Development and Execution of End-of-Mission Operations

Case Study of the UARS and ERBS End-of-Mission Plans

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Abstract

This Paper is a case study of the development and execution of the End-of-Mission plans for the Earth Radiation Budget Satellite (ERBS) and the Upper Atmosphere Research Satellite (UARS). The goals of the End-of-Mission Plans are to minimize the time the spacecraft remains on orbit and to minimize the risk of creating orbital debris. Both of these Missions predate the NASA Management Instructions (NMI) that directs missions to provide for safe mission termination. Each spacecrafts had their own unique challenges, which required assessing End-of-Mission requirements versus spacecraft limitations. Ultimately the End-of-Mission operations were about risk mitigation. This paper will describe the operational challenges and the lessons learned executing these End-of-Mission Plans

I. Introduction

The End-of-Mission operations for ERBS and UARS began after NASA Headquarters directed the Earth Science Mission Operations (ESMO) Project to terminate the ERBS and UARS operations [1]. In the case of ERBS decommissioning was to be accomplished by the end of September 2005. UARS was to be decommissioned by the end of January 2006 [2]. These two missions were some of NASA's oldest operational spacecraft. Both had operated over extended lifetimes, successfully producing very valuable science data for 20 and 14 years respectively. The ERBS and UARS spacecraft had both suffered multiple component failures. In light of the degraded systems, performing the End-of-Mission Activities offered many technical challenges. The Flight Operations Team After struggling to keep these spacecraft operational for years now found themselves in another unique phase of the mission.

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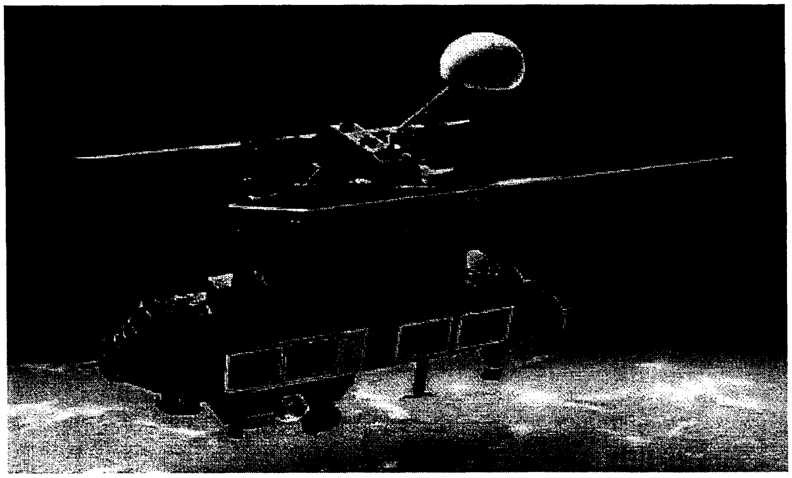
The End-of-Mission goal was to passivate the spacecraft by depleting all the remaining fuel, ensuring the batteries do not overcharge and possible explode, and by eliminating any onboard energy sources that may present the risk of creating orbital debris. This part of the mission was not designed into the spacecrafts. Performing these operations requires careful planning and coordination. Performing orbit-lowering maneuvers required a well thought out maneuver strategy to ensure that all goals could be safely met. Collision avoidance screenings were required to ensure that these maneuvers did not jeopardize other missions. In the UARS case the predicted final maneuvers would leave the spacecraft with a perigee at the same altitude of the International Space Stations (ISS) orbit. Other technical considerations included accounting for the changing performance and characteristics of the propulsion system. As in the case of ERBS, having depleted most of the fuel aboard, the performance of the propulsion system suddenly changed radically and unpredictably. This unpredictability caused an anomaly during the last monthly yaw maneuver. Even though the system characteristic had been modeled to account for the degraded performance, the behavior at the start of the maneuver was greatly different than seen previously.
Many unique mission elements were dealt with during End-of-Mission Operations; much of the system knowledge had been lost due to the age of the missions. The Cadre of Engineers that was required to draw on the diminished resources that were still available. This was another significant challenge in performing all decommissioning activities successfully.

II. ERBS

The Earth Radiation Budget Satellite (ERBS) was deployed from the Space Shuttle Challenger during Shuttle Mission STS-41G on October 5, 1984. ERBS had a scheduled mission life of 2 years. The ERBS was launched into a 611km orbit with a 57° inclination circular orbit. ERBS has continued to operate and provide valuable science for over 21 years. The observatory provided data to form an earth radiation budget, which describes the thermal equilibrium that exists between the Sun, the Earth and space. ERBS carries two payloads, the Earth Radiation Budget Experiment (ERBE) and the Stratospheric Aerosol and Gas Experiment II (SAGE II). ERBE, in turn, comprises two instruments, the ERBE-Scanner (ERBE-S) and the ERBE-Non-Scanner (ERBE-NS). The ERBE instruments measure total solar irradiance, reflected solar radiation and Earth/atmosphere radiation. Absorbed solar radiation is calculated from these measurements. SAGE-II monitors the radiation energy of the atmosphere by determining the amount and global distribution of stratospheric aerosols, constituents such as nitrogen dioxide and ozone, and the natural background formed by ambient constituents [3]

This Spacecraft was developed and launched prior to the NASA directives which required spacecraft to have the ability to safely terminate their mission with controlled reentry. From its final orbit it will be allowed to return uncontrolled to the earth in approximately 17 years. The NASA guidelines preferred method calls for missions to lower their orbit perigee as much as possible, both to minimize the on-orbit lifetime, as well as to deplete all onboard hydrazine fuel. The initial study for ERBS indicates however, that the risks associated with eliminating the remaining fuel by performing post-science mission delta-V maneuvers were very significant, and therefore those maneuvers were not performed. With the exception of orbit lowering, the baseline plan strives to achieve all other NASA mission termination objectives.



After performing 2 300-minutes Fuel Depletion Burns the final Burn was conducted in 2,4 8 and 10 minute increments to ensure that the Spacecraft remained stable. Having spent almost 24 hours trying to deplete the last of the remaining fuel, the ERBS End-of-Mission Team decided that the time had come to terminate the Mission. Starting at 2102z 14 October 2005 the passivation of the spacecraft began. ERBE and SAGE were powered back on and all available power loads were enabled. During the 14 October 2005 2146z support the final tape recorder playback was performed. On board memory was scrubbed and all commandable solar array circuits were taken off-line.
On the final ERBS contact, TDW 2208z, the attitude and momentum control system was disabled and the power

system was put in discharge. The final commands opened the thrusters to allow the remaining fuel to seep out and the transponders were powered off for the last time at 23:00:00

ERBS completed 114941 orbits over 21 years of operations. Though, time had taken its toll the spacecraft refused to go quietly.

III. ERBS Status and Disposal Assessment

The status of the ERBS spacecraft bus limited the options available to the ERBS Flight Operation Team for decommissioning. Since component failures had occurred over the spacecraft's 21-year life, the ability of the spacecraft to satisfactorily complete orbit lowering maneuvers was given a low probability of success. It would have required 90+ Perigee–lowering maneuvers to deplete the remaining fuel. To perform these maneuvers the spacecraft would need to Pitch over 90° without a viable Attitude Control System. Based on an assessment of all the potential disposal options, the only viable option is decommissioning ERBS on orbit.

The GSFC Flight Dynamics (FD) organization had performed extensive analysis to determine the final orbit and attitude based on approximately 175lbs of fuel currently remaining on-board ERBS. The following table provides an estimate of the fuel consumption during the planned ERBS decommissioning thruster burns:

Burn Sequence	Duration	Orbit Impact	Fuel Consumption
Test Burn	20 min	~ 10 km	5 lb
Confidence Burn	300 min	~3 km	65 lb
Long Duration Burn	300 min	> 1 km	65lb
Final Venting	300 min	< 1 km	>60 lb
Total	920 min	~15 km	> 175 lbs

Several analyses of ERBS reentry were performed by GSFC to determine the Debris Casualty Area (DCA). Results of these analyses are summarized as follows:

DCA	Probability of Casualty	Likelihood of Casualty
25.7	0.000396	1 in 2525
33.5	0.000516	1 in 1937
40.3	0.000621	1 in 1610

IV. ERBS Observatory Status

The ERBS was launched into a 611km altitude 57°- inclination circular orbit. Designed for a 2-year life, ERBS was continuously operated and provided very significant valuable science for over 21 years. The observatory provides data to form an earth radiation budget, which describes the thermal equilibrium that exists between the Sun, the Earth and space. ERBS carries two payloads, the Earth Radiation Budget Experiment (ERBE) and the Stratospheric Aerosol and Gas Experiment II (SAGE II). ERBE, in turn, comprises two instruments, the ERBE-Scanner (ERBE-S) and the ERBE-Non-Scanner (ERBE-NS). The ERBE instruments measure total solar irradiance, reflected solar radiation and Earth/atmosphere radiation. Absorbed solar radiation is calculated from these measurements. SAGE-II monitors the radiation energy of the atmosphere by determining the amount and global distribution of stratospheric aerosols, constituents such as nitrogen dioxide and ozone, and the natural background formed by ambient constituents.

A summary of the ERBS mission status, as well as the status of the instruments and spacecraft bus systems is provided in the following section.

A. Mission Status:

ERBS, as of October 2005, had completed all Science Mission and extended Mission objectives

B. Payload Status at Start of Decommissioning:

1. ERBE-S

The ERBE scanner failed on February 28, 1990. It was determined at that time that the elevation beam motor had stopped and the beam was not scanning. After several recovery attempts, the instrument has been powered OFF since March 1991.

2. ERBE-NS

ERBE non-scanner continued to operate nominally. The instrument could not be elevated to perform bi-weekly internal and Solar-calibrations. However, there were no trends or indications of any other problems.

3. SAGE II

The SAGE II instrument experienced a failure in July of 2000. SAGE II was unable to lock on to either sunrise or sunset events. This was believed to be due to excessively noisy azimuth potentiometer readings in selected azimuth regions. An operational work-around had been developed which allows SAGE II to collect approximately 50 percent of the nominal science data.

ERBE-NS was powered-off 22 August 2006 in preparation of decommissioning activities. SAGE II was powered off at the completion of their August 2006 Monthly Scan Cycle.

C. Subsystem Status at Start of Decommissioning:

ERBS was designed and built with considerable redundancy throughout all of its subsystems; however, the spacecraft continued to operate after permanent fail-over to several redundant components. The following subsystem summaries describe the status of each with respect to its ability to support the science mission and to support the End-of-Mission plan.

1. Electrical Power System (EPS)

ERBS was launched with two – 50 ampere-hour Nickel Cadmium batteries, each containing 22 cells. Battery #2 has experienced 5 cell failures and has been disconnected from the main bus as of January 1999. Battery #1 has experienced failures in 3 cells (the last occurring in March of 2000) leaving 19 cells producing a bus voltage of 23V. Due to the cell failures, battery charging is accomplished via ground commands uplinked at least twice per day. The power system continues to support the science mission in its current state.

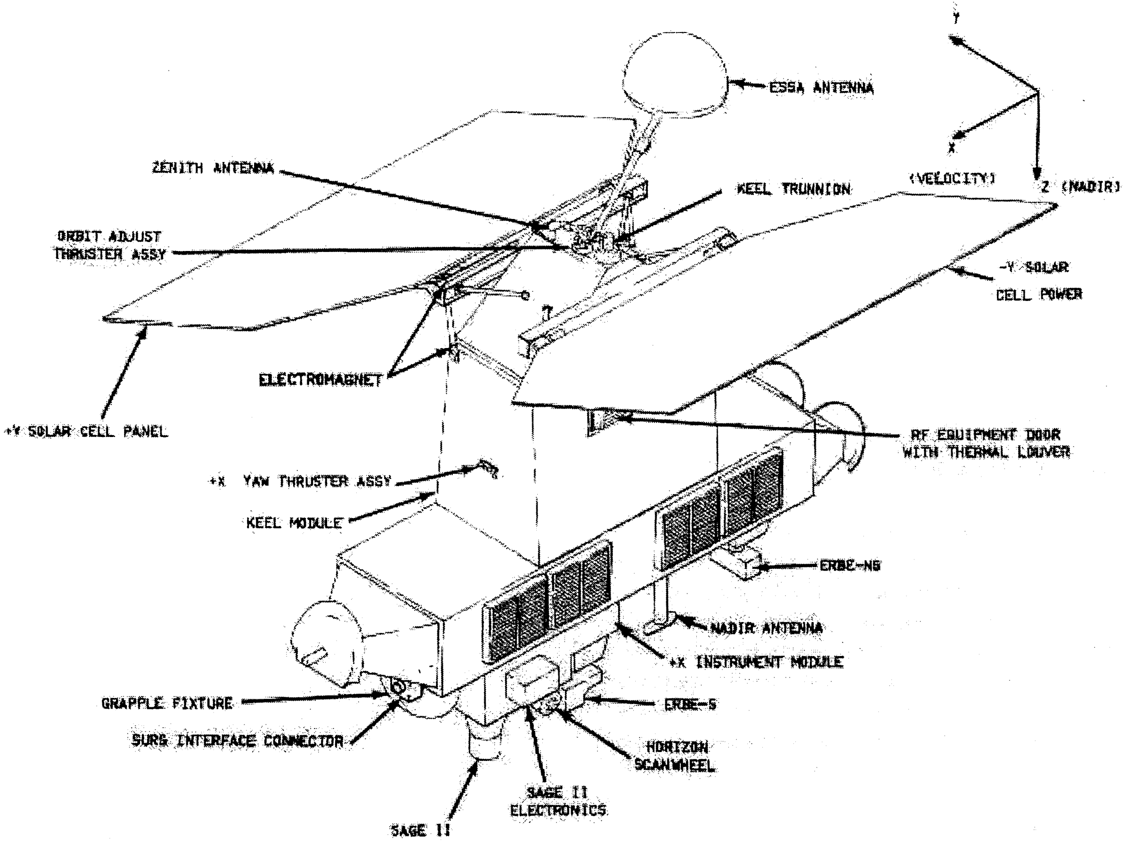


Figure 1; ERBS Spacecraft

Power Management

Power Management required controlling the Battery charge rate. This was accomplished via ground command loads which were uplinked at least twice per day. Three Constant Current Modes from the SPRU were used to charge the battery. The battery was charged at the beginning of day at 2.7 Amps. The middle of the orbit day, the battery is charged at 11.4 Amps, and then back to 2.7 Amps at the end of the orbit day. A 5-Amp discharge rate is used during full sun periods and during shallow discharge periods to minimize battery overcharge. The time in each constant current mode is monitored every orbit to maintain a Charge/Discharge (C/D) ratio of 1.01.

Due to the number of cells, the minimum bus voltage ranged from 21.3 – 24.0 volts. The minimum bus voltage averages was normally above 23.0 volts. The spacecraft would lose all communications if the bus dropped below approximately 20 Volts. A cell failure would drop the average bus voltage by approximately 1.2 volts to 21.8 volts.

2 Attitude Control and Determination System (AC&DS)

The ACDS was comprised of the Magnetic Control System (MCS) and the Reaction Control System (RCS). The MCS maintained attitude control during day-to-day operations, while the RCS was used to support the monthly yaw maneuvers. (As a single array spacecraft in a non-sun synchronous attitude, the yaw maneuvers were required to maintain the sun on the array side of the spacecraft.)

The ACDS system maintained fully functioning Momentum Control System (MCS) components. The system also provided a B-dot mode, which was available for emergency earth re-acquisitions resulting from loss of attitude control which would lead to subsequent power problems. This B-dot mode was activated during the following three periods: July 1987, January 1999, November 2000 and December 2003. B-dot was also exercised during the Yaw anomaly which occurred during decommissioning activities. In each case, the reacquisition mode performed nominally.

Reaction Control System (RCS)

For support of RCS functions, the ACDS had only 1 healthy gyro out of the original 6, and 8 of 8 thrusters were operating nominally at the start of decommissioning activities Thruster performance degraded which resulted in thruster imbalance and unstable performance which will be discussed further in the Yaw anomaly section. In order to extend the gyro lifetime, the unit is powered on only for the period immediately preceding the maneuver until maneuver completion.

With respect to supporting orbit adjust maneuvers; the availability of only 1 gyro precluded the RCS from providing adequate attitude for long ΔV burns. Should the remaining gyro fail during a ΔV maneuver, it is likely that yaw axis control would be lost. Loss of attitude control would eventually propagate into power failures and on to loss of communications. The RCS supported the monthly yaw maneuvers, although the gyro failures caused modifications to the yaw maneuver command sequence procedures. At the time, a Z-axis gyro-only maneuver procedure was being utilized. It should be noted that these maneuver procedures were highly dependent upon the state of the power subsystem. As such, the yaw maneuver procedures had been designed in such a manner to account for the number of remaining cells in the functioning battery. B-DOT mode was disabled during normal operation due to power concerns.

Orbit Adjust Propulsion System (OAPS)

The OAPS, which comprises the propulsion components to perform ΔV burns, was fully operational. In 2002 The ERBS Mission was being assessed and a change in mission orbit was required. Operations were conducted to lower its orbit to approximately 500km Circular orbit. While the ERBS orbit is no longer routinely maintained, the OAPS was used to lower the spacecraft to the calibration orbit.

3. *Communications and Data Handling (C&DH)*

The C&DH subsystem supported on-board command processing and telemetry handling, science and housekeeping data storage, as well as the ability to receive and transmit these commands and data. The C&DH system was comprised of two fully redundant and partially cross-strapped strings to support the command and telemetry functions. Four data recorders were available for data storage. The spacecraft had three RF antennas; all three antennas remained healthy. Nominal command and telemetry functions were performed through the ESSA (gimbaled antenna). Two omni antennas (one nadir looking, the other zenith looking) were available for contingency operations.

Commanding

The C&DH subsystem remained single fault tolerant for real-time commanding as both command strings remained functional. There were two healthy transponder receivers and each receiver could get a command from any one of the 3 antennas. A failure to any component in the real-time command line with the exception of Transponder-A, would of left the spacecraft one failure away from loss of real-time commanding. Being zero-fault tolerant for real-time commanding constituted a trigger point for the Orderly Mission Termination Procedure. With respect to stored command capability, the need to upload battery charge commands twice per day (see EPS discussion above) made this capability essential for continued spacecraft operations. (The power management commands are only available for 12 hours after the last CSM load was uplinked.) Only one healthy Command Storage Module (CSM) exists. This CSM can be accessed by Transponder A only thereby made a failure to Transponder-A receiver a trigger for the Emergency Mission Termination Procedure.

Telemetry

The spacecraft was zero-fault tolerant for telemetry as the loss of the second Digital Telemetry Unit (DTU) or loss of the Telemetry Distribution Unit (TDU) would leave the spacecraft without telemetry capability. Loss of telemetry capability was a trigger for execution of the Emergency Mission Termination Procedure. Other telemetry support components including the transmitters and power amplifier remain single fault tolerant. The loss of the ESSA antenna would result in loss of science data. Housekeeping data would be preserved via the omni antennas to the available ground stations or TDRSS.

Data Storage

All four tape recorders were functioning. ERBS only required that one tape recorder function to capture all SAGE II data and part of the housekeeping data.

4. *Thermal Control System (TCS)*

The TCS comprises a combination of Multi-Layer Insulation (MLI), heaters, louvers and thermal control finishes. The TCS was fully functional.

V. Applicability of NASA Guidelines and Policies to ERBS

ERBS was launched in 1984, prior to NASA's establishment of an orbital debris policy (NSS-1740.14 "Guidelines and Assessment Procedure for Limiting Orbital Debris", dated August 1995). The applicability to ERBS of current NASA End-of-Mission Disposal policies (NPD 8710.3B "NASA Policy for Limiting Orbital Debris Generation", dated April 2004) [4] is limited to defining operations that minimize the ERBS lifetime and minimize ERBS as an on-orbit or reentering debris hazard.

The ERBS/ESMO project complied with the policies and guidelines by:

1. Minimizing the potential for generation of orbital debris due to explosion or collision via venting remaining on-board hydrazine.
2. Removing the ability of the spacecraft to act as an RF source by disabling, to the extent possible, the S-Band receivers and transmitters.
3. Passivating of the Observatory by disabling actuator control functions and by disabling/severing solar power distribution functions to the extent possible.

VI. ERBS Decommissioning Method

ERBS was decommissioned on-orbit by the end of Fiscal Year 2005, as directed by NASA Headquarters with concurrence of the Science Project Office at Langley Research Center. Following NASA guidelines and requirements, fuel was vented from the propellant tank, the spacecraft batteries were disconnected from the solar array and the transponders will be powered off. In order to confirm the ability to maintain a controlled and stable attitude, the plan was to enable all 4 yaw thrusters in a series of calibration tests. Once the End-of-Mission team was confident of the performance of the spacecraft in this configuration, venting operations proceeded. After the second Depletion Burn, spacecraft attitude stability became an issue. Another series of calibration burns were performed. The results of these calibration resulted in a change in the way the final burn was performed, as will be described later. ERBS fuel load had been determined to be approximately 175 pounds ± 22lbs. The final emptying of the fuel tanks indicated that a failure of the tank bladder had occurred and that the thrusters continue to perform past the expected depletion pressure of 80psi.

Implementation of the ERBS End-of-Mission plan required development of an End-of-Mission Plan [4] with a timeline for each of the scenarios anticipated. Most of the procedures involve Instrument turn- off, "maneuver activities", transponder turn-off, and are performed as part of special or normal operations and are well understood and tested.

Ball Aerospace Division (BASD), the spacecraft contractor for ERBS, GSFC Applied Engineering and Technology Directorate (AETD) Engineers and Flight Dynamic personnel, developed simulated venting models to establish the best configuration for venting operations

VII. Implementing ERBS End-of-Mission Plan

Termination of the ERBS mission was the task of the ESMO project and executed by the ERBS End-of-Mission team. To ensure that the Plan was implemented according to NASA guidelines and directives, a Code 300 Peer Review was held. Collision avoidance analysis and conjunction assessment were performed for all maneuver activities, which were screened by Cheyenne Mountain Operation Center (CMOC)

The ERBS EOM Activities were planned out based on Tracking Data Relay Satellite System (TDRSS) and the Deep Space Network (DSN) forecasts. It was desired that DSN Canberra supports were scheduled during the spacecraft eclipse to assess the health and performance of the spacecraft during the venting operations. This was done during the full orbit burns with limited success. The Telemetry and Command (TAC) Front-end Processor had only been configured for nominal GN supports at 8Kbps. Since the Burns were being performed using the omni antenna at a lower data rate, 1.4Kbps, the TAC could not completely support these events. There were no TAC Software engineers available to update the configuration for these events. The Canberra events experienced intermittent telemetry with many dropouts on the Prime TAC. The Backup TAC was completely unable to lock up on telemetry.

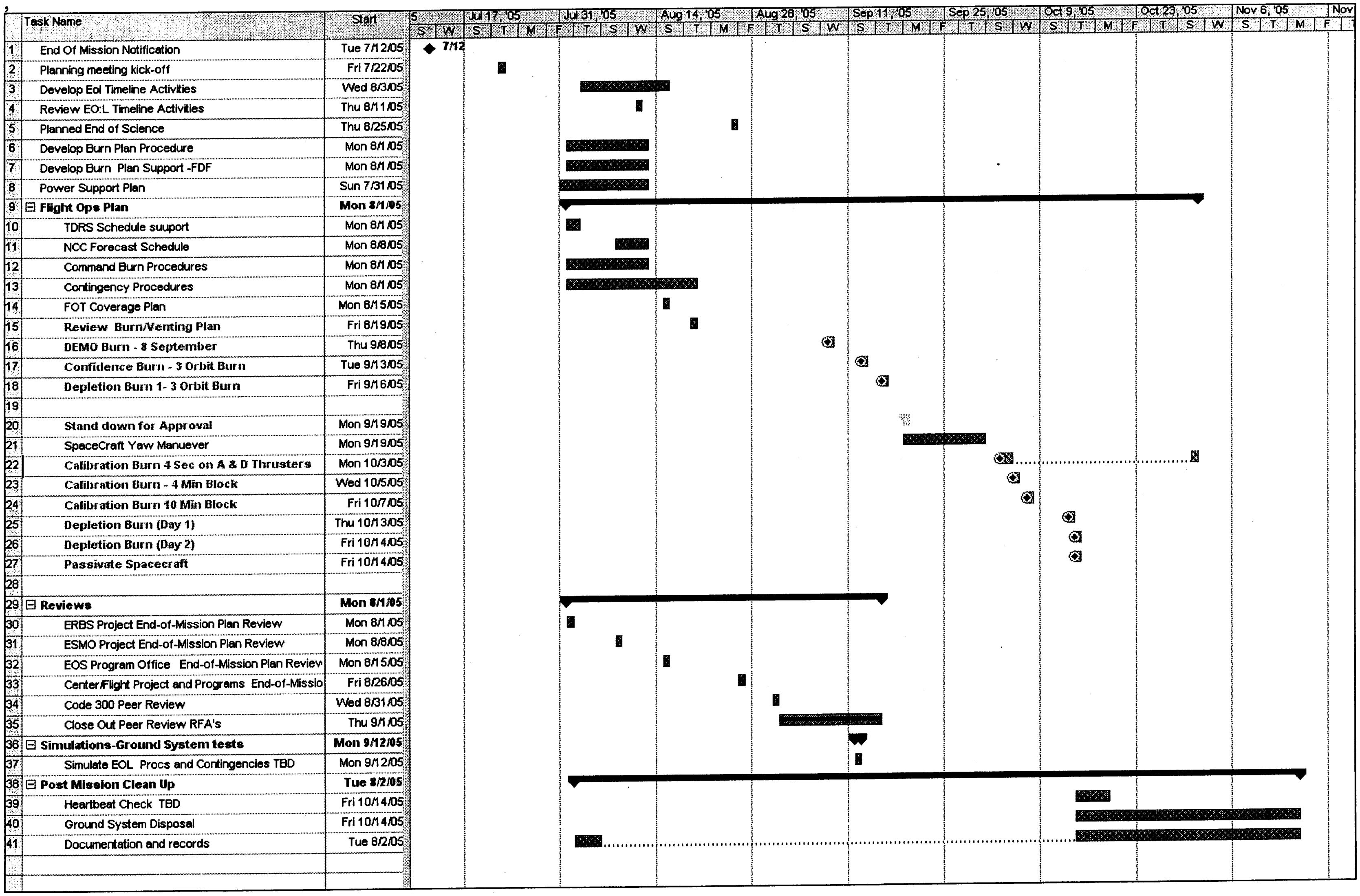
The TDRSS supports for the venting operations were scheduled as critical supports. The planned End-of-Mission activities were executed as follows:

• Demonstration Burn	08 September 2005 11:20 - 11:40
• Confidence Burn	13 September 2005-09-13 11:30 - 16:30
• Depletion Burn 1	16 September 11:30 - 16:30
• Yaw Maneuver	23 September

Thruster A &C Cal	03 October
4 Thruster Cal Burn	05 October
10 min Cal burn	07.October
Depletion Burn 2 (Day 1)	13 October 11:00 - 23:30
Depletion Burn 2 (Day 2)	14 October 11:00 - 22:30
Spacecraft Passivation	14 October 23:00
Heartbeat Supports	15-17 October

The overall Mission Termination Timeline was as follows:

Mission Termination Timeline



	Task Name	Start
1	End Of Mission Notification	Tue 7/12/05
2	Planning meeting kick-off	Fri 7/22/05
3	Develop Eol Timeline Activities	Wed 8/3/05
4	Review EO:L Timeline Activities	Thu 8/11/05
5	Planned End of Science	Thu 8/25/05
6	Develop Burn Plan Procedure	Mon 8/1/05
7	Develop Burn Plan Support -FDF	Mon 8/1/05
8	Power Support Plan	Sun 7/31/05
9	⊟ **Flight Ops Plan**	**Mon 8/1/05**
10	TDRS Schedule suuport	Mon 8/1/05
11	NCC Forecast Schedule	Mon 8/8/05
12	Command Burn Procedures	Mon 8/1/05
13	Contingency Procedures	Mon 8/1/05
14	FOT Coverage Plan	Mon 8/15/05
15	**Review Burn/Venting Plan**	Fri 8/19/05
16	**DEMO Burn - 8 September**	Thu 9/8/05
17	**Confidence Burn - 3 Orbit Burn**	Tue 9/13/05
18	**Depletion Burn 1- 3 Orbit Burn**	Fri 9/16/05
19		
20	**Stand down for Approval**	Mon 9/19/05
21	SpaceCraft Yaw Manuever	Mon 9/19/05
22	**Calibration Burn 4 Sec on A & D Thrusters**	Mon 10/3/05
23	**Calibration Burn - 4 Min Block**	Wed 10/5/05
24	**Calibration Burn 10 Min Block**	Fri 10/7/05
25	**Depletion Burn (Day 1)**	Thu 10/13/05
26	**Depletion Burn (Day 2)**	Fri 10/14/05
27	**Passivate Spacecraft**	Fri 10/14/05
28		
29	⊟ **Reviews**	**Mon 8/1/05**
30	ERBS Project End-of-Mission Plan Review	Mon 8/1/05
31	ESMO Project End-of-Mission Plan Review	Mon 8/8/05
32	EOS Program Office End-of-Mission Plan Reviev	Mon 8/15/05
33	Center/Flight Project and Programs End-of-Missio	Fri 8/26/05
34	Code 300 Peer Review	Wed 8/31/05
35	Close Out Peer Review RFA's	Thu 9/1/05
36	⊟ **Simulations-Ground System tests**	**Mon 9/12/05**
37	Simulate EOL Procs and Contingencies TBD	Mon 9/12/05
38	⊟ **Post Mission Clean Up**	**Tue 8/2/05**
39	Heartbeat Check TBD	Fri 10/14/05
40	Ground System Disposal	Fri 10/14/05
41	Documentation and records	Tue 8/2/05

VIII. ERBS Burn Plan Summary

After many discussions on the status of ERBS and how to best decommission the satellite, it was decided to leave ERBS in its current attitude and use the four orbit adjust thrusters (A,B,C,D) located on the top of the spacecraft to vent all the fuel in the tanks. As a result, the component of the delta-V using those thrusters would be in the radial direction causing the least amount of orbital disturbance [5].

A. Maneuver Group Analysis

The first hurdle to overcome with ERBS was to determine how much fuel was remaining in the tanks. There were many sources of information including blow-down curves and various inconsistent bookkeeping records. The largest uncertainty came from the telemetered value of pressure, which was accurate to ±4 psia. Using a pressure vs. mass fuel curve, this 4 psia difference corresponded to 22lbm of mass. As a result the error bars on the fuel estimate became ±22 lbm. The bookkeeping values that were available were also from a prior de-orbit sequence that was performed in the summer of 2002. Since that time, many yaw maneuvers were performed for which no accounting of fuel usage was done properly due to changes in record keeping approach. As a result, this became another factor of uncertainty. This error was smaller than that of the 4 psia difference in pressure and therefore deemed inconsequential in determining the error bars. Using the several different methods of mass determination, including Pressure-Volume-Temperature (PVT) calculations, bookkeeping, and blowdown curves, a final mass of 175 lbm was estimated for planning purposes. Using the largest known error of ±22 lbm, the final value used was 175±22 lbm as indicated in Table 1.

	Propellant Mass						Total	
	Tank 1		Tank 2		Total		Available	Max Burn
Estimation Method	**lbm**	**kg**	**lbm**	**kg**	**lbm**	**kg**	**delta-v (m/s)**	**Duration (hrs)**
P vs mass (1982 data plot)	65	29	65	29	130	59	60.52	11.43
P vs mass (2002 email)	85	39	85	39	170	77	78.69	15.33
Bookkeeping (29 yaw @ 0.833 lbs / man)	87	39	87	39	174	79	80.55	15.73
PVT	92	42	92	42	184	83	85.07	16.75
Bookkeeping (29 yaw @ 0.3 lbs / man)	95	43	95	43	189	86	87.34	17.26

Table 1 Fuel Mass Remaining Sources

Obtaining the starting mass then yielded the way to actual planning of the maneuvers. The venting of the fuel was supposed to occur during the month of September with four 5-hour burns (Table 5.1.1-2). Ball Aerospace & Technologies Corporation, the manufacturer, was tasked with providing the duty cycles for the four orbit adjust thrusters. These four thrusters were modulated by leaving two of the four on for the entire period while the other two were turned off at a specified interval of time. This modulation sequence provided attitude stability for the spacecraft since the thrusters were not optimally aligned.

	ERBS' End of Mission Burn Plan												
				Burn								**Estimated Decay Rate (years)**	
		Dates (UTC)		**Duration**	**Prop Mass**		**Prop use**	**Apogee Hgt (km)**		**Perigee Hgt (km)**		**+2 Sigma Flux**	**Nominal Flux**
	Burn	**Start**	**Stop**	**(min)**	**Initial**	**Final**	**(lbm)**	**Initial**	**Final**	**Initial**	**Final**	**Maximum Area**	**Minimum Area**
	1	2005-09-08 11:20	2005-09-08 11:40	20.0	175.00	170.81	-4.19	556.1	554.9	489.4	488.1		
	2	2005-09-13 11:30	2005-09-13 16:30	300.0	170.81	110.32	-60.50	562.5	559.9	489.4	488.6		
	3	2005-09-16 11:30	2005-09-16 16:30	300.0	110.32	53.52	-56.80	563.8	561.0	489.3	499.2		
	4	2005-09-20 11:30	2005-09-20 16:11	281.5	53.52	0.00	-53.52	562.5	**564.5**	499.4	**490.7**	**5.3**	**16.9**
	With Propellant Uncertainty												
Nominal Fuel-22 lbm	4	2005-09-20 11:30	2005-09-20 14:23	173.8	31.52	0.00	-31.52	562.5	557.4	499.4	481.6	4.4	13.3
Nominal Fuel	4	2005-09-20 11:30	2005-09-20 16:11	281.5	53.52	0.00	-53.52	562.5	564.5	499.4	490.7	**5.3**	**16.9**
Nominal Fuel+22 lbm	4	2005-09-20 11:30	2005-09-20 18:36	426.2	75.52	0.00	-75.52	562.5	568.6	499.4	493.4	5.5	17.5

Table.2 Burn Plan Using 175±22 lbm mass remaining

IX. ERBS Flight Dynamics Maneuver Summary

1. Burn 1 – Confidence Burn

Burn 1 commenced on September 8th, 2005 at 16:33:29 GMT and had a duration of 20 minutes. It was a calibration burn to test the behavior of the four orbit adjust thrusters, from which Ball Aerospace was able to determine the duty cycle needed to maintain attitude stability. Using the argument of perigee pre- and post-maneuver, an efficiency of +4.5 percent was derived between observed and predicted data.

2. Burn 2 – Confidence Burn

Burn 2 commenced on September 13th, 2005 at 11:55:15 GMT and had a duration of five hours. This was the first of the three large burns to deplete the fuel remaining. The duty cycles were calculated from Burn 1 post-burn analysis and delivered to the FDF from Ball Aerospace. Thrusters B and C were to remain on for 100% of the time while thrusters A and D were turned on and off every two minutes, providing a duty cycles of 84% and 90% respectively. These loads were uplinked to the spacecraft in sets of 20 minute blocks. Using the argument of perigee pre- and post-maneuver, an efficiency of +3.88 percent was derived between observed and predicted data.

3. Burn 3 – Depletion Burn I

Burn 3 commenced on September 16th, 2005 at 11:17:07 GMT and had a duration of five hours. This was the second of the three large burns to deplete the fuel remaining. Due to a disturbance in the attitude for Burn 2, the duty cycles for thruster D were lowered 2% in order to maintain attitude within acceptable tolerances. Using the argument of perigee pre- and post-maneuver, an efficiency of approximately +33% was derived between observed and predicted data. This large discrepancy might be due to the pressurant leaking into the tanks. Investigation is still underway.

4. Burn 4 – Depletion Burn II

Burn 4 was supposed to be executed on September 20th, 2005 but administrative issues caused the burn to be cancelled. As a result of the delay, ERBS had to perform a yaw maneuver with very low pressure remaining in the fuel tanks, which caused unexpected attitude disturbances and heretofore mentioned Yaw Anomaly. Therefore, three more calibration burns were performed –

3 October	**1403 GMT – 16sec thruster A calibration**
	2023 GMT – 16sec thruster C calibration
5 October	**1340 GMT - 4min 4 thruster calibration**
7 October	**1450 GMT – 10min 4 thruster calibration**

The final burn was executed on October 13, 2005 throughout the day using different sized command blocks, which allowed for better attitude stability as well as allowing for the cancellation of the burn as quickly as possible, if needed. Apparently, the pressure in the tanks did not experience a drastic drop when the fuel tanks became empty, but rather the pressure seemed to slowly decrease. As a result, the burn was continued the next day on October 14th, 2005 where it was finally decided to terminate the mission. This slow pressure drop might have been reminiscent of a pressurant leak through the bladder of the tank, causing the pressurant to exit through the thrusters. Any analysis against predictions for this final burn would have shown erroneous results due to this problem encountered above.

The following tables provide a list of the burns for day 1 and 2:

Day 1 (DAY 286) of the Final Depletion;

Burn Start	Block used	Burn Start	Block used	Burn Start	Block used	Burn Start	Block used	Number of burns	TOTAL BURN TIME
11:45:20	10	15:06:19	8	19:55:50	10	23:21:33	4	**41**	**262**
11:55:52	10	15:14:53	10	20:09:06	10	23:25:44	4		
12:06:06	0	15:25:23	10	20:19:17	10	00:43:54	2		
12:07:33	4	15:36:45	4	20:29:25	10	00:47:12	2		
12:11:42	0	16:32:39	10	20:39:30	2	00:50:14	2		
13:18:51	10	18:16:09	4	21:14:53	10	00:53:02	2		
13:28:59	10	18:30:29	10	21:30:19	4	00:55:43	2		
13:39:07	8	18:40:31	10	21:40:25	2	0:58:11	2		
13:48:47	4	18:50:55	10	21:59:42	4	01:00:33	2		
14:44:02	10	19:01:14	4	22:04:58	8				
14:55:55	10	19:45:37	10	23:16:59	4				

Day 2 (DAY 287) of the Final Depletion;

Burn Start	Block used	Burn Start	Block used	Burn Start	Block used	Number of burns	TOTAL BURN TIME
11:33:45	4	16:08:07	10	18:35:39	4	**28**	**254**
11:39:21	10	16:18:17	10	18:45:00	10		
11:49:49	10	16:28:15	10	18:55:00	10		
13:09:53	10	16:38:16	10	19:05:00	10		
13:22:12	10	16:48:41	10	19:33:07	4		
13:34:00	10	17:35:21	10	19:45:00	10		
14:33:33	10	17:45:26	10	19:55:00	10		
14:43:45	10	17:55:44	8	20:17:17	10		
14:54:57	10	18:03:48	10				
15:05:05	10	18:32:28	4				

Final Depletion Burn Summary

Total Number of burns	TOTAL BURN TIME
70	**516 Min**

X. Passivation

Having completed all fuel depletion activities (burns), the ERBS End-of-Mission Engineering Team was satisfied that the threat of explosion had been removed from the propulsion system. The Tank Pressure was showing 40psi and the affects on spacecraft attitude had greatly diminished. It was decided to and passivate the spacecraft as planned and leave the thrusters open when the Spacecraft was terminated. The Thruster valves would close when the bus voltage dropped below 12 volts.

The following steps were performed to decommission the spacecraft:

- Power Off ERBE-NS via Non-Scanner Power OFF procedure.

- SAGE Power OFF.
- Disable appropriate Fault Management.
- Perform Demonstration Burn tests to ensure vent plan was properly modeled.
- Perform Confidence Burn operations over several orbits to ensure the attitude and orbit disturbance can be absorbed and are predictable.
- Perform Depletion Burn.
- Confirm hydrazine depletion.
- Ensure the EPS system the following remains power negative
- Leave Catbed Heaters ON
- Leave Survival Heaters ON
- Leave Instruments ON
- Disable all (4) Commandable Solar Array Circuits
- Change C/D Level to CD 4 (C/D = 1.10 @ 5 C – harder to reach 100 % SOC)
- Disable SPRU VT Reset signal
- Put in -5 Amp Mode
- Disable Command Storage Memory
- Perform final tape recorder playback.
- Disable Command Storage Memory
- Turn RF transmitter OFF.
- Close Network Support.

The ERBS EOM Team was able to perform these operations over three TDRSS contacts. The final steps went smoothly and without incident.

XI. Orbit Determination Accuracy

Predicted post-maneuver ephemeredes were generated using GMAN thrust tables in GTDS Flight-Sectioned ephemeris jobs. Due to the long duration of the burns, it was not possible to utilize burn tables at an interval of 1-second without exceeding the GTDS limit of 5000 records in the thrust table. For this reason, it was necessary to use GMAN thrust tables with an interval of 10 seconds. The accuracy of the predicted post-maneuver ephemeris files generated with the thrust burn tables was good for the initial short burn, but poor for the long burns.

While most ERBS passes were taken in non-coherent mode, following each burn a number of coherent tracking passes were scheduled for the purposes of post-maneuver orbit determination (OD). Coherent, or 2-way, tracking provides TDRS range and Doppler observations. For each maneuver, an acceptable orbit solution was available after three 20 to 30 minute passes. Starting with the first burn, and in a number of subsequent cases, post-maneuver range passes were intermittently bad, showing large biases. Range data was deemed generally untrustworthy on this account, and was excluded from most post-maneuver short-arc orbit solutions in favor of Doppler-only solutions. There was no loss of OD accuracy on this account, with the difference between Doppler-only solutions and solutions employing Doppler and good range data being on the order of 100 meters. ERBS post-maneuver three-pass solutions using only Doppler data had a prediction accuracy of better than 1 km by the next day's orbit update. 1-way data, which provided usable angle observations, was received from the Canberra Ground Station for the first maneuver, but was not used in the solution. The DSN angles were unnecessary due to presence of good TDRS data.

The following table summarizes the accuracy of predicted post-maneuver ephemeris using GMAN thrust tables, and the post-maneuver short-arc ODs for the major burns for which good definitive post-maneuver OD was available. The differences listed are comparisons to longer-arc OD solutions generated on the day following the burn indicated. While the pre-maneuver prediction errors for large burns were considerable after 1.5 days, the error did not grow large enough to hamper acquisition during the 3-5 hour span required for post-maneuver OD.

Maneuver Span	Accuracy of Predicted Post-maneuver Best Estimated Trajectory	Accuracy of Post-maneuver Short-arc Solution
20050908/161329-163329	20 km by 050910/000000	0.090 km by 050910/000000
20050913/115500-165500	295 km by 050915/000000	0.168 km by 050915/000000
20050916/111700-161700	148 km by 050918/000000	0.077 km by 050918/000000

The last valid ERBS TDRS data was received on 051014/213200. No orbit solution was obtainable using the last of the TDRS passes on October 14, and the tracking data showed indications that at the time of termination of tracking the ERBS orbit was still being perturbed by thrusting or outgassing.

Prior to commencement of depletion activities, ERBS OD was supported routinely using the Real-Time Orbit Determination (RTOD) system extended Kalman filter. Due to lack of past experience supporting ERBS maneuvers in RTOD, GTDS was chosen as the prime OD tool for the depletion burns. Nevertheless, FDF did make an effort to fly ERBS in RTOD throughout the maneuvers and was successful in maintaining the ERBS orbit state in RTOD through the depletion sequence by placing ERBS in "upset" mode beginning at the start of each burn and keeping ERBS in upset mode through a sufficient span of post-maneuver tracking data. Placing ERBS in upset mode does not apply any delta-V to the state, but instead applies large state deweighting, forcing the filter to follow the incoming tracking data. In cases where biased range data was not automatically sigma-edited by the Kalman filter, gross measurement deweighting was applied to the range data to minimize its effect on the state update. ERBS was taken out of upset mode after a sufficient amount of tracking data has been received to recover the post-maneuver orbit. For the large burns, at least 3 post-maneuver passes were required. Determination of when the post-maneuver state has reconverged was made by examining the residual of the first point of each post-maneuver pass. Low first point residuals indicate that the state has propagated accurately from the last point of the prior pass and that RTOD has reconverged to an accurate post-maneuver state.

XII. COLA – Collision Avoidance

The NASA policy NPD 8710.3b "NASA Policy for Limiting Orbital Debris Generation" states that the mission's program/project manager responsibilities include "*Consulting with the Department of Defense's Cheyenne Mountain Operations Center prior to significant spacecraft operational or end-of-mission maneuvers*", defined as those resulting in a change of spacecraft altitude of 1km or larger.

Performing collision avoidance (COLA) analysis under circumstances in which multiple maneuvers were planned and executed within a fairly short timeframe was not something the ERBS support teams had done before. There was the added complication that the ERBS and EO-1 maneuvers and collision avoidance analyses were also underway. After several iterations, the team settled on the following:

a. Ephemeris files contain only the next burn (i.e. one burn at a time)
b. Ephemeris files are 7-days in duration
c. Nominal plan: Screen burn/no-burn cases at Burn-2, Burn-1, Burn+1 (updated no-burn only)
d. Not possible for ERBS burns separated by only one day
e. Screen at Burn-1 if the Burn-2 screening contains a conjunctor of concern
f. Criteria for additional analysis/discussion: Total miss distance less than 4km
g. Burn/No-Burn ephemerides from the FDF are delivered prior to 12 EST; the results are delivered by 6PM EST.

For ERBS, the FDF generated the burn and no-burn ephemerides and USSTRATCOM performed the collision avoidance analysis and distributed the results. Due to the complicated situation, the FOT prepared a detailed schedule, updated frequently, which was followed by all parties

XIII. ERBS Flight Dynamics Lessons Learned

1. Lack of maneuver databases made it difficult to accurately assess historical propellant usage.
2. Do not include too much information for maneuver summaries that are deliverables especially if the input is manually entered.
3. Have as much information as possible in electronic form so that finding information is easier: e.g., all the old documents that we had to go through in order to pull out data. It would be less time consuming if we could just do a search on - fuel - and all the pertinent documents and pages come up.
4. ERBS does pre-date all desktop publishing software, but scanning and imaging of old documents in electronic form would have been quite useful.
5. Make sure everyone is cross-trained and proficient on all software used prior to maneuvers.

6. Mixing of SI and English units in output and input was and is dangerous and caused problems during planning and execution of the plan
7. Have hardcopy/softcopy documents located in one central and organized area for the missions. Everyone has documents that pertain to all missions at their desks, in filing cabinets in their offices, and in the ops room. This makes it difficult and time consuming to find documents that pertain to a subject.
8. It is Recommend that future decommissioning efforts not be performed during the same time period if all possible. Working on ERBS and UARS EOM Activities caused confusion by all parties. In some areas, due to availability of FD personnel the same personnel worked the same missions, therefore work load reduced quality checking and meetings.
9. Avoid having mission meetings scheduled on the same day as the maneuvers.
10. Schedule more TDRS coherent tracking data events immediately following the maneuvers. A number of non-coherent passes were scheduled after the maneuver instead. This increased the waiting period to determine an orbit solution before the Network could obtain the success of the maneuver.
11. The GTDS limitation of 5000 records to the GMAN thrust table required propagation through the long burns at a step size of 10 seconds. This may have been a reason for the large prediction errors using the GMAN thrust tables.

XIV. Yaw Maneuver Anomaly

A third 300 minute fuel depletion burn for the ERBS End-of-Mission (EOM) activities was scheduled to occur on 20 September 2005. However, on 19 September all remaining depletion burns were suspended at the direction of Headquarters until further notice. It was anticipated that the remaining amount of the hydrazine fuel would have been depleted during the September 19 burn operations. This stoppage of the decommissioning plan necessitated the execution of a 180 degree yaw maneuver on 26 September in order to keep the sun on the solar arrays, thereby maintaining the spacecraft's power-safe condition. This yaw turn is nominally performed once every month, and in this situation consisted of a +X forward to –X forward maneuver. It should be noted that the original decommissioning plan had the fuel depletion and final spacecraft passivation occurring by 23 September, which would have avoided the need for a yaw turn.

It was realized by the ERBS EOM team prior to the yaw maneuver that a potential problem existed since the procedure, which consisted of open-loop thruster commands activated out of spacecraft normal memory, would require modifications to account for the reduced propulsion tank pressure environment. Ball Aerospace performed analysis that showed that using the previously executed +X to –X forward yaw turn command load with the lower tank pressure would result in the spacecraft tumbling. Since the power subsystem on ERBS had been limping along for years, a tumble condition would very well jeopardize spacecraft safety prior to the planned passivation completion.

An AETD (Code 500) peer review of the +X to -X forward 180 degree yaw turn was conducted on 22 September. This review was held in order to assess the expected spacecraft maneuver performance in light of concerns which were identified following the stoppage of hydrazine fuel depletion activities. Members of the GSFC Mission Engineering and Systems Analysis Division/Code 590 supported the independent review:

> Ball ACDS Engineers presented via teleconference analysis regarding the modification of the command load procedure so as to safely perform the required yaw maneuver. This modification utilized the ACS and Propulsion information gleaned from the 16 September 300-minute depletion burn in order to adjust the pitch thruster commands in the yaw maneuver procedure, thereby accounting for the reduction in the propulsion tank pressure from the previous execution of the +X to -X maneuver, which occurred on 13 July 2005. The analysis revealed that the new thrust level was 85.2% of the July 2005 level. Maneuver simulation using updated thruster forces corresponding to the tank pressure reduction and the modification of the thruster commands showed acceptable yaw maneuver performance. The independent reviewers agreed that the planned modifications to the procedure would result in a successful maneuver.

On 26 September 2005 (Day 269) at 20:13 GMT the 180 deg +X to -X forward yaw maneuver was initiated. An anomaly occurred during the maneuver's execution. It became apparent that the modification of the open-loop pitch thruster commands in the yaw maneuver procedure did not sufficiently remove all of the momentum bias along the spacecraft pitch axis prior to the yaw turn. This resulted in the situation of the ACS trying to precess a momentum vector around 180 deg, thereby causing a large spacecraft nutation. This resulted in the spacecraft starting to tumble, resulting in lower power subsystem charging and intermittent TDRS contacts using the zenith OMNI antenna.

During one of the contacts it was determined that the ACS still had large roll and pitch angles which would have taken the normal ACS controller many orbits to correct. The ACS was then commanded into B-Dot mode at 269/23:48:53 GMT. B-Dot mode utilizes magnetometer information to create torque rod commands which result in the unloading of excess spacecraft momentum.

At 270/02:58:28 GMT, it was observed during a TDRS pass (note that AOS came only 4 minutes prior to the scheduled LOS) that the spacecraft roll and pitch angles were less than 30 degrees. It was then decided to place the ACS back into Normal mode. The ACS was able to correct its pointing attitude so that by the morning of 27 September the spacecraft attitude was back to normal with the power subsystem charging up nominally.

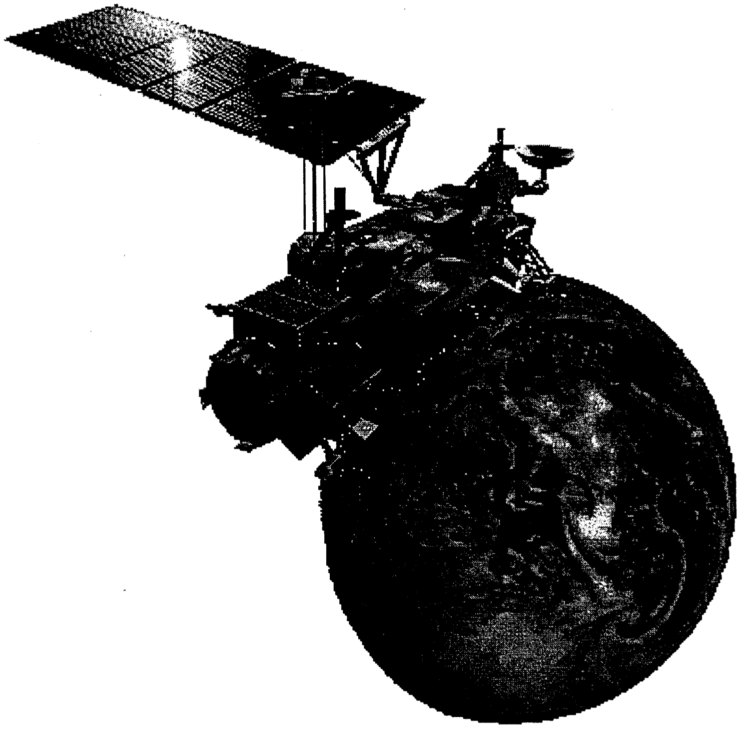
Post-maneuver performance analysis by Ball Aerospace indicted that the thrust level at the start of the burn was actually 72% of the July 2005 level instead of the 85.2%.previously seen on the 16 September Burn. The EOM Team learned the hard way that execution of open-loop thruster firings becomes more precarious as the propulsion fuel level is depleted and that the system would not always remain stable. As expected during the EOM activities.

XV. UARS

The Upper Atmospheric Research Satellite was deployed from the Space Shuttle Discovery (STS 48) on September 15, 1991. The spacecraft mission was research and exploration of the upper reaches of the atmosphere [6]. .UARS was a more robust and fault tolerant spacecraft then ERBS and was able to perform perigee lowering maneuvers and was able to deplete its fuel while significantly shortening its on orbit life.

The instrument operations for HRDI, PEM, SUSIM, and SOLSTICE were ceased on August 5, 2005, except for occasionally activating the PEM instrument for load balancing purposes. The HALOE instrument continued collecting measurements until mid October.

The UARS End-of-Mission Team began decommissioning operations in September of 2005 and performed the final passivation on 14 December 2005. The End-of-Mission Team passivated the spacecraft after having performing a series of Perigee Lowering Maneuvers which lowered the orbit to 518km x 381km. The UARS Team began passivating the spacecraft on DOY 348 14 December 2005 at 1615z. To ensure the power system is stabile an electrical load was placed on the batteries and the Electrical Power system was placed in a low current mode. The Attitude control system was powered off and finally the transponder was power off. The UARS Spacecraft was commanded off at 17:16:37z



UARS completed 78084 orbits over 5208 Mission days. UARS was the first spacecraft of the first major flight element of NASA's Mission to Planet Earth.

The UARS End-of-Mission plan followed the NASA guidelines preferred method which calls for missions to lower their orbit perigee as much as possible, both to minimize the on-orbit lifetime, as well as to deplete all onboard hydrazine fuel. The baseline plan strived to achieve all other NASA mission termination objectives. Formulation and execution of the UARS End-of-Mission Plan involved consideration of current spacecraft capabilities, application of NASA policies and guidelines, and analysis of UARS disposal options. An End-of-Mission operation timeline and associated details are provided

It should be noted that Battery 2 suffered a cell failure on 21 August 2005 just prior to implementation of the End-of-Mission Plan [7]. This failure was one of the predefined trigger points on which the emergency End-of-Mission timelines would be invoked. As the EOM Team prepared the emergency timeline the UARS engineering team developed contingency operations, which allowed the EPS system to remain stabile through the normal EOM timeline.

The UARS Engineering Team also developed a 4 Thruster Mode on the Modular Propulsion system. UARS though equipped with four Orbit Adjust Thrusters, was configured to use just two during normal operations. By updating the Flight Software (FSW), the engineering Team was able to use all four 5lb thrusters during the Perigee Lowering Maneuvers (PLM). This new thruster configuration improved the thruster efficiency from 50% to over 70% thus reducing the numbers of maneuvers from 24 to 8.

As the PLMs were executed the UARS EOM Team coordinated all Collision Avoidance (COlA) activities through the GSFC Debris Avoidance Working Group (DAWG) and Cheyenne Mountain Operations Center (CMOC). As UARS started approaching the International Space Station special care was taken to ensure all concerned parties were aware of the UARS EOM plans and activities. Weekly status meetings were held in preparation of the final maneuver activities. Due to the uncertainty of remaining fuel and the uncertainty of the final orbit, the UARS EOM Team decided that it would prudent to perform Apogee Lowering Maneuvers (ALM) to completely empty the remaining fuel. These activities ensured that UARS and the ISS would have adequate separation and ample screening opportunities to detect a close approach.

UARS orbit will continue to decay until it reenters. The nominal prediction for reentry is July 2009 (4.5 years after the final Burn). This is based on nominal solar flux. UARS will be continually tracked by Cheyenne Mountain Operations Center (CMOC) until it reenters. UARS Was designed, built and deployed from Space Shuttle Discovery (STS-48) prior to NASA policy formulation (launched pre-1993),

XVI. UARS Status and Disposal Assessment

The following items summarize key findings incorporated into the UARS End-of-Mission Plan. These findings reflected status of the observatory, applicability of NASA disposal guidelines, and an assessment of the spacecrafts disposal options. UARS was originally conceived to be retrieved by the shuttle at the end of its mission. Due to changes in the shuttle program this was no longer an option.

On September 28 2001, UARS was designated as a Science Traceability Mission for the Aura spacecraft (launched 15 July 2004). UARS payloads are designated to support the on-orbit validation and calibration of the payloads of Aura for the first year of operations.

XVII. UARS Observatory Status:

The Upper Atmospheric Research Satellite was deployed from the Space Shuttle (STS-48) STS 48 on September 15, 1991. The spacecraft mission was research and exploration of the upper reaches of the atmosphere. UARS was placed in a585 km orbit inclined 57°. It was originally conceived to be retrieved by the shuttle at the end of its mission. Due to changes in the shuttle program this is no longer an option. UARS is more robust and fault tolerant then ERBS and was able to perform perigee lowering maneuvers and was able to deplete its fuel while significantly shortening its on orbit life time.

A. UARS Subsystem Status:

As a whole UARS was still a sound spacecraft but a series of component failure had made it single fault tolerant. It is able to perform its science mission in a reduced role due to Instrument and bus failures

1. Electrical Power System (EPS)

In 1996 1 of the 3 spacecraft batteries suffered an internal failure and was taken offline and placed in reduced service. There had also been failures of the Solar Array Drives (A&B) which impacted UARS ability to optimize the performance of the Power Subsystem. The EPS subsystem is still able to provide sufficient power for the bus and operation up to 7 of 10 instruments (depending on payload combinations and operations and solar beta angle), and supports all command and telemetry functions.

2. Command and Data Handling System (CDH):

UARS has limited data storage capacity. Only one-quarter of the original tape recorder capacity is still available UARS had been able to manage data capture by increasing the number of real-time TDRSS contacts over each orbit balancing the direct downlink and recorder playbacks for achieve their science data goals.

3. Attitude Control System (ACS)

The ACS system has suffered multiple failures over the course of the mission. Both pairs of Earth sensors and Star Trackers had suffered failures and were only used in limited situations Due to these failures only limited on-board (autonomous) safe mode commanding is available. Loss of 5 of the 6 Gyros has impacted the spacecraft ability to meet science pointing requirements. Due to seven years of inactivity the on-board propulsion system had been unserviceable. Through efforts of the FOT the system has been recovered and was available to support orbit-lowering maneuvers.

4. Flight Software (FSW):

UARS has a robust flight software package with ample Fault Management and Telemetry Monitors. There are no limitations within the FSW system that would have impacted the End-of-Mission Activity.

5. Payload Status

Five of the ten of the UARS payloads were still performing routine operations. These five payloads include three earth instruments (HALOE, HRDI, and PEM) and two of the three solar instruments (SUSIM and SOLSTICE). A sixth instrument (MLS) is available but required unique power management for operation. Three instruments are no longer operational: CLAES was designed with a limited life and operations ceased with their as-planned depletion of its cryogen supply, WINDII, Operations ceased in 2000 due to a Y2K problem in the science data process system that was too costly too fix. ISAMS and ACRIM operations ceased due to instrument failures.

X UARS Disposal Method

At the Direction of the ESMO project office, UARS will be lowered through a series of retrograde maneuvers to an approximate 565 km X 375 km elliptical orbit. All the remaining available fuel was vented from its propellant tank. The spacecraft batteries were put in a trickle charge mode all commandable relays were disconnected from the solar array and the transponders will be powered off. Applicability of NASA Guidelines and Policies to the UARS End of Life Plan

A. Applicability of NASA Guidelines and Policies to UARS

Launched prior to NASA policy formulation (launched pre-1993), the applicability to UARS of current NASA End of Life Disposal policies is limited to defining operations that minimize the UARS lifetime and minimize UARS as an on-orbit or reentering debris hazard.

NASA policies and guidelines for End of Life disposal of spacecraft are covered by: NPD 8710.3B and the associated NASA Safety Standard: "Guidelines and Assessment Procedures for Limiting Orbital Debris (NSS 1740.14)". (http://sn-callisto.jsc.nasa.gov/mitigate/safteystandard.html)

1. Disposal Assessment

In preparation for mission termination, various assessments had been performed to determine UARS capability relative to end-of-life disposal. Highlights of these assessments follow.

2. Lifetime Analysis

Based on atmospheric projections, the orbital lifetime projections for UARS in its current (561 km circular) orbit range from 10 to 25 years. Using existing fuel to lower the orbit, the worst case UARS lifetime projection is reduced to less than 5 years from the minimum achievable elliptical orbit.

3. Debris Assessment

The debris field predicted to survive an uncontrolled reentry is approximately 22 m2. [Refer to "Reentry Survivability Analysis of Upper Atmospheric Research Satellite (UARS), JSC-29647, J.J. Marichalar and W.C. Rochelle, January 2002.] This debris estimate is based on a Johnson Space Center Office for Orbital Debris analysis using the Object Reentry Survivability Analysis Tool (ORSAT) program

4. Casualty Risk Associated With an Uncontrolled Reentry Of UARS

Based upon the JSC ORSAT analysis referenced above, the risk of casualty of an uncontrolled UARS reentry has been identified as 1: 3,600.

5. Controlled Reentry Assessment

Controlled reentry of UARS [via planned maneuvers that would result in the UARS debris field being scattered within an uninhabited (ocean) region] is not a viable option. Insufficient fuel is available to achieve the necessary orbit lowering. Even with alternate scenarios, such as drag assisted deboost, insufficient thrust exists to provide the necessary control for performance of the final burn.

6. UARS Shuttle Retrieval Study

The technical feasibility of a UARS recovery by a shuttle was established. However due to significant programmatic challenges (cost, risk, and schedule), NASA Headquarters opted not to pursue this option.

XI Implementing UARS End-of-Mission Plan

As Per the NASA Headquarters directives, a timeline was developed to complete the EOM activity by 31 December 2005. Based on this date, the plan was implemented [7]. Due to the battery anomaly science operations, which were planned to support HALOE through mid December, were conducted only when the bus could support the additional power load. Since fuel depletion activities could only be done while the spacecraft was in reverse flight, the yaw turn to reverse flight executed 12 September 2005 was the jump off point of the EOM Plan. Since most of the EOM Team was also supporting the ERBS EOM activities, this offset allowed them to complete most of the ERBS activities before starting the UARS activities. It should be noted that even with the offset the team was stressed during the dual EOM operations. ERBS EOM operation incurred an administrative delay in completing the execution of the EOM Plan. This delay occurred just prior to the ERBS final depletion burn. This caused almost three week delay in the final passivation of ERBS, which further exacerbated the situation.

A. Flight Software update for 4-Thruster Mode

The most significant engineering decision made in planning the EOM Activities was the decision to modify flight software to enable the Propulsion Modular (PM) to use the four Orbit Adjust Thrusters. A Flight Software Patch was developed by the UARS Engineering Team based on experiences with a similar Propulsion Modular used on Landsat 5. The FSW Patch to allow for 4 thruster operations was uplinked on 30 August 2005 after being tested and verified on the UARS Simulator. This patch involved updating branch commands which deselected the 2 alternate thrusters with no-op commands.

Series of calibration burns were performed to test new mode

Sept 1, 05	6 second burn	Test firing of all four Translation Thrusters
Sept 14, 05	30 second burn #1	Translation thrusters fired followed by attitude firings
Sept 19, 05	30 second burn #2	Translation thruster off pulse w/ attitude firings
Sept 22, 05	2.5 minute burn	Pitch and yaw biases added to account for transient

This patch improved the overall thruster efficiency as well as decreased the number of maneuvers required to deplete the fuel remaining on board the spacecraft from 26 to 8.

B. Mission Termination Actions

The UARS EOM Maneuver Activities were constrained to occurring in view of TDRSS and at apogee or perigee ±10Mins. The FOT Mission Planner was able to work with the FD Maneuver Group to ensure the needed resources were schedule for these activities. Once the resources were allocated by the NCC based on mission priority, conflict resolution was performed to ensure all required supports were scheduled to complete all mission objectives. The TDRSS supports for the maneuver operations were scheduled as critical supports.

The planned End-of-Mission activities were:

Burn 1/8	4 October 2005	Perigee Lowering Maneuver
Burn 2/8	6 October 2005	Perigee Lowering Maneuver
Burn 3/8	12 October 2005	Perigee Lowering Maneuver
Burn 4/8	18 October 2005	Perigee Lowering Maneuver
Burn 5/8	20 October 2005	Perigee Lowering Maneuver
Burn 6/8	1 December 2005	Perigee Lowering Maneuver
Burn 7/8	6 December 2005	Apogee Lowering Maneuver
Burn 8/8	8 December 2005	Apogee Lowering Maneuver
Passivation	14 December 2005	End of Mission

The following steps were performed to decommission the spacecraft:

Passivation Objectives

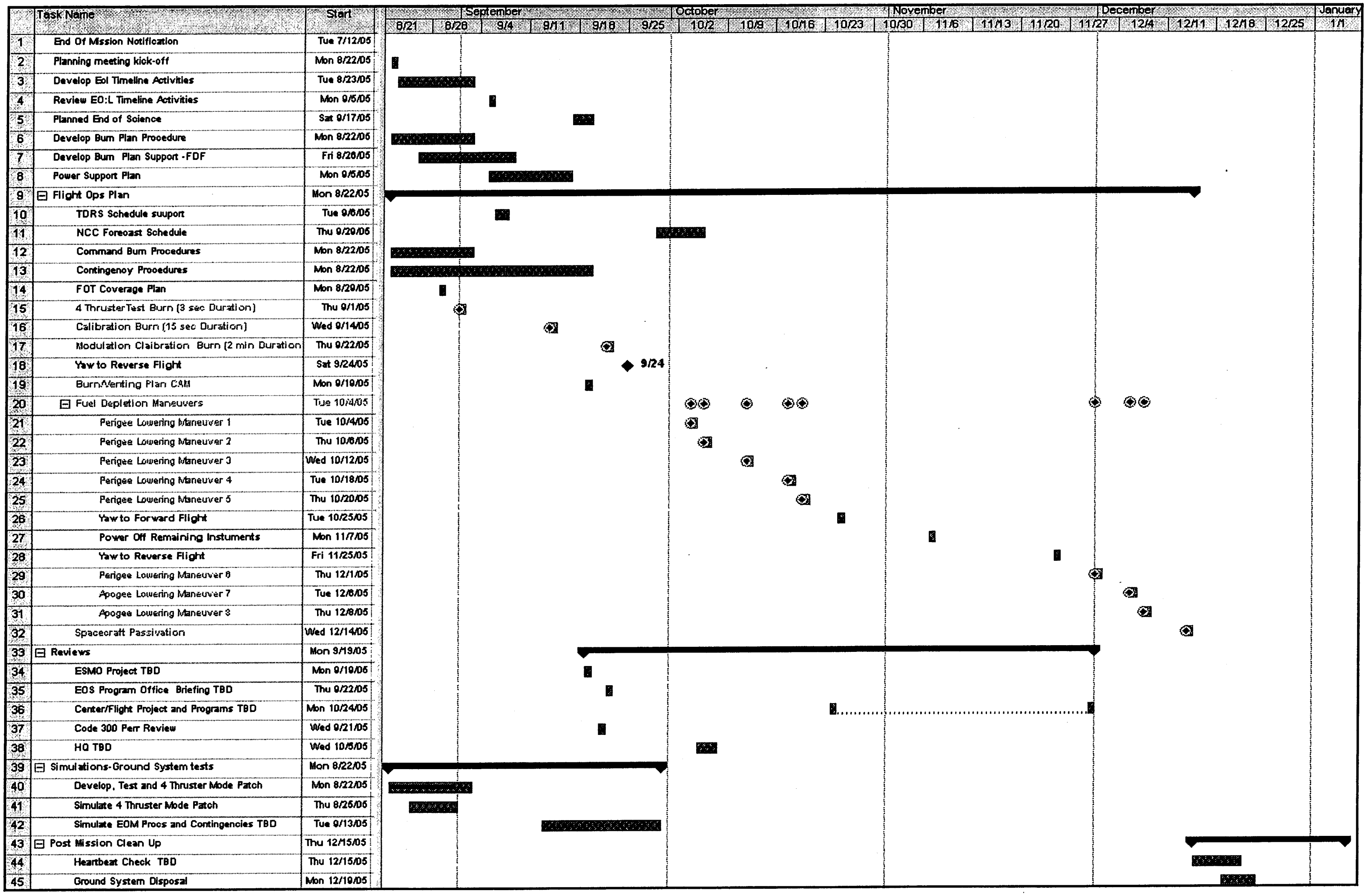
- Limit orbit lifetime after mission completion

- Change circular orbit 553x543km into an elliptical 513 x 381km
- UARS will re-enter uncontrolled in 4 to 4 ½ years
- Make spacecraft chemically inert
- CLAES cryogen tank empty
- Deplete hydrazine fuel tank by lowering orbit
- Power off non-vital components
- NBTR-B Power OFF *
- Platform Sun Sensor (PSS) *
- Solar Array Drive Electronics (SADDE) *
- SSPP Gimbal Drive Electronics (GDE) *
- Power off Instruments via RTS 00 & 01 *
- Some buses come on, will be turned off manually
- Deplete on-board energy sources
- Disable spacecraft attitude control
- Prevent spacecraft from being an RF source

*Indicates action can be done early, prior to any formal passivation activity

The UARS Mission Termination Timeline is given as follows:

Mission Termination Timeline



	Task Name	Start
1	End Of Mission Notification	Tue 7/12/05
2	Planning meeting kick-off	Mon 8/22/05
3	Develop Eol Timeline Activities	Tue 8/23/05
4	Review EO:L Timeline Activities	Mon 9/5/05
5	Planned End of Science	Sat 9/17/05
6	Develop Burn Plan Procedure	Mon 8/22/05
7	Develop Burn Plan Support -FDF	Fri 8/26/05
8	Power Support Plan	Mon 9/5/05
9	⊟ Flight Ops Plan	Mon 8/22/05
10	TDRS Schedule suuport	Tue 9/6/05
11	NCC Forecast Schedule	Thu 9/29/05
12	Command Burn Procedures	Mon 8/22/05
13	Contingency Procedures	Mon 8/22/05
14	FOT Coverage Plan	Mon 8/29/05
15	4 ThrusterTest Burn (3 sec Duration)	Thu 9/1/05
16	Calibration Burn (15 sec Duration)	Wed 9/14/05
17	Modulation Claibration Burn (2 min Duration	Thu 9/22/05
18	Yaw to Reverse Flight	Sat 9/24/05
19	Burn/Venting Plan CAM	Mon 9/19/05
20	⊟ Fuel Depletion Maneuvers	Tue 10/4/05
21	Perigee Lowering Maneuver 1	Tue 10/4/05
22	Perigee Lowering Maneuver 2	Thu 10/6/05
23	Perigee Lowering Maneuver 3	Wed 10/12/05
24	Perigee Lowering Maneuver 4	Tue 10/18/05
25	Perigee Lowering Maneuver 5	Thu 10/20/05
26	Yaw to Forward Flight	Tue 10/25/05
27	Power Off Remaining Instuments	Mon 11/7/05
28	Yaw to Reverse Flight	Fri 11/25/05
29	Perigee Lowering Maneuver 6	Thu 12/1/05
30	Apogee Lowering Maneuver 7	Tue 12/6/05
31	Apogee Lowering Maneuver 8	Thu 12/8/05
32	Spacecraft Passivation	Wed 12/14/05
33	⊟ Reviews	Mon 9/19/05
34	ESMO Project TBD	Mon 9/19/05
35	EOS Program Office Briefing TBD	Thu 9/22/05
36	Center/Flight Project and Programs TBD	Mon 10/24/05
37	Code 300 Perr Review	Wed 9/21/05
38	HQ TBD	Wed 10/5/05
39	⊟ Simulations-Ground System tests	Mon 8/22/05
40	Develop, Test and 4 Thruster Mode Patch	Mon 8/22/05
41	Simulate 4 Thruster Mode Patch	Thu 8/25/05
42	Simulate EOM Procs and Contingencies TBD	Tue 9/13/05
43	⊟ Post Mission Clean Up	Thu 12/15/05
44	Heartbeat Check TBD	Thu 12/15/05
45	Ground System Disposal	Mon 12/19/05

The final passivation of the spacecraft will power on passive EPS power loads to ensure that the batteries do not overcharge and explode. The last steps were to turn off attitude control and RF transponders. The turn off was as follows:

- Turn on EPS load
- Primary heaters (335W) ; Thermostat controlled
- Secondary & ATK heaters (94.5W) ; Thermostat controlled
- Alignment heaters on (A & B master)
- All alignment heaters (110W) ; no thermostat control
- MACS heaters (166W) ; Thermostat controlled
- MPS heaters (105W) ; Thermostat controlled
- Set VT Level to VT-1
- Set Constant Current mode to .75A
- Disable Attitude Control
- Power off Magnetic Torque Rods
- Earth Sensor 2 off (ESA-2)
- TAM 1 & 2 off
- Reaction Wheels off (Roll, Pitch, Yaw, Skew)
- Fine Sun Sensor off (FSS)
- Gyros off
- Turn off RF
- Turn Transponder A on (upper OMNI antenna)
- Halt OBC and force S/C into safehold
- Disable HGA electronics
- Turn Transponder A & B off

XII UARS Burn Plan Summary

This is a summary report of the GSFC Flight Dynamics Facility (FDF) support for the UARS End of Mission. The fuel remaining on UARS was insufficient to re-enter the spacecraft so instead the fuel was vented by multiple maneuvers firing the four orbit adjust thrusters. This produced a net delta-V in the anti-velocity direction at apogee which lowered the perigee altitude. The UARS orbit after the final maneuver was slightly more eccentric, 513 x 381km, with a predicted decay within 5 years.

A. Maneuver Group

The issues face in decommissioning UARS included:

- There was no way to vent fuel except by performing maneuvers
- Insufficient fuel to maneuver to re-entry
- A goal of completing the decommissioning expeditiously so less than optimal maneuvers were acceptable within limits
- Constraints on the maneuver location, such as the need to be performed when in view by a TDRS
- Use of all 4 thrusters simultaneously was not a configuration that had been used during the mission
- The potential of collision with International Space Station (ISS) producing a goal to minimize the time over which this might happen

1. Analysis

The first hurdle to overcome with UARS was to determine how much fuel was remaining in the tanks. There were many sources of information including blow-down curves and different bookkeeping records. A bookkeeping value of 355.6 lbm was obtained from the previous maneuver that was executed on September 2001. A PVT value of 354.1 lbm was obtained using a pressure of 210.735 psia, temperature of 24.55 °C for the small tanks and 12.54 °C for the auxiliary tank. The largest error came from the telemetered value of pressure which was accurate to ±2 psia. Using this error along with the above temperatures and pressures, a range of 357.1 to 351.0 lbm was obtained.

Obtaining the starting mass then yielded the way to actual planning of the maneuvers. A discussion ensued in which all four thrusters were to be used for the deorbit sequence. Perigee lowering was the ultimate goal in order to bring UARS below ISS altitude. Nominally UARS had only been using a two thruster mode for orbit maneuvers. As a result, there were a few test burns to determine how the spacecraft reacted to all thrusters firing. Since the maneuvers were performed retrograde (against the velocity vector) to lower perigee, the change in semi-major axis was used as a benchmark of performance.

The perigee lowering burns were supposed to occur during the month of October and December with a total of seven 18-minute burns and a 4 minute burn (Table 5.1.1-1). There were no maneuvers in the month of November since a yaw maneuver changed the orientation of the spacecraft and thrusters, which would have provided a prograde effect causing perigee to increase instead of decrease.

		Burn	Pre Maneuver (at end of mnv)			Post Maneuver (at end of mnv)		
		Duration	Apogee	Perigee	Propellant	Apogee	Perigee	Propellant
#	Mnv Start (UTC)	(min)	Altitude (km)	Altitude (km)	(kg)	Altitude (km)	Altitude (km)	(kg)
1	2005-10-04 17:09:00	18.000	6942.34	6912.78	156.489	6940.90	6875.26	126.729
2	2005-10-06 15:07:00	18.000	6941.53	6868.13	126.729	6939.44	6835.38	100.787
3	2005-10-12 15:09:00	18.000	6839.36	6844.67	100.787	6838.46	6814.08	77.084
4	2005-10-18 14:43:00	18.000	6940.96	6824.06	77.084	6939.23	6796.99	54.385
5	2005-10-20 12:09:00	18.000	6936.84	6786.87	54.385	6935.49	6761.38	31.579
6	2005-12-01 11:54:00	18.000	6925.76	6769.62	31.579	6924.76	6745.40	10.850
7	2005-12-06 18:25:00	18.000	6923.36	6748.23	10.850	6922.65	6725.06	0.037
8	2005-12-08 18:45:00	4.317	6921.86	6730.19	0.037	**6921.81**	**6724.74**	0.037

Table 4. UARS Perigee Lowering Burn Plans

The planned times of the maneuvers were constrained by several factors. The burn had to be within a TDRS contact, the apogee had to be as closely centered as possible in the pass, and there should be about a 5 minute buffer at the beginning of the pass for maneuver preparation. These three factors added a level of complexity in planning the burns since the products that contain the pass times and apogee times needed to be updated after every burn plan.

2. *Calibration Burns*

There were a series of four calibration burns that were performed prior to the perigee lowering maneuvers. The first two maneuvers, 6 seconds and 13 seconds, were performed when UARS was in an orientation of perigee raising and the last two, 30 seconds and 2.5 minutes, were performed during an orientation where UARS lowered perigee. The following tables show the results of all four calibration burns. A prediction of 90% duty cycle was used for planning of the calibration burns.

3. *Perigee Lowering Maneuvers*

The baseline called for the PLM 1 to be performed 20 September. This maneuver was postponed at the request of NASA Headquarters. The baseline burn plan assumed a higher efficiency then what was actually achieved...
After analysis of the 2.5 minute calibration burn it was noted that the duty cycles were not at 90% as predicted but rather at 71.79% since the A1 and B1 thrusters were performing at about 55% due to off pulsing attitude control. This duty cycle improved over the longer duration burns because the initial attitude transients had a lower impact on the overall burn duration. Using these results the PLMs commenced on October 4th, 2005 and had durations of 18 minutes. The maneuver analysis was very accurate and spacecraft performed smoothly. Due to the UARS Yaw Cycle and the planned burn schedule only 5 of the 8 PLMs were performed prior to the Yaw back to forward flight.

PLM	Date	Start	Duration	Perigee Δ	Duty Cycle*TSF	Efficiency
Burn 1	4 October	17:09:04	18 min	-37.51	.791	+1.24
Burn 2	6 October	15:07:09	18 min	-32.60	.787	+0.27
Burn 3	12 October	15:09:02	18 min	-30.37	.789	+0.64
Burn 4	18 October	14:43:01	18 min	-27.18	.790	-0.30
Burn 5	20 October	12:09:01	18 min	-25-29	.788	+0.46

4. Intermediate Analysis

After Burn 5 an analysis of FDF software was performed since the PVT calculations from the FOT, using the current tank pressure, did not match the GMAN final mass at the end of the burn. There appeared to be a large discrepancy between the two values and GMAN was underestimating the fuel usage per burn. Since the last few burns were not to be executed until December, the analysis went into some depth during the month of November. In this section we will summarize our findings and results.

Prior to starting any analysis, PVT calculations were performed at FDF using actual telemetered pressures for all the burns using the initial loading conditions of the tanks. Tables 5 and 6 summarize the inputs and results.

Initial Conditions of the Tanks

	m0 (lbm)						**Pressure**
	T1	**T2**	**T3**	**T4**	**Total**	T1..T3	**psi**
Loading	55.967	55.967	55.967	283.000	450.900	167.900	303.600
Unuseable	0.000	0.000	0.000	0.000	3.500	0.000	
Useable	54.800	54.800	54.800	283.000	447.400	164.400	

	m0 if full (lbm)					input
	T1	**T2**	**T3**	**T4**	**Total**	
	82.827	82.827	82.827	414.405	661.635	

Tank Volumes (in^3)				
T1	**T2**	**T3**	**T4**	**Total**
2280.000	2280.000	2280.000	11350.000	18190.00

Propellant Density (lbm/in^3)				
T1	**T2**	**T3**	**T4**	**Average**
0.0363276	0.0363276	0.0363276	0.0365115	0.0363736

Temperature									
Centigrade					**Rankine**				
T1	**T2**	**T3**	**T4**	**Average**	**T1**	**T2**	**T3**	**T4**	**Average**
23.40	23.40	23.40	17.40	21.90	533.808	533.808	533.808	523.008	531.108

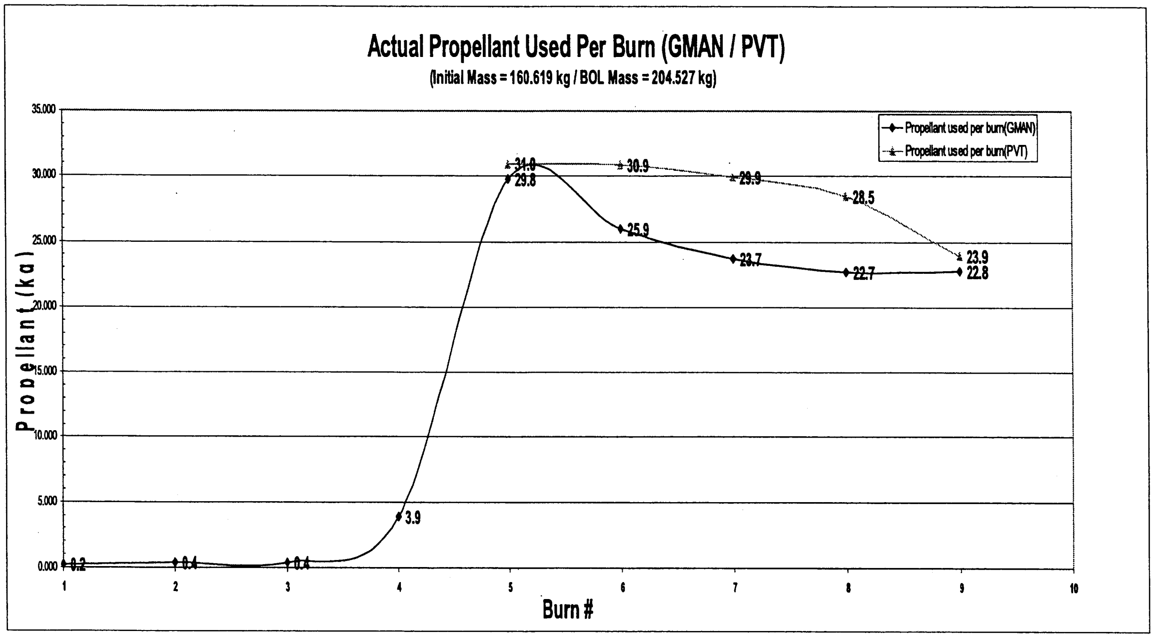
Table 5 UARS Initial Loading Conditions of Fuel Tanks

PVT For all events

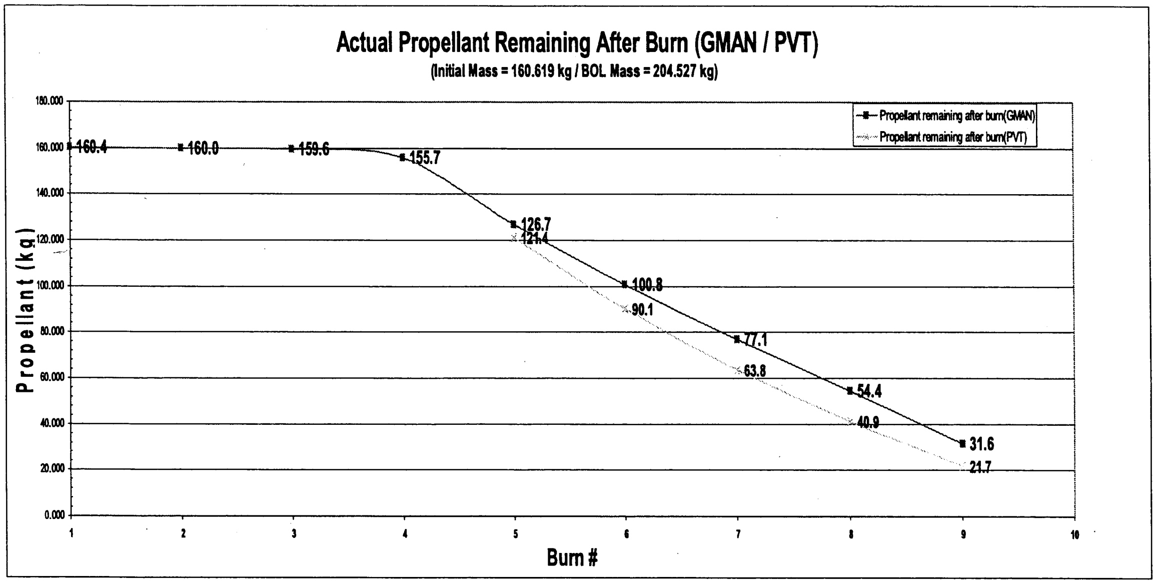
	Pressure	**Temperature (Centigrade)**					**propellant mass (lbm) (eq 3-10 right side)**						**combined**
	psia	**T1**	**T2**	**T3**	**T4**	**Average**	**T1**	**T2**	**T3**	**T1..T3**	**T4**	**Total**	**method**
Pre 6s	210.735	24.55	24.55	24.55	12.54	21.55	42.252	42.252	42.252	126.755	229.192	355.947	353.47
6 s	210.728	24.10	24.46	25.08	12.66	21.57	42.328	42.266	42.159	126.754	229.088	355.842	353.42
13 s	210.441	24.10	24.46	25.08	12.66	21.57	42.273	42.211	42.104	126.588	228.833	355.421	353.00
30 s	209.830	24.10	24.46	25.08	12.66	21.57	42.155	42.093	41.986	126.234	228.288	354.522	352.10
2.5 m	209.254	24.10	24.46	25.08	12.66	21.57	42.043	41.981	41.873	125.898	227.771	353.669	351.25
1	202.707	27.54	26.85	29.29	12.86	24.14	40.124	40.244	39.818	120.186	221.513	341.699	337.70
2	168.590	28.59	27.89	30.36	13.19	25.01	31.335	31.472	30.988	93.794	181.838	275.632	271.06
3	146.510	27.89	27.54	29.29	12.86	24.40	23.779	23.855	23.478	71.113	146.918	218.031	213.49
4	130.460	25.47	25.47	26.16	12.54	22.41	17.119	17.119	16.957	51.195	114.185	165.380	162.15
5	118.410	24.78	25.47	25.47	12.54	22.07	10.620	10.447	10.447	31.513	83.461	114.974	112.02
Post 5	108.380	24.78	25.12	25.12	12.54	21.89	3.946	[illegible]	[illegible]	[illegible]	52.677	64.334	61.53
	100.000	24.78	25.12	25.12	12.54	21.89	0.000	0.000	0.000	0.000	0.000	0.000	0.00

Table 6 UARS PVT Calculations for Burns 1-5

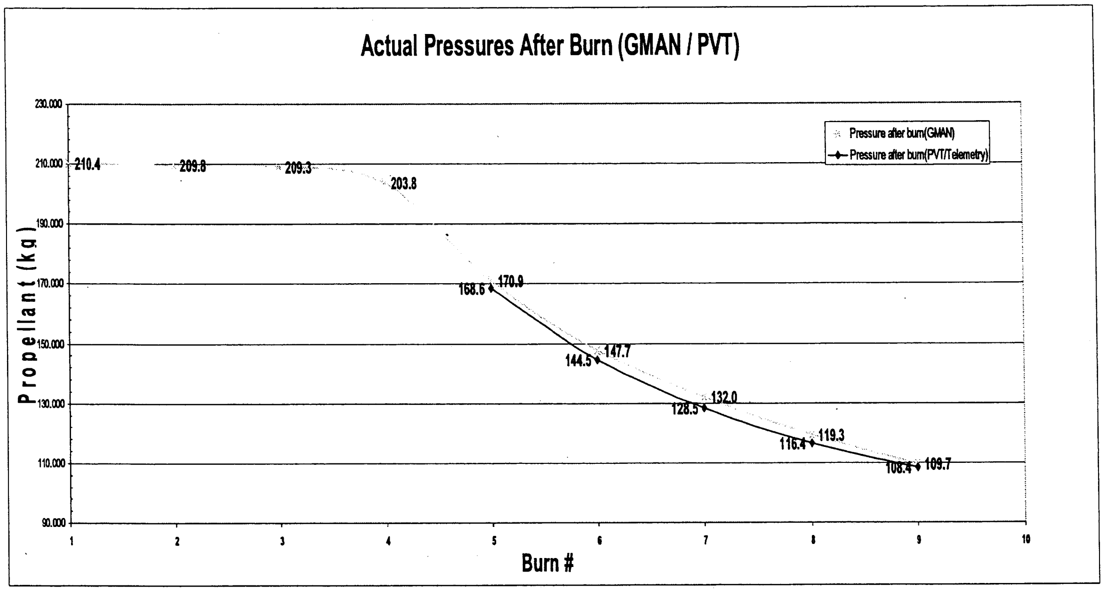
Using the PVT values, the differences between GMAN and the PVT calculations for mass usage, remaining mass, and end pressures were calculated and plotted in the figures below. The calibration burns were included in the GMAN data but not for the PVT calculations. Graph 1 shows that the software was underestimating the fuel usage by about 5-6 lbm per burn when compared to PVT calculations. As a result, there was a difference of about 10 kg at the end of burn 5 between GMAN and PVT even though the difference in pressures was only about 2-3 psia (Graph 2).



Graph 1 – UARS GMAN vs. PVT Mass Used per Burn

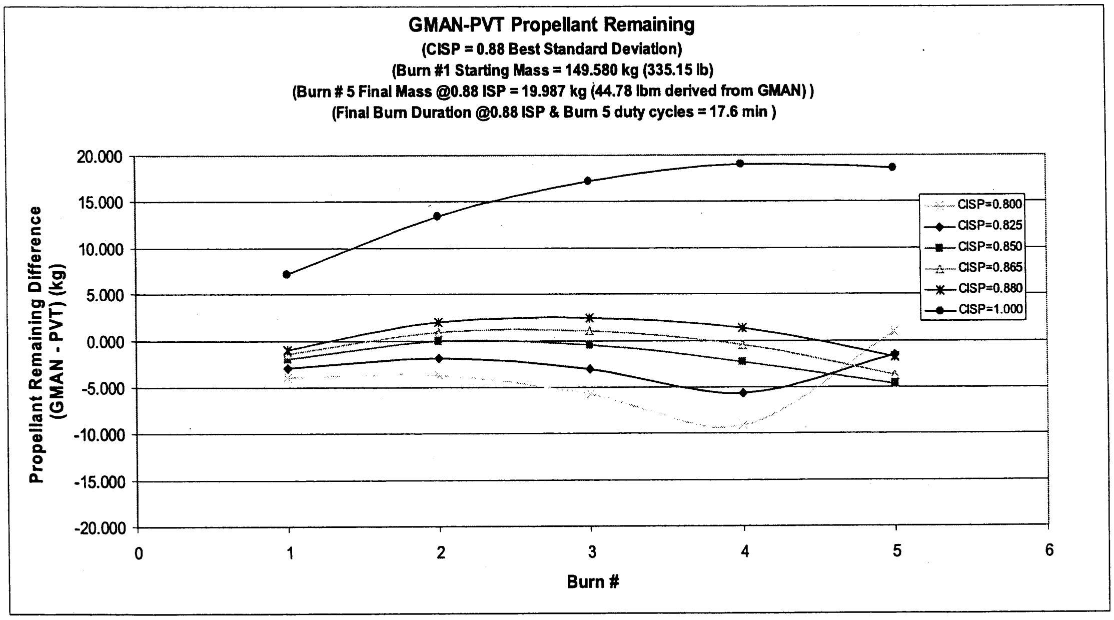


Graph 2 – UARS GMAN vs. PVT Fuel Remaining After Burn



Graph 3 – UARS GMAN vs. PVT Pressures After Burn

This difference between GMAN and PVT calculations had to be resolved since the PVT calculations were deemed as a true observable. An analysis of the GMAN ISP equation was performed in order to obtain a scaled ISP equation that more closely correlated to the PVT calculations. The ISP equation was scaled by using a multiplicative factor other than 1.0. Several different factors were applied as shown in Graph 3. In this figure, the difference using several different ISP scale factors and the PVT calculations are plotted. The curve that best fit the PVT calculations was the 0.88 curve. As a result, this factor was used for later analysis and maneuver planning.

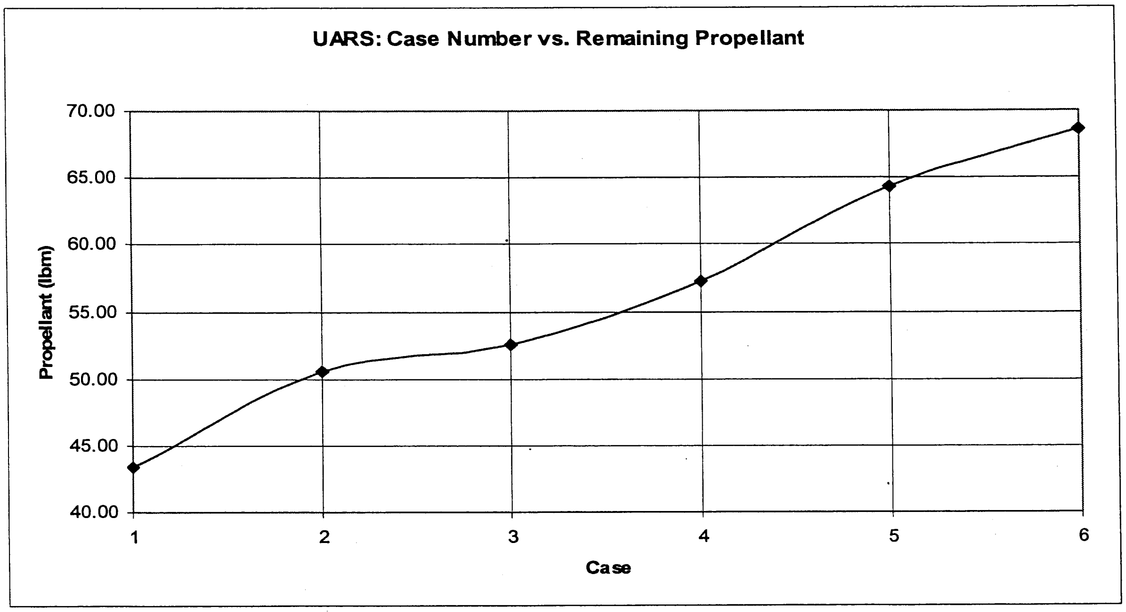


Graph 4 – GMAN – PVT Difference in Propellant Remaining for Burns 1-5

During the course of the analysis that was performed to rescale the GMAN ISP equation, two different values for the volumes of the tanks and different initial loading conditions surfaced. As a result, this information became a source of error in the PVT calculations that were obtained. This complication yielded the data contained in the following Table 7 and Graph 5. The table summarizes all the possible combinations of two sets of volumes and three sources of loading conditions and the figure shows the current propellant mass for the six cases in the table.

		T1	T2	T3	T4	
	Current Temperature (C)	24.78	25.12	25.12	12.54	
	Current Pressure (psia)	108.38	108.38	108.38	108.38	
1		554-FDD-92/029R0UD0				
		T1	T2	T3	T4	
	Pressure (psia)	303.60	303.60	303.60	303.60	
	Volume (in^3)	2352.070	2352.070	2352.070	11494.040	18550.250
	Temperature (C)	23.40	23.40	23.40	17.40	
	Initial Propellant mass (lbm)	54.800	54.800	54.800	283.000	
	Current Propellant mass (lbm)	-0.798	-0.896	-0.896	43.413	43.413
2		554-FDD-92/029R0UD0 (70DegF)				
		T1	T2	T3	T4	
	Pressure (psia)	303.60	303.60	303.60	303.60	
	Volume (in^3)	2352.070	2352.070	2352.070	11494.040	18550.250
	Temperature (C)	21.11	21.11	21.11	21.11	
	Initial Propellant mass (lbm)	54.800	54.800	54.800	283.000	
	Current Propellant mass (lbm)	-1.768	-1.867	-1.867	50.592	50.592
3		UARS POCC Hydrazine Remaining Algo				
		T1	T2	T3	T4	
	Pressure (psia)	303.60	303.60	303.60	303.60	
	Volume (in^3)	2328.900	2322.400	2328.570	11390.400	18370.270
	Temperature (C)	23.40	23.40	23.40	17.40	
	Initial Propellant mass (lbm)	54.800	54.800	54.800	283.000	
	Current Propellant mass (lbm)	0.727	1.060	0.653	50.078	52.519
4		UARS POCC Hydrazine Remaining Algo (70DegF)				
		T1	T2	T3	T4	
	Pressure (psia)	303.60	303.60	303.60	303.60	
	Volume (in^3)	2328.900	2322.400	2328.570	11390.400	18370.270
	Temperature (C)	21.11	21.11	21.11	21.11	
	Initial Propellant mass (lbm)	54.800	54.800	54.800	283.000	
	Current Propellant mass (lbm)	-0.224	0.113	-0.299	57.126	57.239
5		ATK: Diaphragm Tanks Data Sheets				
		T1	T2	T3	T4	
	Pressure (psia)	303.60	303.60	303.60	303.60	
	Volume (in^3)	2280.000	2280.000	2280.000	11350.000	18190.000
	Temperature (C)	21.11	21.11	21.11	21.11	
	Initial Propellant mass (lbm)	54.800	54.800	54.800	283.000	
	Current Propellant mass (lbm)	3.946	3.855	3.855	52.677	64.334
6		ATK: Diaphragm Tanks Data Sheets (70DegF)				
		T1	T2	T3	T4	
	Pressure (psia)	303.60	303.60	303.60	303.60	
	Volume (in^3)	2280.000	2280.000	2280.000	11350.000	18190.000
	Temperature (C)	23.40	23.40	23.40	17.40	
	Initial Propellant mass (lbm)	54.800	54.800	54.800	283.000	
	Current Propellant mass (lbm)	3.034	2.942	2.942	59.673	68.591

Table 7. UARS Fuel Remaining After Burn 5 Using All Possible Combinations of Volumes and Loading Conditions



Graph 5 –PVT Case Number vs. Propellant Remaining

As the plot shows, the different loading conditions and volumes have a great effect on the remaining mass. There is a difference of about 25.178 lbm (11.421 kg) from the first case to the fifth case. Since the uncertainty in the fuel remaining was so large, a different set of conditions were imposed on the maneuvers following burn 5. Case one was used to determine how long it would take to burn off the minimum amount of estimated fuel remaining. This value was calculated to be 17.23 minutes using GMAN software with a rescaled ISP equation of 0.88. Since there was less than a minute of error for an 18 minute burn, burn 6 was to be executed as burns 1-5 had been before with lowering of perigee. The remaining mass following burns 7 and 8 was all within the error of the analysis described above. It was decided that the maneuvers should be done to lower apogee instead of perigee because the UARS altitude at perigee was approaching ISS altitude. The uncertainty of the maneuver posed the problem of having accurate predictions for collision avoidance with ISS when lowering the UARS's perigee even further.

*5. **Burn 6***

Burn 6 commenced on December 1st, 2005 at 11:53:58 GMT and had a duration of 18 minutes. Using the semi-major axis pre- and post-maneuver, an efficiency of +1.62 percent was derived from comparing observed and predicted data. It was predicted that the main tanks were almost empty at the end of this burn. There was no temperature drop in the fuel observed from telemetry, which gave reason to believe that the tanks still had some fuel remaining.

*6. **Burn 7***

Burn 7 commenced on December 6th, 2005 at 16:08:00 GMT and had a duration of 18 minutes. Using the semi-major axis pre- and post-maneuver, an efficiency of +3.04 percent was derived from comparing observed and predicted data. This maneuver was an apogee lowering maneuver rather than a perigee lowering maneuver as discussed in the intermediate analysis section.

A fuel temperature drop was observed at the very beginning of this burn which gave reason to believe that the 3 main tanks were empty and that there was only fuel left in the auxiliary tank. As a result, GMAN was re-executed with an ISP multiplicative factor of 1.0 for burns 6, 7, and 8 to determine whether the earlier PVT calculations were in error. After executing GMAN for these three maneuvers a prediction of 2 minutes for burn 8 was obtained for fuel depletion.

7. *Burn 8*

Burn 8 commenced on December 8th, 2005 at 16:26:01 GMT and had a duration of 1.5 minutes. Using the semi-major axis pre- and post-maneuver, an efficiency of -56.57 percent was derived from comparing observed and predicted data. This large discrepancy is due to the exhaustion of the fuel remaining on board. The pressure decreased at a faster rate towards the end than was anticipated by the software model. This maneuver was also apogee lowering.

The fact that the maneuver lasted for 1.5 minutes indicated that the GMAN ISP equation was correct with a multiplicative factor of 1.0. It seems that the inconsistency of volumes and loading conditions provided too great an error to use PVT calculations to determine the mass remaining in the tanks.

A final orbit state was obtained by the Orbit Determination Group on December 12th, 2005 after the last burn sequence:

Position Vectors -6690.218350 -552.600873 1556.115452 (km)
Velocity Vectors 1.749675210 -4.102465692 6.115431364 (km/sec)
Interval Between Ephemeride Points . 60.000
Coordinate System is .... TRUE OF DATE
Epoch (YYYYMMDD.HHMMSSSSS) 20051212.100000001
Semimajor Axis (km) ... 6825.681605 Flight Path Angle (deg) 89.914719
Eccentricity .... 0.009685 Eccentric Anomaly (deg) 171.159502
Inclination (deg) .... 56.992218 Period (min) 93.535995
Arg of Perigee (deg) ..... 204.377139 Perigee (km) 381.441334
Right Ascension (deg) .... 176.061191 Apogee (km) 513.649276
Mean Anomaly (deg) .... 171.074225 Mean Motion (deg/day) 5542.251423
True Anomaly (deg) .... 171.244376 GHA at epoch (deg) 79.804602
Perigee Argument Secular Rate of Change (deg/day) .. 1.901298248
Ascending Node Secular Rate of Change (deg/day) .... -4.281864983

Decay Estimates

The UARS final orbit state vector from was propagated to predict the orbital decay. The propagation was done with STK using the lifetime analysis tool. As can be seen in Figure 13, UARS will re-enter within 4.3 years when propagated using the nominal Jacchia-Roberts flux model.

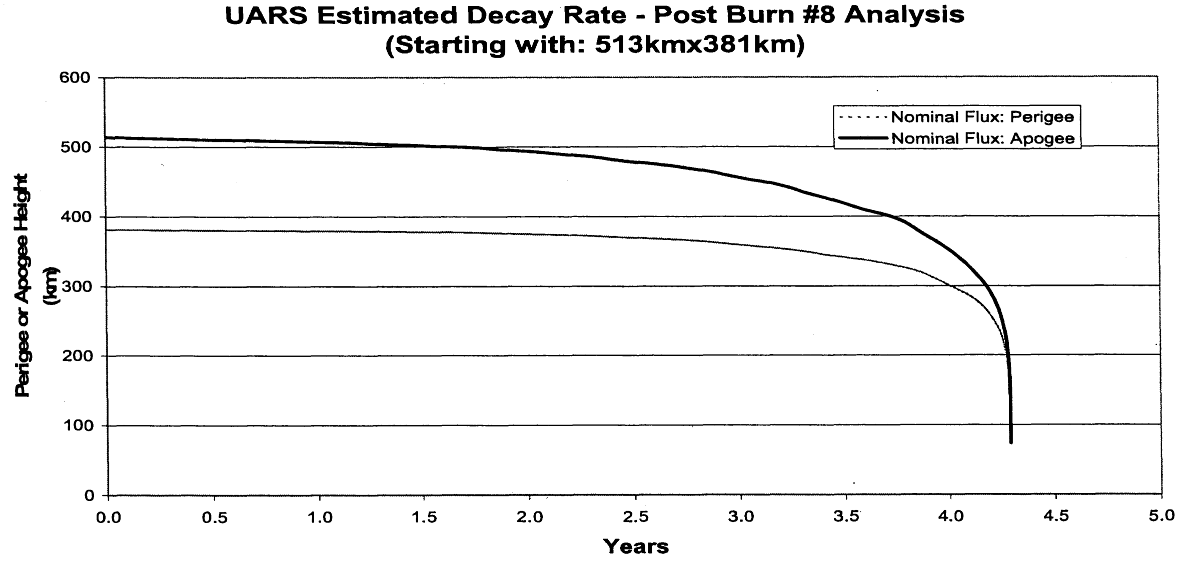


Figure 13 – UARS Apogee and Perigee Decay

XIII Orbit Maneuver Results

Orbit task personnel supported all UARS calibration and deorbit burns in real time. The orbit task was required to provide acquisition data throughout the deorbit sequence, to generate all routine and special request UARS products, and to provide Collision Avoidance (COLA) ephemeris files to Cheyenne Mountain personnel for COLA screening. The orbit task also provided ephemeris files to the maneuver planning task for the purposes of planning and calibrating the maneuvers.

The 18-minute deorbit burns changed the UARS orbit by approximately 150 km (mainly along-track) by the end of the first two hours after the burn. The finite burn modeling capability of GTDS was employed to generate a pre-maneuver prediction which would be good enough to maintain acquisition during the 1-3 hours required after a maneuver to obtain an updated orbit solution. Predicted post-maneuver ephemeredes were generated using GMAN thrust tables in GTDS Flight-Sectioned ephemeris jobs. The thrust table generated by GMAN contains thrust vectors at 1-second intervals throughout the duration of the burn. GTDS adds these thrust vectors to the force model during each integration step, thereby allowing GTDS to model a finite burn using the precise 3-dimensional GMAN model.

For burns which were expected to run their full planned duration (Burns #1-6), a single predicted post-maneuver vector with an epoch shortly after the burn end time was sent out prior to burn start. However, prior to execution of Burn #7 and Burn #8 there was considerable uncertainty as to how long the burns would actually last, due to the uncertainty in the fuel remaining onboard UARS. FDF performed analysis prior to Burn #7 and reached the conclusion that 4 minutes was the maximum amount of error allowed in the predicted versus actual burn end time, in order to maintain acquisition throughout the 3-hour post-maneuver short-arc orbit determination (OD) processing span. As a result the following procedure was used for acquisition data support for Burn #7 and Burn #8.

1. The burn was divided into 4-minute intervals and a separate GMAN burn prediction was generated for each possible burn duration case, using these intervals. For example, for the 24-minute Burn #7, predictions were generated for 4-minute, 8-minute, 12-minute, 16-minute, 20-minute, and 24-minute burn durations.

2. A nominal (expected) burn duration was selected and a single post-maneuver IIRV was generated and sent to White Sands based on that duration. The IIRV epoch was chosen to be after the end of the burn pass and before the start of the next pass.

3. Additional post-maneuver IIRVs were generated using each of the contingency burn durations generated in Step 1. The epoch for the contingency IIRVs was chosen to be after the end of the burn pass, but *before* the epoch of the nominal IIRV from Step 2. The contingency IIRVs were generated, but not transmitted before the burn. Setting the epoch of the contingency vectors earlier than the epoch of the nominal vector that was actually sent to White Sands ensured that, in the case a contingency vector needed to be sent, it would replace (kick out) the nominal vector with a later epoch. All contingency vectors were generated to the same epoch, since only one of the set would possibly need to be sent.

4. When the burn was complete and the actual duration was known, the contingency vector generated using the burn duration that was within 2 minutes of the actual burn duration was sent to White Sands, overriding the pre-maneuver vector sent prior to the burn.

This methodology was employed successfully for both Burn #7 and Burn #8. In the case of Burn #7, the burn was approximately 12 minutes longer than expected, requiring an immediate post-maneuver vector update. Burn #8 terminated 10 minutes earlier than the selected nominal case, also requiring an immediate update.

There was one instance, Burn #6, for which an incorrect post-maneuver vector was sent prior to the burn. In this case, an ephemeris which did not include the burn model was promoted as operational and used to generate the post-maneuver IIRV. Burn #6 ended at 20051201/1212 UTC and a subsequent pass at 1232 UTC was successful, but the UARS MOC and White Sands reported no RF on the pass beginning at 1328 UTC. FDF quickly realized that an incorrect vector had been sent and updated White Sands with a proper post-maneuver IIRV, which resulted in acquisition.

XIV Orbit Determination Accuracy

UARS received nearly continuous 2-way TDRS Range and Doppler tracking throughout the entire deorbit period. The dense tracking meant that four to six TDRS 2-way passes were available for short-arc post-maneuver OD in the first 3-4 hours after each maneuver. No problems were observed in either the TDRS Range or Doppler data at any time during deorbit operations, and all post-maneuver solutions used both the Range and Doppler observations.

Table 8 summarizes the accuracy of predicted post-maneuver ephemerides using GMAN thrust tables, and the post-maneuver short-arc ODs. The differences listed are comparisons of each to longer-arc OD baseline reference solutions generated on the day following the burn indicated. The numbers reported are the maximum ephemeris difference observed in the first 24 hours following the end of the maneuver. All of the post-maneuver short-arc solutions used 5 or 6 passes of TDRS Range and Doppler data, with the exception of the Burn #7 short-arc solution, which used 4 passes. With the exception of Burn #3, all of the predicted post-maneuver Best Estimated Trajectories were generated using an initial state determined from OD on the day of the burn, using all tracking data up until the burn start. As the table shows, the predicted post-maneuver ephemerides generated from the GMAN files were more than adequate for post-maneuver acquisition, and the accuracies of the short-arc solutions were quite good. Solutions performed following Burns #7 and #8 indicated that, in emergency situations, the orbit could be recovered with accuracy sufficient for acquisition with as little as one to two passes of post-maneuver TDRS range and Doppler data.

	Maneuver Span	Accuracy of Predicted Post-Maneuver Best Estimated Trajectory (Km)	Accuracy of Post-Maneuver Short-Arc Solution (Km)
1	20051004/1709-1727	12.863	0.032
2	20051006/1507-1525	6.395	0.123
3	20051012/1509-1527	24.243[1]	0.438
4	20051018/1443-1501	17.569	0.147
5	20051020/1209-1227	34.678	0.401
6	20051201/1154-1212	46.709	0.033
7	20051206/1608-1632	38.257	0.356
8	20051208/1626-1627	NA	0.113

Table 8. Pre-maneuver and Short-Arc Ephemeris 24-hour Prediction Accuracy

[1] *This prediction was generated on the day prior to Burn #3.*

The last valid UARS TDRS data was received on 20051214/171601 UTC. While the ERBS orbit was observed to be significantly perturbed by apparent out-gassing or other thrust-related forces right up until last contact, no such effect was observed on UARS. All solutions following UARS fuel depletion were clean and absent of any apparent perturbation straight up through the last contact.

Prior to commencement of deorbit activities, UARS OD was supported routinely using the Real-Time Orbit Determination (RTOD) system extended Kalman filter. Due to lack of past experience supporting UARS maneuvers in RTOD, GTDS was chosen as the prime OD tool for the deorbit burns. Nevertheless, FDF did make an effort to fly UARS in RTOD throughout the maneuvers and was successful in maintaining the UARS orbit state in RTOD through the deorbit sequence by placing UARS in "upset" mode beginning at the start of each burn and keeping UARS in upset mode through a sufficient span of post-maneuver tracking data. Placing UARS in upset mode does not apply any delta-V to the state, but instead applies large state deweighting, forcing the filter to follow the incoming tracking data. Due to the magnitude of the UARS maneuvers, it was necessary to manually increase the amount of deweighting applied to the UARS state over that applied by the "canned" RTOD upset in order to get enough uncertainty added to the state quickly enough to accept all of the post-maneuver tracking data. UARS was taken out of upset mode after a sufficient amount of tracking data had been received to recover the post-maneuver orbit, typically after four to six post-maneuver passes. Determination of when the post-maneuver state had reconverged was made by examining the residual of the first point of each post-maneuver pass. Small first point residuals indicated that the state had propagated accurately from the last point of the prior pass and that RTOD had reconverged to an accurate post-maneuver state.

XV COLA – Collision Avoidance

The NASA policy NPD 8710.3b "NASA Policy for Limiting Orbital Debris Generation" states that the mission's program/project manager responsibilities include "*Consulting with the Department of Defense's Cheyenne Mountain Operations Center prior to significant spacecraft operational or end-of-mission maneuvers*", defined as those resulting in a change of spacecraft altitude of 1km or larger.

The UARS support teams had experience with performing collision avoidance (COLA) analysis under circumstances in which multiple maneuvers were planned and executed within a fairly short timeframe from the ERBS EOL support. There was the complication that the ERBS and EO-1 maneuvers and collision avoidance analyses were also underway. After several iterations, the team settled on the following:

a. Ephemeris files contain only the next burn (i.e. one burn at a time)
b. Ephemeris files are 7-days in duration
c. Nominal plan: Screen burn/no-burn cases at day Burn-2, Burn-1, Burn+1 (updated no-burn only)
    1. Not possible for UARS burns separated by only one day
    2. Screen at Burn-1 if the Burn-2 screening contains a conjunctor of concern
d. Criteria for additional analysis/discussion: Total miss distance less than 4km
e. Burn/No-Burn ephemeredes from the FDF are delivered prior to 12 EST; the results are delivered by 6PM

For UARS, the FDF generated the burn and no-burn ephemeredes and USSTRATCOM performed the collision avoidance analysis and distributed the results. The decisions on the advisability of additional maneuvers were made by the Debris Avoidance Working Group with input from USSTRATCOM. Due to the complicated situation, the FOT prepared a detailed schedule, updated frequently, which was followed by all parties.

The FDF provided 52 files for COLA analysis between 9/17/2005 and 12/09/2005. These Files provided the basis of the Conjunction assessment screenings. The CA Summary provided the closest distance of the closest approach found with that prediction for each ephemeris provided. The potential for close approach to the International Space Station (ISS) was also of interest and noted separately.. Ironically the first Close approach was from the ERBS spacecraft.

The closest approach for the burn scenario in the Oct 10 analysis was a less than 2km approach with object 3599, COSMOS 249 debris. The time of closest approach was predicted to be Oct 16 09:08:46 UTC with a miss distance of 1873 meters of which 619 meters were in the radial direction. The closest approach for the non-burn scenario was 6.3km. The closest predicted approach between UARS and the ISS occurred with the burn scenario, where the predicted miss was 110 km.

The COLA conjunctions were with various debris objects, rocket bodies, and the following spacecraft: TRMM, SAMPEX, MONITOR-E, KUPON, EKRAN 20, RADCAT, BIRD 2, WIRE, ERBS, SIMSAT 1, MTI, JB-3 A, JB-3 B, JB-3 C, IGS 1A, ROSAT, OFEQ 5, DART, USA 55, QUICKBIRD 2, GRACE 2, EXPLORER 21, METEOR PRIRODA, ROCSAT 1, ASTRO E2, HESSI, ASTERIX, NAGION 2, NMONITOR-E, SAMPEX, ETS 7. Also, the following COSMOS were identified: 1732, 1271, 1544, 1378, 1805, 1726, 1707, 1500, 1574, 405, 1733, 1505, 1939, 1842, 1436, 1633, 1666, 1743, 1408, 1222, 1626, 1825, 803, and 240. By far the bulk of the conjunction approaches identified were with debris and rocket bodies.

XVI Attitude Group

The onboard Attitude Determination & Control Subsystem (AD&CS) performed well during the burns, maintaining attitude and body rates to within acceptable limits. One apparent exception to this was the second Test/Calibration burn – nominally a 30-second burn – that apparently terminated after 13 seconds. The translation thruster stopped firing due to attitude disturbance at 13 seconds, and by the time the attitude rates had dropped below the threshold for the burn to resume, the total duration of the burn had elapsed, so that no further thrusting occurred. Later, longer burns indicated that translation thrusting typically resumed approximately 35 seconds after initial burn start. The second Earth Sensor Assembly (ESA2) was turned on prior to each burn, but was used in FD primarily to indicate changes in spacecraft roll and pitch. Data quality or ground data processing issues made the use of ESA2 data in ground attitude solutions a detriment to solution accuracy, possibly since the spacecraft altitude during End-of-Mission was below the range originally planned for during Earth sensor assembly and mounting. Accurate ground attitude determination was only possible during periods of valid Digital Sun Sensor (DSS) data, which occurred at intervals predicted in FD by the Guide Star Occultation (GSOC) utility. (The deorbit maneuvers did not necessarily occur during intervals of valid DSS data.) Outside of these intervals, ground attitude determination could only make use of Three-Axis Magnetometer (TAM) data, which did not produce very accurate attitude solutions, as expected. Inertial reference unit (IRU, or "gyro") data were available and of good quality throughout the End-of-Mission span, allowing the accurate propagation of attitude solutions and/or attitude sensor measurements to other time points. Given these considerations and caveats, the most useful data available for presentation are the gyro data and the onboard attitude as determined by the UARS AD&CS.

XVII. Lessons Learned

A. FOT Personnel

The declining health of the spacecrafts and the constant budget cuts drove the more experienced analysts and engineers away when that experience was needed the most. This was a concern when it came time to perform the more complex end of life operations

Though UARS has been operational for fourteen years there were still members of the team who supported launch. This level of system knowledge is increasingly rare in the age of lean fast operations teams. Comparing the UARS to the ERBS EOM activities the benefit of the mission experienced team is undeniable when it came time to perform the more complex end of life operations.

With ERBS staffing became an issue towards the end of the mission. Until 2002, there were two dedicated Offline engineers, one mission planner, and eight console analysts (two analysts per shift). With the normal streamlining of operations, when the end of life operations began, there was only one day engineer/mission planner, and four console operators; this put a very big strain on the flight operations team. The sole day engineer was responsible for implementing the end of life activities, scheduling the TDRSS/DSN supports required, building the block and normal command memory sequences required, and ensuring that they were executed correctly. All of this was done while performing the normal day to day operations of the spacecraft.

Due to attrition, the expertise of the ERBS flight operations team was elsewhere. Two of the console operators were brand new to flight operations, and still learning their jobs at the start of the end of life operations. The other two operators had never been involved in these types of complex operations without a day engineer's supervision. To remedy this the Console operators were doubled up (two operators per twelve hour shift) with the newer operators on day shift with the day engineer. The operators were able to help each other in areas they were not familiar with but doubling them up caused them to work longer shifts. The flight operations team performed their jobs well but it could have been done more efficiently with a full team.

B. NASA/Ball Aerospace Engineers

The end of life operations could not have been performed without the NASA Institutional engineering support through the AETD. The two Ball ERBS engineers (one of which had been with ERBS since its beginning) knew the spacecraft's propulsion and attitude systems thoroughly and had been supporting the monthly ERBS yaw maneuvers for years. They also had the benefit of being able to confer with other ERBS subsystem engineers (Command and Data Handling, Electrical Power) still working for Ball Aerospace. The two AETD engineers supporting the end of life operations had been supporting it for years and knew their subsystem thoroughly as well. The Attitude engineer had been working ERBS since the beginning and had a very good working relationship with the Ball engineers. The Power engineer had been working with the degraded power subsystem for years and knew exactly how to maintain it during the extended thruster burns.

For UARS The ESMO System Engineering Support was vital to the Maneuver operations. The ESMO/FSWM support had developed and implemented the 4 Thruster Mode Patch. They had the spacecraft's propulsion and attitude systems and had been supporting UARS for years. The FSW and Simulator Engineers allowed the Engineering team to pursue improvement and verify maneuvers operations, which reduced the complexity and duration of the EOM operations.

C. ERBS Ground System

Since the mission lasted twenty-one years, a ground system upgrade was required. The original system was a main frame (PDP 1170) that was phased out in favor of a PC based ground system (Eclipse). The new system performed very well, but due to lack of funding, the known discrepancies with the system were never fixed. This became very evident during the end of life activities. The biggest problem was building the special block memory loads required for the very long fuel depletion thruster burns. The new ground system would not accept the block command loads generated by the in-house command management system. The Eclipse developer, created a work around for the problem that worked well, but the work around added to the already labor intensive task. Also, contingency command procedures, imported from the old ground system, would not work which led to manual intervention during very time limited operations.

D. UARS Ground System

Since the mission lasted fourteen years, a ground system upgrade was required. The original system was a main frame (PDP 1170) that was phased out in favor of a PC based ground system (Eclipse). The new system performed very well, but due to lack of funding, the known discrepancies with the system were never fixed. This became very evident during the end of life activities. The biggest problem was using the Real-Time plots during the calibration burns. The new ground system would incorrect plot time critical telemetry points. These incorrect plots caused the engineering team much consternation when they were trying to characterize the four-thruster mode patch. The Eclipse developer was aware of this problem which had been shelved at the end of the system development without further efforts.

E. ERBS Spacecraft Documentation

The ERBS flight operation team was blessed with very good spacecraft documentation. The original documentation developed before launch was still being used by the flight operations team at the end. It gave a very thorough rundown of the spacecraft's subsystems and instruments, as well as, a listing of the all the ERBS commands and telemetry.
The ERBS flight operations team kept very detailed records of the normal and special operations performed. There were files for each of the monthly yaw maneuvers performed, as well as, the Delta V and instrument calibrations maneuvers performed in 2002.

All of the spacecraft subsystem and instrument anomalies/failures were well documented. The documentation included any work around required for each case.

Ground System Documentation
The Eclipse system was documented very well. However, the support equipment was not due to the multiple transitions of contractor personnel through the life of the mission. There was no documentation on the Telemetry and Command front end computer, particularly on how to change and troubleshoot the desktops for different supports. Also, there was no documentation on the offline Trending system, particularly on how to manipulate data files. The knowledge for both of these systems was lost through attrition and never documented.

Standard Operations Procedures
The flight operations team developed standard operations procedures for the normal and special operations that needed to be performed. The day to day operations were described very well and any new person could perform them with limited help. However, some of the contingency operations procedures were either not complete or the contingency was not addressed at all. This became a problem during the end of life operations where out of the norm operations were necessary during decommissioning. For instance, the block command loads were not addressed at all and the instrument block loads were not described anywhere in the documentation..

F. UARS Spacecraft Documentation

The UARS flight operation team was blessed with very good spacecraft documentation. The original documentation developed before launch was still being used by the flight operations team at the end. It gave a very thorough rundown of the spacecraft's subsystems and instruments, as well as, a listing of the all the UARS commands and telemetry. In this electronic age it would have made thing much easier if these documents were stored in an electronic format. Much time was wasted, paging through hardcopies looking for data..

Ground System Documentation
The Eclipse system was documented very well. However, the support equipment was not. The benefit of the CDHF Trending system and operators was immeasurable. They allowed rapid turn around of the high-rate data which allow the engineers to quickly assess the spacecraft performance during the EOM activities. Their knowledge, particularly on how to manipulate data files, greatly reduced the turnaround time on maneuver assessment. Their contribution allowed the UARS Engineering Team to work around the Eclipse real-time plot discrepancy.

G. FD Lessons Learned

1. Lack of automation dramatically reduced the efficiency of the functions necessary for EOM support.
2. Lack of maneuver databases made it difficult to accurately assess historical propellant usage.
3. Have as much information as possible in electronic form so that finding information is easier: e.g., all the old documents that we had to go through in order to pull out data. It would be less time consuming if we could just do a search on - fuel - and all the pertinent documents and pages come up. UARS does pre-date all desktop publishing software, but scanning and imaging of old documents into electronic form would have been quite useful.
4. Make sure everyone is cross-trained and proficient on all software used prior to maneuvers.
5. Mixing of SI and English units in output and input was and is dangerous and has caused problems for maneuver group.
6. Have hardcopy/softcopy documents located in one central and organized area for the missions. Everyone has documents that pertain to all missions at their desks, in filing cabinets in their offices, and in the ops room. This makes it difficult and time consuming to find documents that pertain to a subject..
7. Recommend that future decommissioning efforts not be performed during the same time period if at all possible. UARS and ERBS caused a great deal of confusion by all parties. In some areas, the same personnel worked the same missions, therefore work load reduced quality checking and attending meetings. Many of the mission meetings were scheduled on the same day as the maneuvers.
8. Recommend Project schedule more TDRS coherent tracking data events immediately following the maneuvers. A number of non-coherent passes were scheduled after the maneuver instead. This increased the waiting period to determine an orbit solution before the Network could obtain the success of the maneuver.
9. The exercise of generating and evaluating the UARS ephemeredes for potential collisions was useful in that it was a good test of our ability to generate these ephemeredes repeatedly.
10. The policy of only predicting through one maneuver even when multiple ones were planned was a good one for this circumstance. It was difficult to generate precise predictions for the UARS maneuvers. Post-maneuver predictions made before the maneuver did not provide good indicators of conjunction possibilities. Adding a second maneuver to the prediction would have been burdensome, since the possibility of performing the first maneuver but not the second would also need to be included, without generating much benefit.
11. Designate a single point of contact for each organization involved (e.g., FD or FOT) to disseminate needed information to members of each organization, and to act as a clearinghouse for information going out of the organization. (But not for actual products being provided, only for communication.)
12. Provide a list of loop-designations for various organizations.
13. Report potential problems outside of the organization only after internal consensus has been reached on whether or not a problem exists, and after some concrete information on the problem has been obtained.
14. Generate staffing schedules for various support elements and maintain them in a common location.
15. Provide basic training to personnel in various support elements regarding procedures, products, and duties to be provided or performed during EOM support.
16. All mail messages concerning EOM for a particular satellite should contain the spacecraft name in the 'subject' area. We received many messages regarding both UARS and ERBS plus our normal messages and it was difficult at times to determine which spacecraft a particular e-mail concerned.
17. Given adequate lead-up time and resources, previously operational software and procedures could have been adapted to better support EOM activities. What was needed during normal operations support is not the same as what was required during EOM.
18. Keep clear records for each day during important events so that we can recreate the effort at the end of the event.
19. Lack of recent sensor calibration results decreased the accuracies of attitudes determined on the ground, particularly when TAM data alone were available for processing. In the case of UARS, IRU, DSS, and TAM should have all been calibrated as soon as the FHST's began to show evidence of degradation.

Suggested Improvements

1. Agree to format of any special deliverables prior to proceeding with maneuvers so that automation of such a product can be performed in a timely manner. This will reduce the number of errors due to manual inputs.
2. Create a database of all pertinent materials that may be asked of FDF personnel so that the information can be easily accessible.
3. Use one system of measurement, either SI or CGS, so that mixing of units does not happen. All software used should conform to one system.
4. Evaluate the use of newer software that provides better capabilities in terms of maneuver planning.
5. Decommissioning activities for several satellites should be performed in series rather than parallel. The first mission should be done with all maneuvers prior to starting the next mission's maneuvers. This will provide personnel working on both missions to concentrate on one specific mission at a time.
6. Avoid scheduling a meeting for one satellite on the same day as a maneuver for the other would not be a problem in this case. This will also solve the problem of receiving email messages without headers and having to decipher which mission it is associated with.
7. Staffing schedules should be used and distributed to all personnel associated with the decommissioning activities.
8. Electronic logs for each section/task should be maintained in case there are handovers between shifts and there are some non-nominal activities that off-shift personnel are not aware of.

XVIII. Conclusion

Performing End-of-Mission Operations is a unique Mission Phase and needs to be recognized as such. Earlier Satellites usually were just turned off or suffered mission ending failures. New spacecraft need to incorporate End of Mission Plans into the design of the spacecraft system. Larger LEO observatories such as GLAST, NPP and NPOES are designed with reentry plans for their vehicles. Smaller explorer programs have conformed to the NASA's Reentry and Orbital Debris Guidelines by limiting on-orbit life to less then 25 years.

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