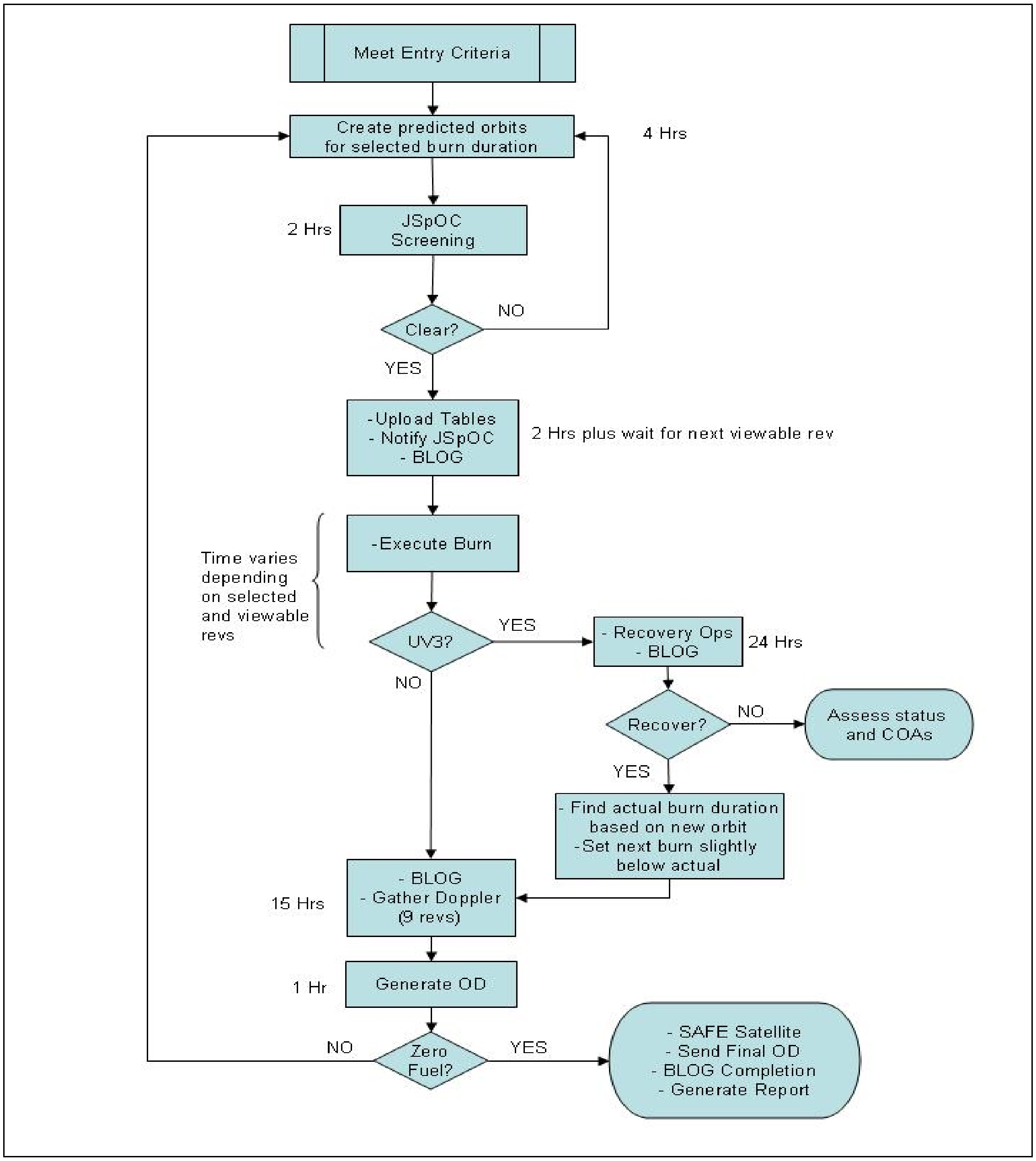

Figure 6: GFO Disposal Burn Decision Matrix

From the flowchart it was determined that if everything remained nominal, it was possible to perform one disposal burn per day, but that pace would definitely be tight and did not account for crew rest or potential delays in receiving conjunction assessment (CA) screenings or sufficient Doppler data. The NAVSOC GFO team was small, consisting of just three fully qualified console engineers, one partially qualified engineer, and an orbital analyst who ran the GFO Orbit Analysis (OA) software and performed the Doppler orbit determinations. In addition to this small group of GFO engineers, NAVSOC assigned one officer to oversee the disposal effort, coordinate with external agencies, and act as a safety observer.

The Ball GFO team was even smaller with just two engineers who provided primary support to NAVSOC over the phone during actual supports and in between supports while planning the next step. Ball Aerospace had a number of in-house engineers who were GFO subsystem experts and provided assistance as needed, but they were not available for the actual real-time supports.

The JSpOC Conjunction Assessment Team was not manned for 24/7 operations, so any difficulties with the conjunction screenings could potentially delay our schedule as well. With limited personnel concerns in three areas, the decision was made to allow two days between disposal burns in order to provide sufficient turn-around time and prevent fatigue.

E. **Choosing a Start Date:**

26 October marked the first day in which the eclipses would be long enough to provide sufficient cooling for Wheel 3 to allow other heat-producing components to be turned on. Stable control had not been regained on 26 October. The spacecraft experienced a series of UV2 and UV3 events from 20 through 27 October. The SCPV had been connected on 15 October, increasing the battery's power available, but for some reason the UV faults were occurring more often, not less. Ball's engineers examined what data was available and postulated a theory that the two "failed cells" had recovered partially. The deep cycling leading to the UV3 faults appeared to have reconditioned the cell. As explained earlier, with the SCPV connected, the battery now had one too many cells and was unable to sufficiently charge all of the cells. Once the SPCV was disconnected on 27 October, the power condition stabilized somewhat, allowing a successful detumble and acquisition of the 2-wheel Acquire Sun mode on 30 October.

From 2-wheel Acquire Sun, the spacecraft had to be placed in a stable 3-wheel Point mode in order to meet our entry criteria before commencing with a de-orbit burn. Throughout the full-sun period, the spacecraft had not been able to hold 3-wheel Point for more than a few days at a time, so we needed confidence that it was stable now. We commanded GFO to 3-wheel Point on Friday, 31 October with the intent of observing it through the weekend. If it performed well, the first disposal burn would take place at approximately 0200 local time on Tuesday, 04 November.

F. Go/No-Go Criteria:

Because GFO had both power and attitude control problems, it was necessary to carefully monitor the telemetry for the battery and Wheel 3. Each time the spacecraft entered a UV3 condition and each time Wheel 3 exceeded its design parameters it was rolling the dice as to whether Wheel 3 would be permanently damaged or if telemetry would be obtainable. Further damage or continuous loss of telemetry could prevent a successful disposal and trap the spacecraft in an undesirable orbit. The team set three hard limits which, if not met, would postpone the burn until the telemetry points could be brought back under control. These limits were:

1) In-Sun Bus Voltage > 30V
2) End-of-Eclipse Bus Voltage > 24V
3) Max Wheel 3 Voltage Divergence > -23V average

G. Crew Assignments:

As mentioned above, both the NAVSOC and Ball teams were small. NAVSOC staggered the crew to ensure a relatively "fresh" set of eyes were available at critical times. Since the satellite contact occurred at 0200 local time, two senior console engineers would arrive at 0200 and be available for the first two commanding supports following each burn. They would stay until mid-afternoon preparing table uploads and pass plans, and conduct recovery operations if required. The third console engineer would arrive around 0500 local to analyze the data from the previous two supports and help conduct the two California supports if necessary. He would remain until late afternoon compiling and analyzing data collected during the passes and would also double-check the pass plans and tables created by the other engineers. The junior engineer remained on a normal day shift and coordinated the daily telecon with Ball, cross-checked upload files, processed DSU data and helped conduct the afternoon supports. Since he was on a normal schedule, he also served as a ready back-up in case we determined we needed more help in the wee hours of the morning. The OA also remained on a normal schedule since the time to collect the required Doppler data mostly coincided with a normal work day. The officer, who would not be conducting any on-console operations, would come in at 0200 local and stay until all supports for the day had been conducted in order to provide timely communication and coordination, and allow the engineers to make the best use of the minimal time they had between supports. In addition, she was responsible for ensuring all checklist items had been completed and Go/No-Go criteria had been met before authorizing each burn as a "go."

On the Ball side, one engineer was responsible for generating orbit predictions for each burn. These would be submitted to the JSpOC for conjunction assessment. Once cleared, he would provide the post-burn state vector for the chosen orbit. After the burn, he would revise the prediction models to account for observed thruster efficiencies so the next prediction would be more accurate. The other engineer would be joining NAVSOC during the post-burn supports via telephone to provide real-time spacecraft expertise. Between supports, he would also review telemetry data and check the table uploads prepared by NAVSOC. Both engineers would join NAVSOC in a daily telecon to review GFO's current status and make decisions on the next course of action. They also provided the link to the subsystem experts at Ball who were helping us to work through this very difficult problem.

IV. Disposal Operations

By Monday, 03 November, GFO had remained in a stable 3-wheel Point over the weekend, but the temperature on Wheel 3 was causing voltage divergence well above the established Go/No-Go criteria. We had been making yaw adjustments throughout the weekend, and the temperature was finally leveling off. We believed one final adjustment would bring the temperature back within desired limits, but it would take roughly 18-24 hours for the wheel to cool sufficiently. The first disposal burn was delayed 24 hours. In order to make best use of the delay, we decided to test the spacecraft's ability to yaw into the burn orientation without conducting the actual burn. This would allow us to see how Wheel 3 responded to the maneuver, as well as seeing how the spacecraft handled the additional minutes without the array in the sun. This was dubbed a "Practice Acquire Delta-V" and would take place during the same time the burn would have happened. DSU data from after the Practice Acquire Delta-V showed a successful execution; however, Wheel 3 saw an increase in temperature due to the temporary sun orientation. This gave us cause for concern with burns of longer duration, but for the initial short duration burns we could proceed as planned. As a precaution, we planned to place the spacecraft in 2-wheel Acquire Sun as soon as possible following the burn in order to insure Wheel 3 over-stress did not cause any more UV3 events.

A. Disposal Burn #1:

On Tuesday afternoon, we checked the DSU data and confirmed that we had now met all Go/No-Go criteria. The first burn sequence would begin at 0214 local (1014 Zulu) on 05 November. The actual thrusters on duration would be 2 minutes. The burn was to take place approximately 15 minutes after eclipse exit but out of sight of NAVSOC ground stations. NAVSOC would have a viewing opportunity at 0227 local for roughly 9 minutes. We would have two additional viewing opportunities on the two following orbits, lending additional time to analyze and command if necessary should an anomaly occur.

As the first post-pass commanding window opened, the transmitter RF came in strong, indicating the spacecraft was not in survival mode. GFO was successfully placed in 2-wheel Acquire Sun and key telemetry points were verified to be nominal. Everything looked good…a little too good. A look at thruster temperatures confirmed that the thrusters had not fired as planned. Review of the available data indicated the CSM file containing the maneuver sequence of commands had an improper date, and that there was not a problem with the satellite itself. While we were glad the satellite was fine, the incorrect date was a pride-hurting human error that delayed the first disposal burn. This was a significant emotional blow for our team. It also spoke to how much of a toll the past 6 weeks of anomalies, recoveries, and disposal planning was taking on the crew. We would not allow that mistake to happen again.

The bad news kept coming. It was also about this time that one of our main crew members had a family emergency which would take him out of the picture for the remainder of the disposal. We were now down to just 2 fully qualified on-console engineers. Fatigue would be an even bigger issue now. The remaining NAVSOC team huddled up to evaluate our situation and decided we could keep the same schedule with a little juggling of the crew.

B. Disposal Burn #1 – Take Two:

The next attempt at the first burn was initially rescheduled for a 24 hour turn-around. However, analysis of telemetry indicated a need to delay. DSU data for GFO throughout the night indicated that the battery was cooling to temperatures close to the limit for survival heaters to turn on. Activation of battery heaters would raise the battery temperature, but would also transfer additional heat to Wheel 3 over time. This additional heat would almost certainly push Wheel 3 temperatures past Go/No-Go criteria. In order to prevent battery survival heaters from coming on during eclipse (which has a strong possibility of causing a UV3), we chose to turn the battery heaters on during full-sun periods to allow the battery to warm. Heaters were then disabled during a pass later in the day but in time to allow Wheel 3 to cool below Go/No-Go levels before attempting the first burn again on Friday, 07 November.

We decided to make one modification to this attempt. Instead of proceeding directly to 2-wheel Acquire Sun, the temperature of Wheel 3 would be evaluated, and we would only go to 2-wheel Acquire Sun if necessary. On the afternoon of 06 November, all Go/No-Go criteria were met and the files were uploaded for the burn…this time with the CSM file checked and rechecked and rechecked again just to be sure.

Real-time telemetry collected approximately 10 minutes after the first disposal burn indicated that the burn completed successfully. All key telemetry readings were within acceptable post-burn parameters and indicated that the thrusters had fired as planned. Telemetry also indicated that while Wheel 3 temperatures were increasing, there was no immediate need to go to 2-wheel Acquire Sun. We would continue to monitor this condition during the remainder of the morning passes.

C. The Pitch Maneuver:

DSU telemetry from during and after the burn indicated that while the 2 minute burn was successful, extending the burn duration beyond 2 minutes would likely increase Wheel 3 temperatures to unsafe limits. This was due in part to the normal Delta-V orientation (achieved via yawing the spacecraft as shown in Figure 7), which placed Wheel 3 directly into sunlight, raising the wheel temperature significantly. Fortunately, the new maneuver orientation Ball was developing, dubbed the "Pitch" maneuver (Figure 8), was almost ready. The Pitch maneuver would produce the same thrust vector but orient the spacecraft so Wheel 3 was shaded by the solar array throughout the maneuver, and the solar array would remain pointed towards the sun. The advantage of this orientation was that it would keep the Wheel 3 temperature low enough while simultaneously extending burn durations.

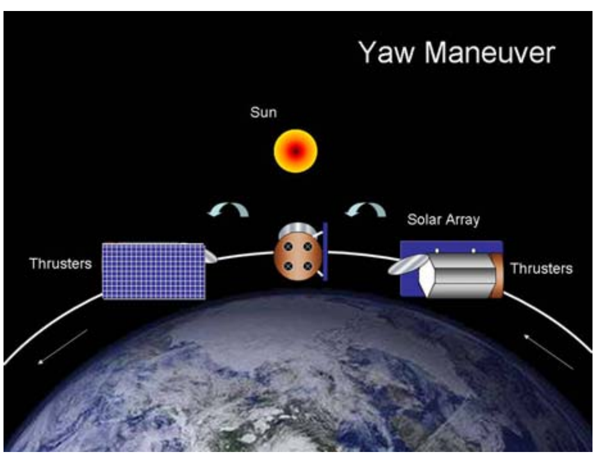

Figure 7: Yaw Maneuver Solar Array and Thruster Angles

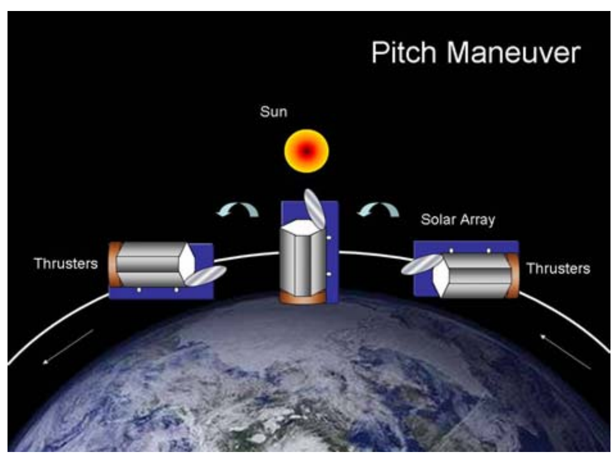

Figure 8: Pitch Maneuver Solar Array and Thruster Angles

CSM tables were prepared to conduct a practice Pitch maneuver with no thruster firings during the established maneuver window approximately 0200-0500 local (1000-1300Z) on Sunday, 09 November. DSU telemetry from this practice maneuver was analyzed to ensure the calculated maneuver did not induce any unexpected conditions.

The practice Pitch maneuver went well and indicated that the temperature of Wheel 3 did not get as high as with the Delta-V "Yaw" maneuver.

D. Disposal Burn #2:

The first actual Pitch Delta-V (5 minute burn duration) was scheduled to occur early Tuesday morning, 11 November. However, on 10 November, several attempts to load a new Initial Condition Vector (ICV) were unsuccessful. Analysis of the telemetry indicated that the Julian time on the spacecraft was not incrementing along with the UTC time. We executed a processor reset in order to clear the stuck Julian time and get GFO to accept a new ICV file. This processor reset automatically placed the spacecraft into 2-wheel Acquire Sun, requiring us to command it back to 3-wheel Point one revolution later. The need for a processor reset was troubling because, amidst all the other problems, it caused us to speculate about a possible deterioration of the processor brought on by the rash of UV faults. If the processor failed, we would be stranded in whatever orbit we were in, so this underscored the need to complete the burns as expeditiously as possible while minimizing further UV faults.

Disposal Burn #2 took place on 13 November using the Pitch maneuver and completed successfully. Reaction Wheel 3 remained stable and we began collecting the required 9 orbits of Doppler data while beginning preparations for Burn #3 (8 minute duration) on 16 November. And we hit our next speed bump.

While tracking during the orbits immediately following the burn was fine, several orbits later the Doppler and Space-Ground Link System (SGLS) antennas were unable to get a clean signal. The RF signature seemed to indicate the ground station was tracking a side lobe. Without the ability to accurately track the spacecraft, we could not gather enough data to complete an orbit determination and converge on a solution. Without converging on a solution, we could not update the antenna pointing angles to better point at the spacecraft. The problem was being caused by a combination of the predicted orbit, generated from Satellite Tool Kit (STK), and the longer burn durations. The predicted orbits had larger than expected errors because of errors in the predicted thruster efficiency. To accurately predict thruster efficiency, it is necessary to calibrate the thrusters by actually firing for the expected length of time under similar conditions of temperature and pressure. Given the need to complete this operation quickly, the jump from a 2 to 8 minute burn was too great to predict thruster performance with the necessary accuracy. As a result, the errors resulting from these longer burns were causing the satellite to diverge from the predicted orbit faster than the shorter burns. The Doppler antenna could manage 9 orbits of data with the shorter burns, but was barely getting 3 or 4 with the longer burns. Assuming we could get an accurate OD and re-point the antennas, we would be restricted to shorter burns. But first we needed a way to accurately point the antennas.

E. Joint Operations:

The JSpOC tracks space objects and reports on potential collisions. For the UHF Follow-On (UFO) and Fleet Satellite (FLTSAT) spacecraft, NAVSOC routinely requests and receives Vector Covariance Messages (VCMs) from the JSpOC. We had been sending them predicted orbits before each burn so they could continue to track GFO post-burn for conjunction assessment with other satellites and objects. They had no problems tracking GFO real-time and were able to provide a VCM for us several hours after the burn. This VCM was used to repopulate the antenna pointing angles by bypassing the Doppler system and generating the file manually. The new angles worked, and we were once again able to track the satellite on our own using GFO's Doppler data as inputs.

The next morning, the S-band antenna in California was unable to track GFO. In fact, the antenna wasn't even slewing during the GFO support. The SOC operators had just used the antenna for a UFO support and it performed flawlessly. We were a bit perplexed as to why this was happening. After some investigation, we found a single diagram in one of the manuals that described a series of files generated by the Doppler system when the system was first installed. Since that time, NAVSOC had upgraded the California antenna drive system to more closely resemble the equipment at Maine and Guam. At the time of the upgrade, it was determined that the system would no longer need certain files that were generated automatically. Since nothing was hurt by allowing the system to generate these files each time an OD was performed, the software was never modified to not create them. As it turned out, the California antenna drive system was still using one particular file. Since we were no longer running actual Doppler ODs, but rather directly populating the files we knew were being used, the file in question contained old data which was rejected by the drive system as being invalid. Manually generating this file was not as easy as the pointing angles files. We set our ground systems personnel working on the task and resigned ourselves to only having two antennas to work with.

Since the JSpOC VCM process worked very well, we asked the JSpOC if it would be possible to set this up as standard procedure for all the remaining GFO burns. This allowed us to continue to use the longer burn durations, vice shortening the burn lengths to keep the predicted and actual post-burn orbit tracks from diverging so quickly. (Note: It wasn't that the Doppler antennas couldn't track the satellite fast enough, it was that the difference between the predicted and actual post-burn orbit tracks diverged much faster with longer burns.) It would also shorten the time required to turn around an orbit determination. Using the Doppler system, we needed 15 hours to collect 9 orbits worth of tracking data. Using JSpOC VCMs, we only needed about five hours. The JSpOC agreed to provide us with VCMs after each burn, and we changed our plan to repopulate our antenna pointing files using the VCM information. (This was now very much a Joint Operation.)

F. Gaining Momentum towards the Light at the End of the Tunnel:

Disposal Burn #3 (8 minute duration) completed successfully on 16 November. Data analysis showed Wheel 3 responded favorably to the 8 minute burn and the spacecraft was left in 3-wheel Point. Burn #4 would be the first 10 minute burn. If everything went well, we would only have four burns left until all the fuel was depleted. With the new, shortened OD turnaround thanks to the JSpOC, we assessed that we could now conduct one burn per day. This schedule was a little more aggressive than we preferred, but given that it was already mid-November due to all the unexpected delays, we knew we had to pick up the pace. On 26 November, the angle of the sun in relation to the spacecraft would prevent us from using the Pitch maneuver, relegating us back to performing 2 minute burns to keep Wheel 3 cool. With only 9 days to complete 4 burns, there was very little room for error. The remaining 4 burns were predicted for 18-21 November at 10 minutes duration each.

As soon as we announced this schedule, Murphy showed up with his Law. While Disposal Burn #4 went off without a hitch, following the burn, the ICV failed to go valid again. When the spacecraft initiated the ICV, it froze the orbit propagator in a similar manner as the ICV issue that occurred the week before. This was more evidence pointing towards the processor going bad. We were able to initiate a processor reset and to upload and enable a new ICV during the afternoon passes. However, there was intermittent telemetry during both afternoon supports preventing us from placing GFO into 3-wheel Point. Real-time telemetry collected during the intermittent passes showed Wheel 3 voltages exceeding the Go/No-Go criteria, forcing the planned burn for 19 November to be postponed 24 hours.

Murphy wasn't done. Around the time the burn should have occurred, GFO suffered a UV3 which engineers were not able to recover from during the support on which it was discovered. There were no additional sunlit passes available for approximately 8 hours, and we couldn't begin preparations for the next burn until we recovered from the UV3. While we waited, we analyzed the telemetry which had been collected just one orbit prior (a small piece of luck, but we'd take any we could get at this point). Analysis from the telemetry indicated that the cause of the UV3 was likely due to the battery getting cold enough to allow the battery survival heater to turn on. The load of the heater was more than the battery could handle during the eclipse portion of the orbit.

When the next pass finally rolled around, the orientation of the random tumble from the UV3 had allowed the battery to warm significantly and to charge at a healthy rate. CSM commands were adjusted to heat the battery during the sunlit portion of the orbit for a longer duration in order to keep the battery temperatures above the battery survival heater turn on threshold. It would take the rest of the day to fully recover GFO from the UV3, but recovery happened without any further difficulties and planning was finally underway for Disposal Burn #5 scheduled for 21 November.

G. Racing the Clock:

We now had just 5 days left for 3 burns and a bunch of tired crew members. Our aggressive "one burn per day" schedule was going to be very risky. On the other hand, we didn't have enough time left to go back to one burn every two days. If we did not complete all three burns prior to 26 November, we would have to take the remaining fuel (anywhere from 10 to 30 minutes worth) and burn it off in 2 minute increments. Sometime in the wee hours of the morning on 20 November while staring at our flowchart, a list of non-eclipsed support times and locations, and the number of remaining burns, something finally clicked in our sleep-deprived minds. Because of the location of our ground sites, we could actually do a burn once every 1.5 days! If the remaining burns executed as planned, the modified burn schedule would allow us to complete GFO's de-orbit within 4.5 days and meet our target date of 26 November without introducing the unnecessary risk of an overly aggressive schedule.

The new plan alternated uploading files over Guam at 1400 local to burn over Maine around 0200 local with uploading files over Maine at 0200 local to burn over Guam around 1400 local. The new schedule was as follows:

Burn #5 - Approximately 1400 local (2200Z) 21 November 2008, 10 minutes duration (Guam)
Burn #6 - Approximately 0200 local (1000Z) 23 November 2008, 10 minutes duration (Maine)
Burn #7 - Approximately 1400 local (2200Z) 24 November 2008, 10 minutes duration or remaining fuel (Guam)

Disposal Burn #5 completed successfully, and, we got a bonus. The commanding window coincided with the latter part of the burn, so we got to “see” the thrusters firing in real-time telemetry and the spacecraft rotating back to its nominal 3-wheel Point orientation.

H. **Disposal burns #6 and #7:**

Disposal Burn #6 completed successfully as well. Battery and Wheel 3 telemetry were nominal. While we were preparing for Burn #7, the Ball Engineers informed NAVSOC that based on their models and pressure reading from the propellant tank, their propellant specialist predicted we would have just about 10 more minutes of thrust than originally thought, requiring one additional burn. Burn #7 would lower perigee below the required 500 km point, so we could check off one part of the disposal criteria. But in order to deplete the remaining propellant, we had two options: add one additional 10 minute Delta-V, or fire opposing thrusters to deplete the fuel without moving the spacecraft. Since every kilometer below 500 km would reduce GFO’s time remaining on orbit, we chose to schedule one more burn. But it would have to be just 24 hours after Burn #7, assuming nothing else went wrong. Fortunately, Burn #7 went off without a hitch.

I. The Final Support:

Burn #8 was to begin at 2352Z (1552 local) on 25 November with final safing and shutdown occurring just 27 minutes later at 0019Z 26 November. It was desired to complete safing as soon as possible after the burn because with all fuel depleted, the spacecraft would be without its most essential survival feature, the ability to self-induce a power-positive tumble. If the spacecraft went into UV3 or SP1 before we could send the final commands, it could potentially be stuck on orbit with fully pressurized batteries and present an explosion/debris hazard.

We pre-loaded 27 safing commands into the CSM for automatic execution following the Delta-V and reserved 5 commands to be sent from the ground to complete safing and shutdown. The CSM commands would automatically execute once the satellite was in view so engineers could verify the commands executed properly. Once the commanding pass started, we would collect the final batch of DSU data for documentation purposes, and to verify the final pressure state of the propellant tanks. Then the CSM safing sequence would execute. Finally, the last 5 commands would be sent, including turning the downlink S-band transmitter off for the final time.

As we approached the commanding window, there was a small gathering in the SOC to watch the final support. As soon as telemetry was acquired, we quickly checked the thruster temperatures to try to gauge how long they had burned. They were quite warm at 60 degrees C, indicating they had been expending fuel for close to the full ten minutes. Ball’s prediction had been dead on (See Table 2). Then we checked the propellant tank pressure. It was just 8 psi (down from 400 psi at launch), indicating the tank was indeed empty and no longer posed an explosion hazard.

Burn #	Date/Time	Burn Duration (Min)	Tank Pressure After Burn (PSI)
1	7NOV/1155Z	2	182
2	13NOV/1152Z	5	166
3	16NOV/0953Z	8	147
4	18NOV/1000Z	10	131
5	21NOV/2234Z	10	119
6	23NOV/1006Z	10	110
7	24NOV/2155Z	10	102
8	25NOV/2352Z	10	8

Table 2: Disposal Burn Data

With everything indicating as expected, we dumped the DSU data for the final time, collecting the telemetry from the final burn, then started the safing sequence which began with commanding all fuel valves open. Next, GFO was "tricked" into shutting down by placing it in a configuration where the normal fault responses to insufficient power would not be allowed to shed loads, thus keeping the battery depleted as much as possible. This was accomplished by the following:

- The Power Control Unit was commanded to hold the battery at the lowest possible state of charge (VT2).
- Three power busses (Non-Essential Bus, Attitude Control Bus, and Payload Bus), which would normally be automatically shed when battery power became insufficient, were bypassed to guarantee the loads would remain connected to the battery, ensuring power would continue to be drawn.
- Sufficient loads were commanded "on" to draw current from the battery at a rate that would exceed GFO's ability to recharge the battery between eclipses.
- All battery heaters were powered off. With these heaters off, the temperature of the battery was dramatically reduced, which dramatically reduced its ability to accept charge.

These steps would eventually discharge the battery below the point where the Power Control Unit (PCU) could be supported (bus voltage < 19 V), essentially turning it off. At that point, all solar array segments were disconnected from the power bus with the exception of one hardwired segment. This one segment of the solar array was still capable of powering the spacecraft and attempting to recharge the battery when in the sun, creating the possibility of the batteries recharging enough to bring the PCU back to life. In order to ensure the PCU remained off, two additional resistive loads, the catalyst bed heaters and the magnetometer heaters, were left on. If the battery ever gained enough charge to revive the PCU, these two components would continue to draw more current than the single solar array segment could provide, and rapidly pull the bus voltage back below 19 V. Effectively, GFO would never achieve a power-positive state again. Power was removed from the reaction wheels, setting GFO adrift. At 00:18:40 Zulu on 26 November 2008, with all disposal requirements fulfilled, GFO's transmitter was disabled and turned off for the last time.

V. Summary

GFO's final Apogee/Perigee was calculated to be 783 km/456 km[+] according to the final VCM delivered by the JSpOC. The orbital lifetime depends heavily on solar activity, which is described probabilistically. Drag depends on solar activity, which controls the upper atmosphere density and is difficult to predict accurately. Marshall Space Flight Center publishes +2 sigma, nominal, and -2 sigma predictions of solar activity. Analysis conducted by Ball Aerospace Corporation in December 2008 using these tools indicated the following:

+2 Sigma	Nominal	-2 Sigma
3.9 years	15.6 years	>25 years

Table 3: Solar Activity GFO Post-Mission Lifetime

The Solar Cycle 24 Panel estimates (updated May 2009) predict a cycle with below average activity (average sunspot activity is 114; cycle 24 prediction is currently 90) and a cycle peak in May 2013. Therefore, as of July 2009, it is expected that GFO's orbit will decay to atmospheric re-entry sometime between 15.6 years and 25 years from final shut-down, or between 2024 and 2033. If Solar Cycle 24 is more active than predicted, or Solar Cycle 25 is above average, GFO may decay more quickly.

"The decommissioning of GFO, including the lowering of its orbit to ensure a natural reentry within 25 years and the passivation of its energy sources, was fully compliant with NASA, U.S. Government, and international spacecraft disposal guidelines. The achievement was especially commendable due to the seriously degraded state of the spacecraft's critical support systems. Moreover, GFO was designed prior to the implementation of specific disposal requirements by NASA or the adoption of space debris mitigation guidelines by the United Nations. Hence, the GFO flight control team has set a high standard for operators of other spacecraft, both old and new. This feat was summarized before the Scientific and Technical Subcommittee of the United Nations' Committee on the Peaceful Uses of Outer Space in February 2009."

[+] Mean elements (Kozai formulation, as implemented in Satellite Tool Kit) with respect to an Earth equatorial radius of 6378 km.

Nicholas L. Johnson
Chief Scientist for Orbital Debris
NASA Johnson Space Center

After 33 days, 13 UV faults, 17 processor resets, 8 disposal burns, a lot of caffeine, and the help of many dedicated people at NAVSOC, Ball Aerospace, and the JSpOC, the disposal of this power-challenged satellite with an attitude control problem was a success. In retrospect, there were a lot of decisions made "on the fly" with the best information we had at the time. But were they necessarily the best decisions? According to SI 505-4, "*Throughout a satellite's life, each SATCOM System Expert (SSE) responsible for the satellite in support of the SOM, or their equivalent for non-SATCOM systems…will ensure every SSE-designated satellite maintains adequate disposal capability…*"

In light of this requirement we must ask ourselves, "Did we wait too long to begin disposal operations?" There are certainly good arguments on both sides. GFO was the only spacecraft providing the Navy with this data it needed. But, did that need for data justify stranding the spacecraft in orbit to get several more months of data? This is a debate that may never be resolved. The sudden drop in battery capacity forced our decision for GFO, but future programs may benefit from conducting more frequent "support/terminate" criteria reviews which trend data and attempt to predict when the disposal will need to commence. Other questions we are still exploring include:

- Did our desire to complete disposal quickly result in decisions that actually risked being able to successfully complete disposal (e.g., resulted in avoidable UV3)? Would it have been better to move slowly and accept the risks associated with having to conduct many more short burns with the degraded spacecraft?

- In streamlining operations, did we allow the number of fully qualified engineers to fall too low, putting our ability to respond to an extended anomaly at risk? How do you justify manning to anomaly levels in an austere budget environment?

- Could we have reasonably foreseen the problems with our ground system while developing the original disposal plans for 31 December, and developed a contingency plan ahead of time? How much effort should be devoted to developing a robust disposal plan while the spacecraft is healthy? How much planning is too much?

We will continue to ask ourselves these and other questions, and hope that GFO's disposal will help other satellite operators prepare for their future disposals.

Acknowledgments

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