Design Lessons Learned from Temperature Management of Galileo's Retro-Propulsion Module

Robert Gounley [1]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Launched in 1989, the Galileo mission added dramatically to our understanding of the Jovian system and our entire solar system[1]. To make best use of limited resources, the Galileo Orbiter used excess power from its Radioisotope Thermoelectric Generators (RTGs) for temperature management of its Retro-Propulsion Module (RPM). This paper describes operational challenges introduced by this design and how, despite major mission changes through development and flight, they were overcome through a challenging six-year interplanetary cruise to Jupiter. This case study offers lessons for missions planning to couple critical spacecraft subsystems in unconventional ways.

I. Introduction

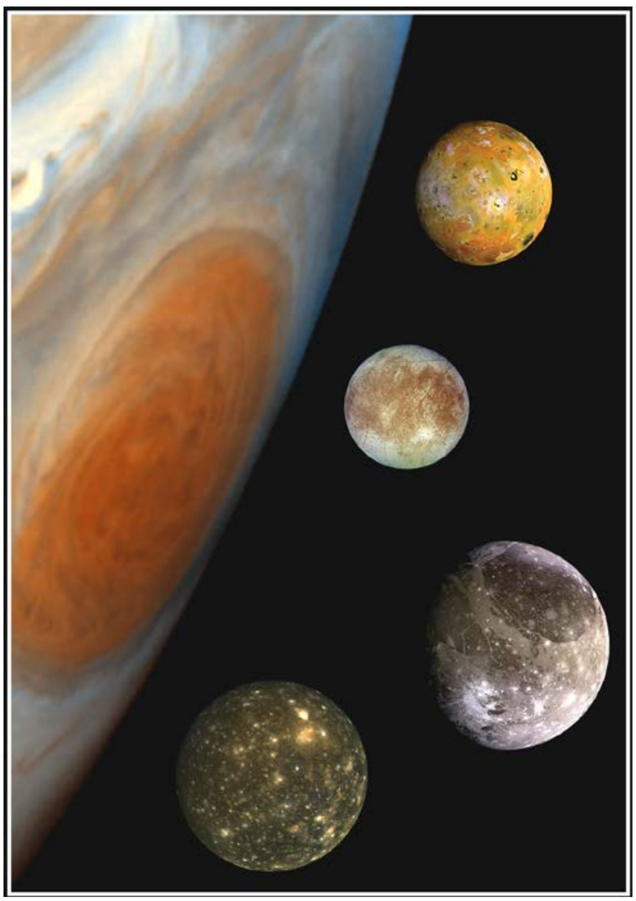

Figure 1. Galileo Images of Jupiter and its Largest Moons *(top to bottom - Io, Europa, Ganymede, and Callisto)*

On 7 December 1995, NASA's Galileo Orbiter arrived at Jupiter. It first collected scientific data transmitted from Galileo's Jupiter Atmospheric Probe then, like NASA's Juno spacecraft in 2016, performed a large Jupiter Orbit Insertion (JOI) maneuver to enter Jovian orbit. There, the Orbiter performed a highly successful exploration of Jupiter's atmosphere, satellites (see Figure 1), and magnetosphere until, on 21 September 2003, ground operators decommissioned the Orbiter by a targeted entry into the Jovian atmosphere, much like its Probe nearly eight years earlier. Its demise protected the mission's greatest discovery – evidence of a massive ocean of water under satellite Europa's crust that may support extremophile life -- from possible biologic contamination. Other Jovian discoveries include discovery of large thunderstorm systems in the planet's atmosphere, a magnetic field around the satellite Ganymede, and a full measure of the volcanic activity on satellite Io.[1]

Until arriving at Jupiter's locale, the spacecraft (see Figure 2) consisted of an Orbiter with an atmospheric Probe mounted at its base. The Orbiter was a dual-spinner, combining features of spinning and three-axis stabilized spacecraft. Its Spun Section stabilized the Orbiter and gave fields and particle instruments broad exposure to the local space environment. The counter-rotating Despun Section carried an articulating scan platform and inertial sensors to provide fine pointing for remote sensing instruments, turns, and small maneuvers. It also carried an articulating relay antenna to receive data from the Probe. When spun and despun sections were

[1] Systems Engineer, Project System Engineering Group, JPL/Caltech, Pasadena, CA 91109.

rotated in unison, the resulting "All-Spin" mode provided stability during sun acquisition turns and, at a higher spin-rate, for large axial maneuvers and Probe Release.[2]

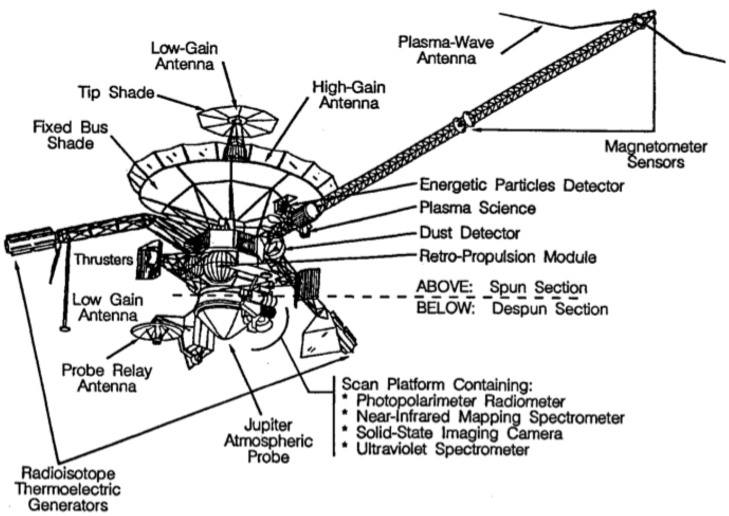

Figure 2. Galileo Spacecraft Showing Three Major Parts -- Spun Section, Despun Section, and Probe *(High-Gain Antenna shown fully deployed)*

Two Radioisotope Thermoelectric Generators (RTGs), mounted on Spun Section booms, furnished all electrical power. The Orbiter carried no batteries; its Power/Pyro Subsystem (PPS) automatically directed excess power (power margin) to shunt heaters on its Retro-Propulsion Module (RPM).[3] The module, at the Spun Section's base, carried massive propellant tanks that dampened temperature excursions when power margin changed -- for example, when loads switched on or off. Ground operators were responsible for designing command sequences that controlled the Orbiter power margin so that propellant temperatures were always safe for RPM thrusters to operate.[4]

On most missions, ground operators program commands to turn off non-essential loads to maintain a minimum power margin in reserve against anomalous power changes that might exceed the power available (undervoltage). From this experience, Galileo's designers expected that power constraints for RPM temperature management (power margin neither too low OR too high) would have only minor operational impacts. In the end, this design imposed great demands on mission planning, command sequencing, and onboard fault protection.

As interplanetary missions increase in complexity, spacecraft designs must still accommodate constraints on cost, risk, and spacecraft resources (mass, power, memory, etc.). Sometimes, this encourages novel designs that, like Galileo, couple critical subsystems in unconventional ways. Examination of Galileo's RPM temperature management can help spacecraft designer better anticipate operational impacts and plan accommodations.

II. Galileo's Mission

A. Science Objectives

Galileo's first science objective was to investigate the chemical composition and physical state of Jupiter's atmosphere with its atmospheric Probe. The second, to investigate the chemical composition and physical state of Jovian satellites, employed a suite of four remote sensing instruments on the scan platform. Finally, an investigation of the structure and physical dynamics of the Jovian magnetosphere was achieved with fields and particle instruments on the Spun Section.[1]

Table 1. Galileo Mission Summary[13]

Mission	Galileo (GLL)
Mission type	Outer planet Orbiter with Probe
Competed vs. Directed	Directed
JPL Role	Project management, Orbiter, ground systems
Partners / Contractors	NASA Ames Research Center and Hughes Aircraft Company: Atmospheric Probe Germany: Spacecraft propulsion system, two science experiments
Primary Science Objectives	Investigate the structure, physical state, chemical composition, physical dynamics and interactions of Jupiter, its magnetosphere, rings, and satellites
Cost	Development: $892 M Primary / Extended Mission Ops: $525 M for total of $1.417 B International Contribution: + $110 M
Inception Launch Interplanetary Cruise Prime Mission Europa Mission Millennium Mission	November 1977 October 18, 1989 October 18, 1989 - December 5, 1995 December 5, 1995 - December 7, 1997 December 8, 1997 - December 31, 1999 January 1, 2000 - September 21, 2003
Launch Vehicle Launch Site	Space Shuttle Atlantis and two-stage Inertial Upper Stage (IUS) Cape Canaveral Air Force Station

B. Mission Events

Per NASA policy in the 1970s and 80s, Galileo would launch into Low-Earth Orbit on NASA's Space Shuttle. There the spacecraft would be injected into interplanetary space by an upper stage mounted to its base. Galileo's original mission called for a direct two-year interplanetary cruise to Jupiter with no intermediate encounters or gravity assists. Launch delays and changes to the upper stage forced many mission redesigns. The final trajectory -- Venus-Earth-Earth Gravity Assist (VEEGA) -- used three gravity assists to reach Jupiter in six years (see Figure 3).[1]

After its first Earth flyby, Galileo performed close observations of Asteroid 951 Gaspra on 29 October 1991, becoming the first spacecraft to encounter a minor Solar System body. On 28 August 1993 Galileo encountered Asteroid 243 Ida and discovered a small satellite, later named Dactyl, orbiting about it. In July 1994, roughly 1.6 Astronomical Units (AU) from Jupiter, Galileo imaged fragments of Comet Shoemaker-Levy 9 striking the planet.[1]

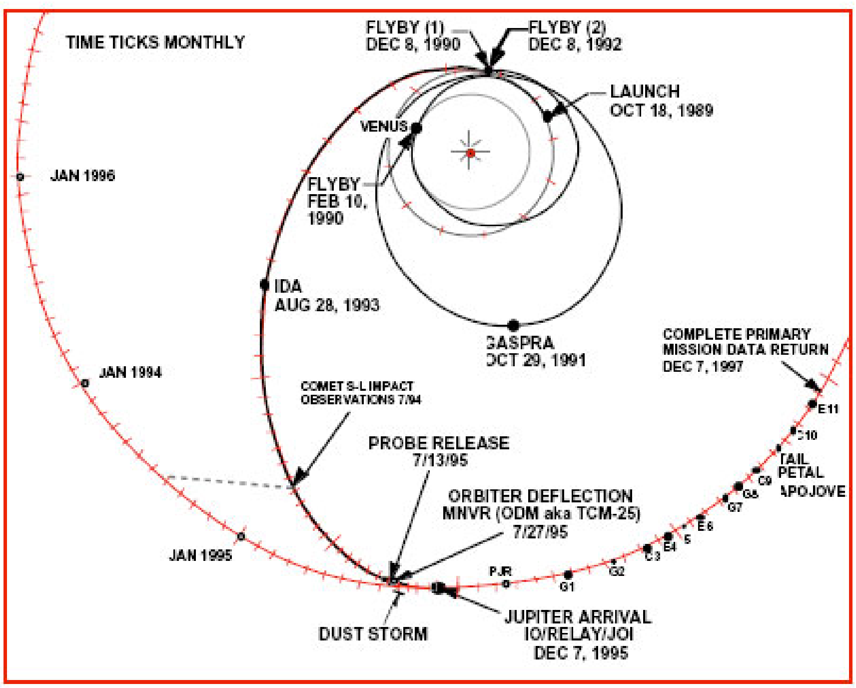

Figure 3. Galileo VEEGA Trajectory

On 13 July 1995 the Orbiter released Galileo's atmospheric Probe. Two weeks later, the Orbiter performed the first sustained burn of its 400-N main engine, enabling it to overfly the Probe's entry site. On 7 December 1995, the Probe arrived at Jupiter where, decelerated by its heat shield and parachute, science instruments gathered atmospheric data for transmission to the Orbiter. Overhead, the Orbiter received this data while collecting its own science data of the Jovian magnetosphere. (For the same day, remote sensing observations of Jupiter's satellite Io had been planned, but were cancelled due to problems with Galileo's onboard tape recorder). Following Probe data collection, the Orbiter successfully performed Jupiter Orbit Insertion.[1]

After a final 400-N burn to raise orbital periapse (perijove), Galileo began its Orbital Science phase. During its prime mission (concluding 7 December 1997) and two extended missions, it conducted extensive observations of

Jupiter's satellites (Io, Europa, Ganymede, and Callisto), atmosphere, and magnetosphere. Galileo flight operations continued until its propellant supply was nearly depleted. On 21 September 2003, the Orbiter was decommissioned with its own targeted entry into Jupiter's atmosphere.[1]

While the RPM central body received some warmth via thermal coupling to the Spun section's electronic bus, it had no electronics for self-heating. Instead, the Power/Pyro Subsystem diverted excess spacecraft power into RPM shunt heaters (see next section) fastened to aluminum structure around the propellant tanks.[5]

III. Orbiter Design

A. Retro-Propulsion Module (RPM)

The RPM provided propulsion for Galileo's attitude control and trajectory correction maneuvers. It used high-pressure helium to feed a hypergolic combination of monomethylhydrazine fuel and nitrogen tetroxide oxidizer to its twelve 10-N thrusters, used for trajectory corrections and attitude control, and a 400-N main engine for large maneuvers to be performed after release of the Probe (see Figure 4). The RPM was built by Messerschmitt-Bölkow-Blohm under contract to the Federal Republic of Germany who donated it to NASA.[6]

Tankage, a propellant isolation assembly (PIA) and a pressurant control assembly (PCA) comprised the RPM's central body. For shuttle safety and fault tolerance throughout the mission, the PIA/PCA was designed with a highly redundant pressurization system to connect pairs of pressurant, fuel, and oxidizer tanks. Helium pressurant was fed through one of two redundant pressure regulators. Activation of any backup RPM component required firing one or more single-use pyro valves. Non-redundant check valves impeded fuel and oxidizer vapors from reacting upstream of the propellant tanks. Downstream, redundant latch valves blocked propellant flow until a 10-N thruster valve was commanded open (see simplified view in Figure 5).[6]

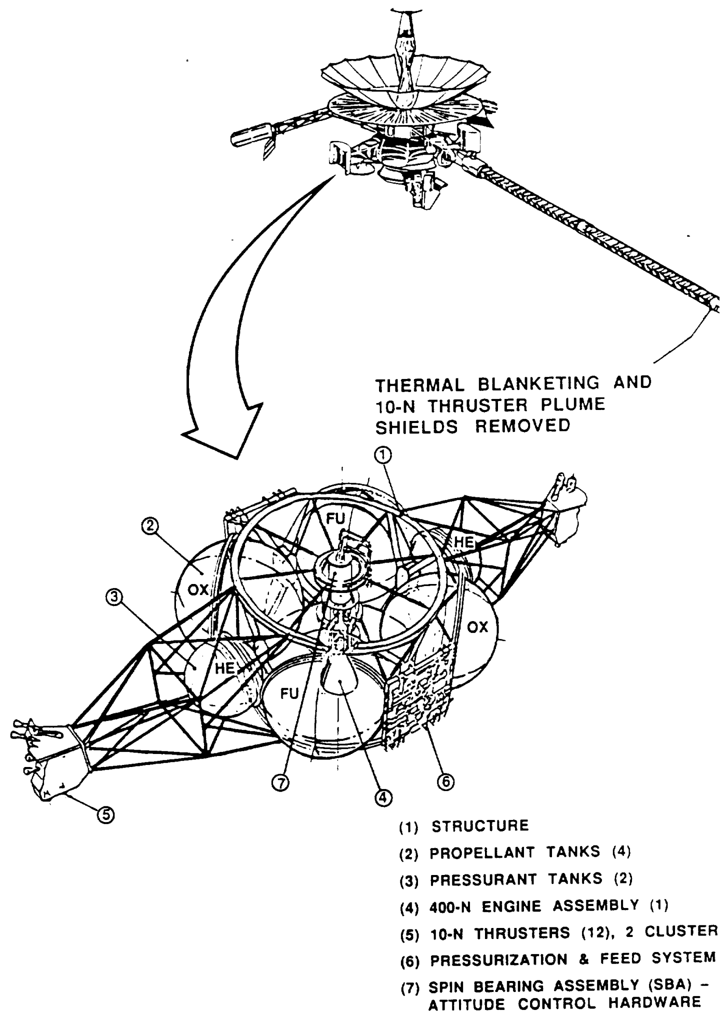

Figure 4. Three-Dimensional View of Galileo's RPM

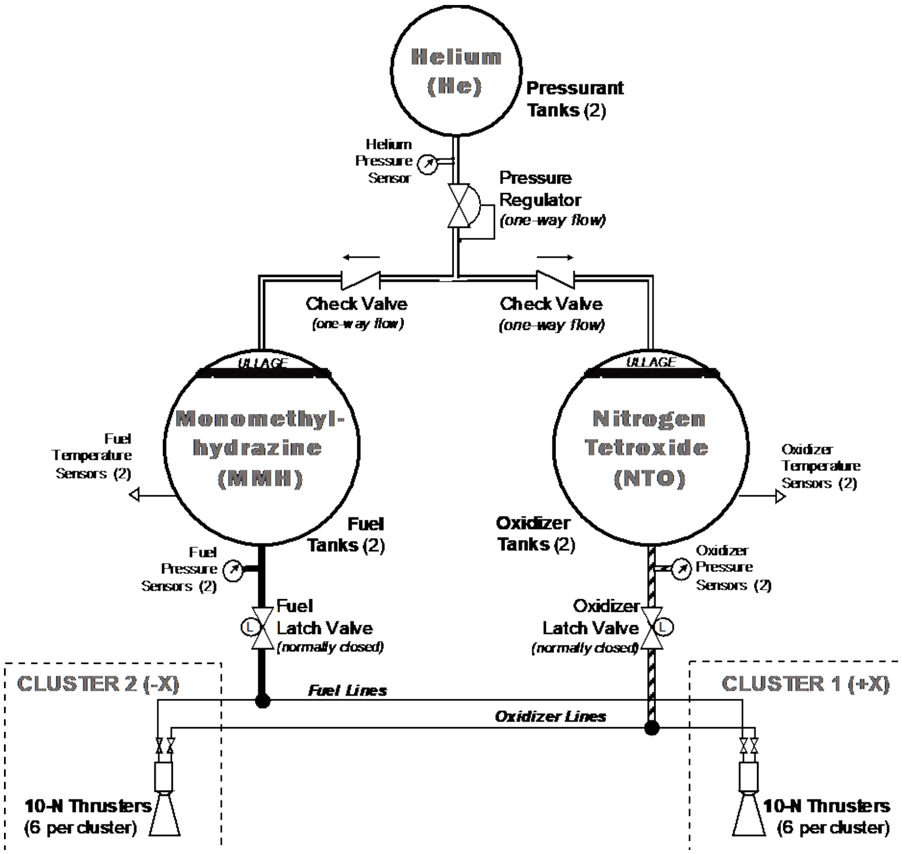

Figure 5. Simplified RPM Pressurization and Feed System Schematic
(For a full schematic, see References 5, 6, or 11)

B. Power/Pyro Subsystem (PPS)

The Orbiter's PPS processed and distributed 30-volt DC and 50-volt AC power to spacecraft loads (aka, "users"). Figure 6 illustrates its functional design.[2]

Two RTGs were the Orbiter's only source of power. Both RTGs were fueled with plutonium dioxide in 1985 to support a planned 1986 launch. Thereafter, their electrical output slowly diminished as expected due to radioisotope decay and other physical processes.[3] Through the life of the mission, strategies were adjusted to perform planned activities while operating fewer loads concurrently. This became a major consideration for applying RPM Shunt Heaters for thermal control.[9]

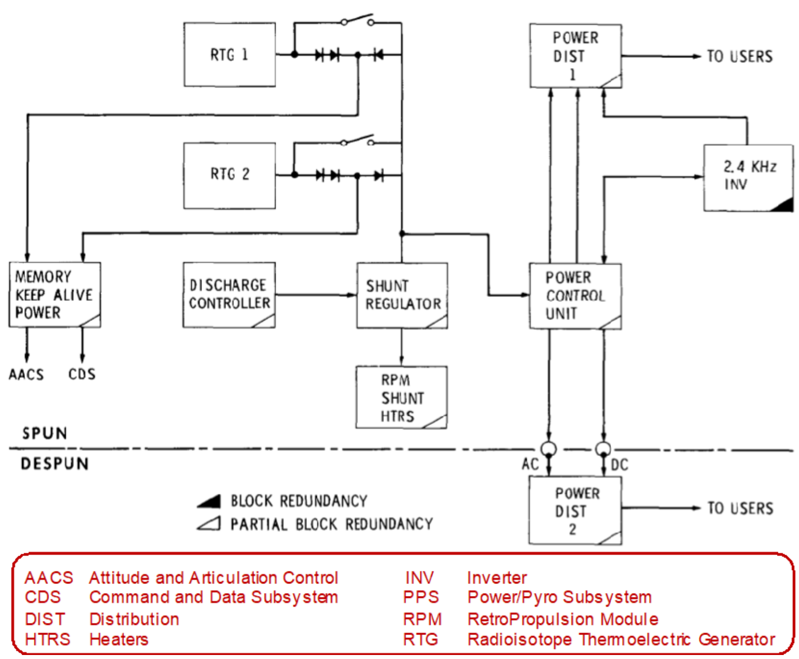

Figure 6. PPS Functional Block Diagram

C. RPM Temperature Control

RPM shunt heaters provided a finely-tuned mechanism for controlling propellant temperatures. The RPM's large mass, especially while fully-loaded with propellant, meant that perceptible temperature changes required that changes to average power be sustained for days. Short-term power changes, such as powering inertial sensors for the duration of spacecraft turns, had little effect.[4]

When, for example, propellant pressures needed to be in a specific range for thruster firing, propellant temperatures would be adjusted with long-term changes to power margin – typically by switching one or more designated heaters on or off. Galileo did this with heaters originally intended for other purposes.[4]

History of the Galileo Project illustrates why this hardware design was chosen and why its operation was much more cumbersome than anticipated.

IV. Evolution of RPM Thermal Design

Galileo was on the cutting edge for interplanetary spacecraft designed in the 1970s and 80s. It was the first to carry an atmospheric Probe to an Outer Planet. While the two Voyager spacecraft preceding it had only to survive brief exposure to Jupiter's intense radiation, the Galileo Orbiter required long operations in this environment. Also, it would launch on the U.S. Space Shuttle -- the first interplanetary spacecraft to do so.[1]

A. Mass Limits

Like most interplanetary spacecraft, Galileo's design was challenged by mass constraints. While Shuttles were originally designed to carry up to 65,000 kg into Low-Earth Orbit, Galileo needed to also carry a large upper stage to deliver it onto an interplanetary trajectory. In addition, the Orbiter would carry 935 kg of propellant for propulsive maneuvers and attitude control.[5] For the mission to remain viable, Galileo's dry mass was strictly limited.[2]

Changes to Space Shuttle manifest delayed Galileo's launch many times. This and other programmatic considerations required several mission redesigns utilizing different upper stages and interplanetary trajectories, some with and some without gravity assists. All redesigns affected mass constraints. The final, pre-Challenger, mission design called for Galileo to launch in May 1986 with a cryogenically-fueled Centaur upper stage that would place it on a direct, two-year trajectory to Jupiter.[2]

B. Power Limits

Power consumption became yet another design driver. As Galileo's design matured, demands on power usage grew and became a major concern. For periods of peak science operations, designers were encouraged to find ways to reduce power consumption.[2]

One power-reducing option was to substitute steady-state heaters with Radioisotope Heater Units (RHUs). With each generating one watt of heat, they could be mounted anywhere steady-state heat was required and the radiation from radioisotope decay could be tolerated. They could be used to warm selected portions of the spacecraft without electrical power.[7]

Temperature control of the RPM's central body required 44 RHUs.[4] Unfortunately, RHUs were expensive, hazardous, and heavier than conventional heaters. The Project had strong incentive to use as few RHUs as possible, while still meeting power constraints.[2]

C. An Integrated Solution

Responding to these conflicting constraints led Galileo's designers to an innovative solution -- thermally couple the PPS to the RPM.[4]

1. Attach Shunt Heaters to RPM

Originally, Galileo was designed with variable output shunt heaters that directed their heat into space through a shunt radiator. To thermally isolate from the spacecraft bus, the radiator was mounted near the base of a deployable science boom. With cabling it would have weighed about 4 kg.[4]

In 1979, a novel solution for saving mass was devised. Rather than providing dedicated structure to mount conventional shunt heaters onto the exterior of the spacecraft mount them internally as film heaters onto RPM structure, allowing the removal of 2.2 kg of RHUs. The redesign saved mass and cost while utilizing heat that otherwise would have been dumped into space.[4]

2. Power Management for the RPM

Ordinarily, high spacecraft power margins are desirable -- they provide leeway against power faults that might otherwise trip an undervoltage. On Galileo, extra power margin warmed the propellant tanks where thermal expansion of the fuel and oxidizer would raise their pressures. The sensitivity of propellant pressures to margin was greatest immediately after launch, when propellant tanks were fullest. During interplanetary cruise, consuming propellant for delta-V maneuvers and attitude control would slightly diminish temperature/pressure effects; only large maneuvers near Jupiter would relax them appreciably.

Circa 1979, the principle constraint on propellant tank pressure was a pressure limit of 18.1 bar for continuous operation of the 10-N thrusters. Continuous thrusting would only be applied for large axial maneuvers and to spin the orbiter up/down for Probe Release and 400-N engine maneuvers like JOI. These are all pre-planned activities, allowing time, if necessary, to power additional spacecraft loads to lower power margin, cool the propellant, and bring propellant pressures within the 18.1 bar limit.[8]

Meanwhile, no propellant pressure limit had been identified for pulse-mode operation of the thrusters. Originally, pulse-mode was intended only for small maneuvers, turns, and autonomous corrections for pointing and spin-rate. With the information available, designers planned to allow propellant pressures and temperatures to range freely for most of the two-year cruise to Jupiter. Only prior to continuous firings of the 10-N thrusters might the propellant need to be “pre-conditioned” by adjusting power margin to cool the tanks to within a few degrees C of the temperature of the previous repressurization (lock-up). Otherwise, a pressure limit of 20 bars would be maintained allowing temperatures approximately six degrees C above lock-up

No new heaters were added for power margin adjustment. Galileo would use existing heaters with relatively broad operating constraints – at least as understood during initial spacecraft design. For example, decontamination heaters on instruments and calibration targets could be powered anytime the instruments were not operating. Others, like the +/- RTG Boom Deploy Device heaters only needed to be operated for brief periods when the booms were moved to keep the spin axis properly aligned; otherwise, they could be on or off.[9]

Drawing from these criteria, the heaters in Table 2 were selected for controlling propellant temperatures. (The majority of operating constraints, shown in the last column, weren’t widely known when the strategy was originally formulated.) Besides heaters, the Contamination Monitor, a normally-powered 2-watt load, might be turned off for fine power margin adjustments.[9]

Table 2. Heaters for Propellant Temperature and Pressure Management[9,10]

Heater	Dissipation	Original Application	Location	Comments / Constraints
External Shunt Heater 1A	45 watts	Dissipate excess power during launch[2]	Scan platform structural supports	• Used while Galileo in shuttle bay; used to lower power margin at launch to avoid excess heat to Spun Bus electronics (propellant tanks unpressurized at launch, so their temperatures not primary concern) • Unsuited for fine adjustments
External Shunt Heater 2A	45 watts	ditto	ditto	ditto
Bus Distribution Heater 1	45 watts	Temperature control of Spun Bus electronics	Multiple sites around Spun Bus	• In flight, seldom required for Spun Bus temperature control • Thermal coupling between Spun Bus and RPM made this heater less efficient for propellant temperature / pressure control
Near-Infrared Mapping Spectrometer (NIMS) Optics Heater 1	39.6 watts	Repel contamination; outgas deposited contamination	NIMS Optics	• Never power single optics heater (thermal distortion) • Never power during NIMS operation (exceed operating temperatures) • Power post-launch (repel outgas contamination) • Power during/after maneuvers/turns (repel thruster/engine contamination) • (Recommended) power while other decontamination heaters are powered (contamination deposits on colder surfaces)
NIMS Optics Heater 2	39.6 watts	ditto	ditto	ditto
Bus Distribution Heater 2	30 watts	Same as Bus Distribution Heater 1	Same as Bus Distribution Heater 1	Same as Bus Distribution Heater 1
Bus Distribution Heater 3	25 watts	Same as Bus Distribution Heater 1	Same as Bus Distribution Heater 1	Same as Bus Distribution Heater 1
NIMS Shield Heater	26.4 watts	Repel contamination; outgas deposited contamination	NIMS Radiator Shield	• Never power during NIMS operation or 48 hours prior (exceed operating temperatures) • Power post-launch (repel outgas contamination) • Power during/after maneuvers/turns (repel thruster/engine contamination) • Power while other decontamination heaters are powered (contamination deposits on colder surfaces)
Radiometric Calibration Target for NIMS (RCT-NIMS)	24.2 watts	Calibrate NIMS	Scan platform sunshade	• Never power during NIMS or SSI science observations or 24 hours prior • Power for NIMS calibration • (Recommended) Power post-launch (repel outgas contamination) • (Recommended) Power during/after maneuvers/turns (repel thruster/engine contamination) • (Recommended) Power while decontamination heaters are powered (prevent contamination on colder surface)
Solid State Imager (SSI) Flash Heater	15 watts	Repel contamination; outgas deposited contamination	SSI Radiator	• Never power during SSI operation or 4 hours prior (exceed operating temperature) • Power post-launch (repel outgas contamination) • Power during/after maneuvers/turns (repel thruster/engine contamination) • (Recommended) Power while other decontamination heaters are powered (contamination deposits on colder surfaces)
RTG Boom Deployment Device Heaters	15 watts	Warm hinges while rotating RTG booms	RTG Joints	• Power during RTG boom deployment (launch) • Power while moving RTG booms to adjust Orbiter mass properties (prevent hinges from binding)
Photometric Calibration Target (PCT) Heater 1	14 watts	Repel contamination; outgas deposited contamination	PCT mounted to science boom	• Never power during NIMS operation (exceed NIMS operating temperature) • Power post-launch (repel outgas contamination) • Power during/after maneuvers/turns (repel thruster/engine contamination) • (Recommended) Power whenever other decontamination heaters are powered (contamination deposits on colder surfaces)
Bay E Replacement Heater	12 watts	Control Probe check-out electronics temperature	Despun electronics	• Until Probe Release, always power when Probe check-out electronics unpowered; never power when Probe check-out electronics powered • After Probe Release, no constraints
Bay C/D Shunt Heater	8 watts	Control Despun electronics temperature	Despun electronics	• After launch, concerns about thermal cycles causing solder joint damage to electronics in these bays; limit heater use
PCT Heater 2	7.8 watts	Same as PCT Heater 1	Same as PCT Heater 1	Same as PCT Heater 1
Bay B Replacement Heater	4 watts	Same as Bay C/D Shunt Heater	Despun electronics bay	• After launch, concerns about thermal cycles causing solder joint damage to electronics in these bays; limit heater use

3. Integrate RPM Constraints into Sequence Design

Typically, Galileo activities employed stored command sequences operating over periods of weeks to months. Beginning months in advance, operations teams planned events, checked constraints, and, once the sequence was mature, the Orbiter Engineering Team (OET) would model power margin changes, estimate their effects on propellant temperatures and pressures, then select heaters to compensate.[10]

The greatest pressure to temperature sensitivity would be immediately after launch, when propellant tanks would be at their fullest. By the start of the Jovian tour, it will have expended so much propellant that power margin would have little impact on propellant pressures. Then, even large sustained power margins could not violate pressure limits.[10]

As originally planned, Galileo was to fly a two-year cruise to Jupiter.[1] Operations would have been simple and repetitive, requiring little effort to manage propellant temperatures and pressures.

That was not to be.

V. Interactions

A. Propellant Pressures

1. Initial Pressurization

When Galileo's propellant tanks were filled for launch, a small launch ullage (unfilled propellant tank volume) was reserved for helium pressurant. Were they filled completely with propellant, which is nearly incompressible, tank pressures would be inordinately sensitive to temperature changes; the compressible helium served to cushion thermal expansion of the liquid. For safety, propellant tanks were pressurized to only 3 bar for launch -- too low for thruster operation.

Once activated in flight, the RPM's pressure regulator flowed high-pressure helium into the tanks until downstream pressures triggered it to "lock up" and stop the flow. For initial pressurization, the regulator was set for a minimum propellant pressure of approximately 17.7 bar. This established a pressure versus temperature profile that, as described below, was subject to change throughout the mission.

2. Expending Propellant

Warming propellant tanks above their lock-up temperature raises their pressures. Power margin management was used to keep temperatures below levels that would raise pressures above operating limits.

At pressures above lock-up, burning off propellant, for attitude control or maneuvers, drops propellant pressure (see Figure 7A). A sufficiently large maneuver (dark line) brings the pressure back down to lock-up. Thereafter, pressure versus temperature follows a different pressure versus temperature curve -- one with a higher lock-up temperature (pressure versus temperature curve moves to the right). Expending propellant also increases the volume of helium in the propellant tanks; with a larger proportion of compressible helium to incompressible propellant, tank pressures become less sensitive to temperature (pressure versus temperature curve becomes shallower). For all but the biggest maneuvers, this would be a small effect.

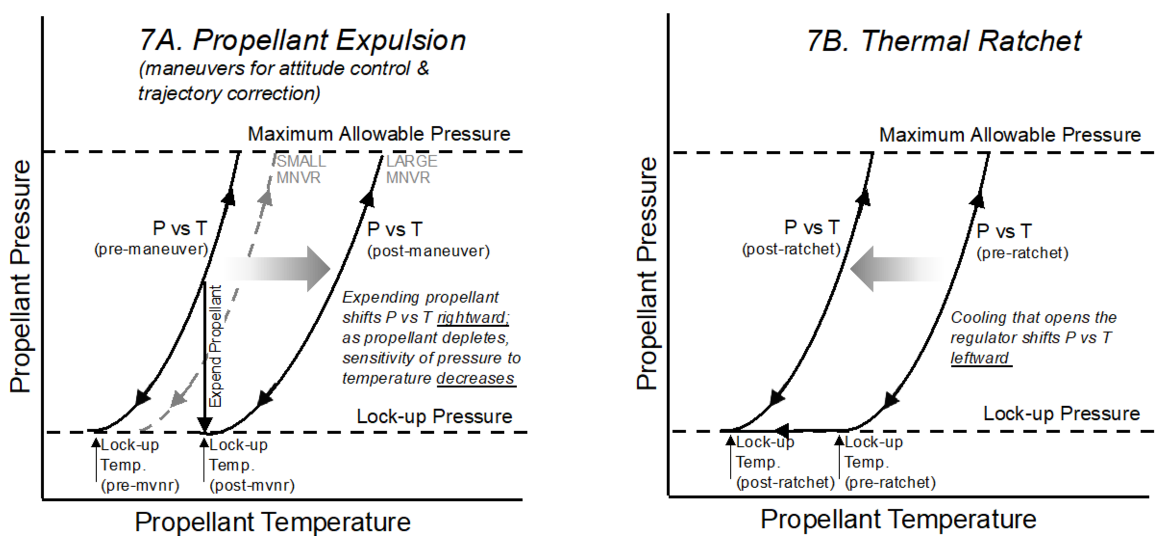

Figure 7. Changes to Propellant Pressure versus Temperature Curves

A small maneuver that doesn't repressurize the tanks still affects pressure versus temperature. Figure 7A's light, dashed line shows how the curve shifts with a new lock-up temperature between the previous value and the current temperature.

3. Thermal Ratcheting

As shown in Figure 7B, if propellant temperature drops below the current lock-up temperature, the pressure versus temperature curve moves to the left, creating conditions where a maximum allowable pressure will be reached at a lower temperature level than before. This was called a "thermal ratchet" because, without expending propellant, the change to the pressure versus temperature curve lasts indefinitely -- an important consideration when managing temperatures for pressure control.

4. Constraints on Average Power Margin

For most operational scenarios, average power margin set bulk propellant temperatures. While the RPM's central body thermally coupled to the Spun Bus, the only large departures from its total power dissipation would be power-mode changes to the S and X-band transmitters; such changes would be infrequent and planned well in advance. Sun exposure also affected propellant temperatures but, in the original mission, solar illumination would only decrease between Launch and arrival at Jupiter. For some large Trajectory Control Maneuvers (TCMs), the Orbiter's attitude might place the RPM broadside to the sun, but their duration would be too short to warm hundreds of kilograms of propellant significantly.

Thus, propellant expenditure and thermal ratchet made the allowable range of propellant temperatures a moving target. If the range were too cold, power margin might be trimmed low enough to make susceptibility to undervoltage a concern. Too warm, and Orbiter would need to sustain power margins so high that large loads could not be powered on for long periods. Thus, current constraints on propellant temperature determined current constraints on average power margin.

This meant that propellant expenditure and thermal ratchet had to be considered in the power margin / propellant temperature strategy. The simplest approach would to keep the range of allowable propellant temperatures in a zone where average power margins would be easy to maintain for planned activities. If necessary, planned maneuvers could be utilized to shift the range upward and thermal ratchet to drive them downward. As propellant burns off, pressures become less sensitive to temperature so control of power margin could be less rigorous. At Jupiter, with most propellant expended, power margin could range freely for science operations.

B. Propellant Loading

As originally planned for a 1982 launch, Galileo would launch with 763 kg of usable propellant for launch on a direct Earth to Jupiter trajectory. Changes to the Space Shuttle Program's launch manifest created launch delays that made it necessary to plan for alternate trajectory requiring more delta-V. To provide mission designers greater flexibility, Galileo's propellant load was increased to 935 kg usable propellant -- the most its fuel and oxidizer tanks could carry safely.

C. Fault Protection

Fault Protection for interplanetary missions must assure that, if a potentially serious fault is detected, it will reorient and maintain the spacecraft in safe attitude and otherwise establish a safe power, thermal, and telecommunications configuration while awaiting instructions from Earth. To accommodate solar conjunctions or missed telecom passes, Galileo was designed for two weeks unattended post-fault operation. A “Spacecraft Safing” program would perform the necessary transitions; the resulting configuration (power state, spin-rate, attitude, etc.) was called the “Post-Safing” state.[2]

For temperature control, Galileo was safest while keeping a sun-pointed attitude. At any time, Spacecraft Safing might be called upon to perform a turn to this attitude. While this feature would have been inconsequential for the 1986 mission, it became a major issue for the 1989 launch.[2]

D. Design Constraints

1. No Additional Heaters for RPM Thermal Control

Control of RPM temperatures could have been greatly simplified had dedicated heaters of appropriate sizes been added solely for power margin adjustments. This was not done for several reasons.

First, Orbiter's design had been completed before many of the operational complexities of RPM thermal control were recognized fully. Adding heaters posed a threat to cost and schedule. Meanwhile, more serious issues, like the effects of Jovian radiation on electronic components, were being addressed. The Project applied its limited resources to fixing them, trusting operational strategies would be devised to maintain propellant conditions with the heaters available.

2. Avoid Power-Cycling Heaters for RPM Thermal Control

Power cycling passive loads might have made propellant temperature management easier. The Galileo Project's philosophy was to minimize power cycles in order to maximize hardware life -- even for passive loads. So long as some combination of heaters could achieve the designed set-point, power cycles were to be avoided.

3. Limitations on Heater Operations

As originally conceived, the heaters identified for controlling propellant temperatures and pressures came with relatively few constraints. When some might need to be turned on or off for specific activities, others might be utilized in their place. Within these parameters, options could be considered that would satisfy power margin control requirements while still maintaining a state preferred by the science instrument or engineering subsystem most directly affected by the heater state.

As shown in Table 2, almost every heater came with operational constraints and preferences – far more than anticipated when placing shunt heaters on the RPM was first considered. Many were known before the planned 1986 launch; more were identified before and after the 1989 launch.

E. Operating Philosophy (1986 Launch)

Propellant temperature management for 1986 launch would begin by setting propellant temperatures at launch to levels slightly above the predicted steady state conditions post-launch. This would assure that thermal ratchet would pull the allowable temperature range downward, towards a preplanned zone, rather than drive propellant temperatures upward, along the pressure versus temperature curve. This would keep propellant pressures low for initial use of the 10-N thrusters.

The allowable temperature range would be planned around average power margins sustainable through interplanetary cruise. For mission planning, spacecraft activities had already been modeled for power consumption and heaters selected for use in those modes. Plans called for using these modes to identify candidate heaters as the actual activities were developed and iterated for uplink. Once the exact sequence of activities was specified, they would be modeled for power consumption and effects on RPM pressures and temperatures. As needed, heater selections would be adjusted to assure power margins were compatible with the allowable propellant temperature range.

VI. Consequences of the Challenger Disaster

By January 1986, Galileo had been delivered to NASA's Kennedy Space Center in preparation for launch aboard Space Shuttle Atlantis that May. Galileo's RTGs had been fueled with plutonium dioxide and awaited Orbiter integration.[3] The tragedy of STS-51L -- Challenger's last flight – cancelled Galileo's 1986 launch opportunity. Ultimately, launch was postponed until October 1989.[1]

A. Launch Delay

1. Reduced RTG Power at Launch

RTG decay lowered their beginning-of-mission output from 600 to 586 watts. Smaller power margins would keep propellant temperatures cooler, but also shift RPM power margin constraints downward as well.

2. VEEGA Trajectory

Post-Challenger, the Shuttle-Centaur program was cancelled. New constraints on Shuttle payload mass precluded Galileo from launching with a three-stage IUS. No other suitable unmanned launch vehicle was then available. Galileo's only option was a Shuttle launch with a less-powerful two-stage IUS. This upper stage lacked the energy for a direct two-year trajectory to Jupiter -- Galileo would launch on the six-year VEEGA trajectory described in Section II.B.[1]

Now, with heliocentric distances as low as 0.7 AU, solar heating posed a propellant temperature / pressure concern. While a new sunshade could diminish those effects, power management would now have to compensate for the remainder. (This operational adjustment would have been unavailable with the original design that used fixed heat levels from RHUs to warm the RPM central body.)

Unfortunately, the longer cruise time would further deplete RTG power output for Jupiter activities. Besides lowering the RPM's power margin operating box for Jupiter arrival, power constraints for near-full propellant tanks increased from two years of interplanetary cruise to six.

On Galileo's original mission the spacecraft would be quiescent for most of its journey to Jupiter. Except for instrument check-outs, no science operations were planned. There would be few activities requiring heaters to be turned on / off to control propellant temperatures and pressures. Now, on the VEEGA mission, Galileo would perform science operations during flybys of Venus, Earth, and two asteroids. These proved to be valuable rehearsals for science operations at Jupiter. They also required many more power adjustments for the RPM while it still had most of its propellant.

B. 10-N Thrusters

1. Hazards of Continuous Thrusting

In 1988, thrusters similar to Galileo's failed on the TVSAT-1 communications satellite. It was later determined that Galileo's thrusters posed a risk to mission success if operated as originally planned. For Galileo to launch in 1989, replacement or major redesign of the thrusters was infeasible. Instead, operational work-arounds were devised.[6]

2. Pulse-Mode Operation

Continuous-mode operations were removed from all thruster activities – only pulse-mode would be allowed. In addition, pulsing for large maneuvers would be limited to segments lasting about an hour, then the thrusters were allowed to cool before continuing to the next segment. Maneuvers requiring more than a work-day to execute would be split into multi-day portions. Through it all, propellant pressures, and hence the power margin driving propellant temperatures, needed to be carefully controlled.[10]

3. New Pressure Constraints

Even if autonomous pointing and spin-rate corrections were inhibited, onboard fault protection must always be capable of turning to sun-point for thermal safety. To enable this without risk to the thrusters, propellant tank pressures would be constrained to a new limit, 18.5 bar, <u>at all times</u>. (Reference 4 incorrectly states this limit only applied during maneuvers.) This was an extremely conservative value established for large maneuvers. Typically, autonomous thrusting would require very few pulses; testing showed that such operations could be performed safely at higher limits.[6]

For fully loaded tanks on the 1989 mission, allowable temperature above pressurization would be no more than 2 degrees C compared to 10 degrees C for the 1986 mission. The post-launch operating zone had become a very small box.[9] (Note: Reference 4 incorrectly states this constraint applied only to planned maneuvers.)

No new heaters could be added to help RPM temperature management – the as-built PPS had no more power switches available. The operating strategy planned for a 1986 direct trajectory had be applied with even greater rigor.[10]

VII. Launch Preparations

A. Launch Constraints

During launch preparations, external support equipment for the spacecraft and air conditioning for the Shuttle's payload bay enabled operators to impose a specific bulk temperature for lift-off. The RPM's large mass would hold propellant to this value through the period of launch, deployment, and IUS burns. Thus, when propellant tanks were pressurized about 30 minutes after Orbiter separation from the IUS, their bulk temperatures at lift-off would define fuel / oxidizer pressures versus temperatures for the period between launch and the first TCM, approximately 21 days after launch.

B. Operational Challenges (Early Cruise)

The RPM temperature management strategy assumed Orbiter command sequences would use standardized command blocks to operate the Orbiter. From these, standard heaters could be used to trim power margin.

While true for later stages of the mission, the first several months of Galileo mission operations were dedicated primarily to checking out engineering and science instrument hardware. These were non-standard activities, designed and developed months before launch. At the earliest opportunities, every assembly that could be exercised was individually tested to confirm they would function properly when required while also allowing time for troubleshooting. RPM temperature management required many tweaks to accommodate late changes.

VIII. Flight Operations

Until now, the paper has presented only a concept for controlling propellant temperatures and pressures with power margin. It will now describe how the design worked in practice.

A. Launch

On 18 October 1989, Galileo launched atop a two-stage solid-propellant IUS aboard Space Shuttle Discovery (STS-34). In Earth orbit, shuttle astronauts deployed the stack, enabling the IUS to propel Galileo onto its six-year flight to Jupiter.[1]

Up to this point, RPM propellant tanks were isolated from the pressurization system. After separating from the IUS, pyrotechnic valves were fired to release high pressure helium into fuel and oxidizer tanks. Pressurization was nominal. Afterwards, as RPM temperature equilibrated to the space environment, propellant tanks cooled (see Figure 8). As fluid contracted from the falling temperatures, check valves between the propellant tanks and the pressure regulator opened/closed to trickle more helium into them. Initially, pressures remained constant.

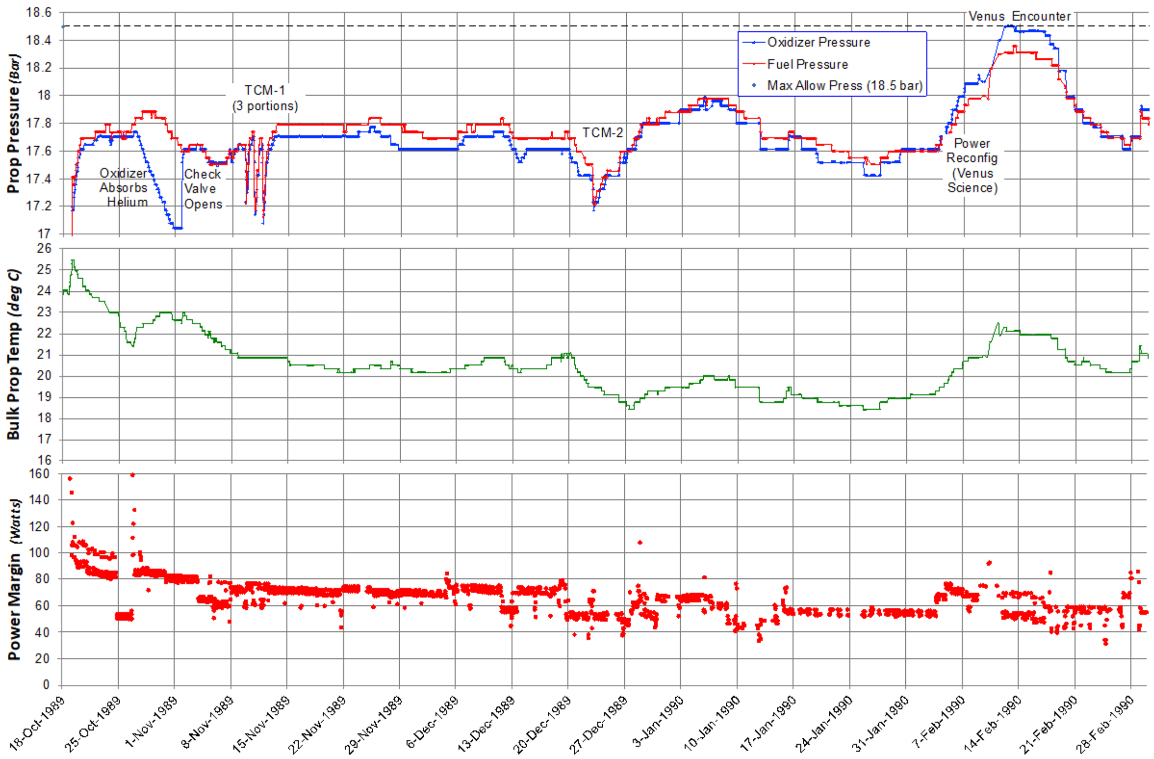

Figure 8. Propellant Pressures, Bulk Temperatures, and Power Margin *(Launch to Venus Flyby)*

About one-week post-launch, planned activities stepped down average power margin for several days before returning to previous levels. Apparently, the resulting temperature variation caused oxidizer in the tanks to absorb helium from their ullage volume, but the pressure drop did not immediately unseat the oxidizer check valve. Pressures between fuel and oxidizer began to diverge, creating concerns that the 10-N thrusters might have to operate in an unsafe pressure regime. After several days, differential pressures opened and reseated oxidizer check valve; afterwards fuel and oxidizer pressures tracked closely through temperature variations.[5] (Six years later, this check valve's performance would have great operational impacts to Jupiter approach operations.)[11]

Meanwhile, the Orbiter was commanded through a full check-out of its engineering subsystems. For steady-state power changes lasting a day or more, heaters identified in Table 2 were turned on / off to keep average power margin stable for RPM temperature / pressure control. At times, use of these heaters proved problematic. Heaters on the NIMS, SSI, and PCT were provided to protect sensitive surfaces from contamination caused by spacecraft outgassing and operation of RPM thrusters and main engine. When instruments were not in use, their preferred state is to remain continuously powered, lest cooler surfaces collect contamination released from warmer ones. While most contaminants collected on sensitive surfaces might be outgassed later, less volatile materials might adhere and diminish instrument / calibration target performance. Due to concerns for potential science impacts at Jupiter, use of these heaters for the RPM required authorization by Galileo's Project Office. Since heater selection could not be made until after the main command sequence had been designed and power/temperature models run, there was frequently little time to reach agreements with instruments teams concerned about the long-term health of their hardware. Sometimes, real-time commands were used to correct heater states while the sequence was operating.

Galileo's first Trajectory Correction Maneuver, TCM-1, was performed in portions, split over consecutive days. Each day, enough propellant was consumed to activate the regulator and repressurize the tanks. Temperature maintenance assured repressurizations did not move allowable steady state power margins into a zone that would later be difficult to maintain – for example, requiring average power margins below the 20 watts reserved to minimize undervoltage risk.[11] TCM-1 expended enough propellant to expand allowable temperature changes from two to three degrees C.

During Venus Flyby (9 – 10 February 1990), the RPM faced twin thermal challenges. There, the spacecraft received about twice the solar thermal input as at launch. Science operations near Venus constrained the heaters available for RPM temperature management. Further, higher steady-state power margins were needed to accommodate short-term power demands by the science instruments, scan platform, and tape recorder. As planned, the temperature at which the propellant tanks last repressurized meant that the RPM could accommodate higher power margin. Near flyby, pressures peaked at the 18.5 bar limit.

Throughout the mission, propellant temperatures and pressures would be allowed to increase near encounters, although none as high as for Venus.

B. Venus-Earth Cruise

For much of Venus-Earth Cruise, low downlink data rates limited Galileo to critical activities, including several large maneuvers. As before, propellant temperatures were maintained to keep repressurizations from ratcheting safe temperatures, and hence average power margins, down to levels that would be difficult to maintain.

Earth Flyby #1 repeated the pattern of accommodating larger power margins during encounters. Due to lower solar flux, maximum propellant temperatures and pressures were lower than Venus Flyby.

C. Earth-Earth Cruise

The two-year cruise between Earth flybys should have been a relatively quiet period for Galileo operations. Venus and the first Earth flyby had exercised all the Orbiter's instruments and provided excellent rehearsals for the flyby of asteroid 951 Gaspra -- a major scientific event. Engineering subsystems had behaved well and operations had settled into a routine. No new challenges for propellant temperature and pressure maintenance were anticipated.

1. High-Gain Antenna (HGA) Deployment

Galileo's HGA was originally planned to unfurl, umbrella-like, during final stages of the launch sequence. Thereafter, it would be the primary telecommunications link with Earth, supporting downlink data rates up to 134 kbps at Jovian distances, but only when the Orbiter pointed directly at the Earth. For most off-Earth attitudes, for example during large axial maneuvers or while sun-pointing after a major spacecraft fault, an omnidirectional Low-Gain Antenna (LGA) could provide a downlink rate 40 bps -- sufficient for monitoring the health of engineering subsystems.[12]

The deployed HGA, however, was not designed for the maximum solar flux on the VEEGA trajectory; excessive solar exposure could deform its carbon-composite ribs, warping the reflective gold-mesh used to focus S and X-band radio signals. For VEEGA, the Orbiter was modified to carry a parasol that would shade the undeployed HGA while flying in a Sun-pointed attitude between Launch and the first Earth flyby. A second LGA was added to support telecommunication during periods of Venus-Earth cruise when sun-pointing placed the first LGA, mounted on the tip of the HGA, out of view from Earth.[12]

Galileo's trajectory determined that HGA deployment could be safely performed in April 1991. There, sun exposure would be safe for the HGA and equipment that would be freshly illuminated with the Orbiter in an Earth-pointed attitude. It also provided time to check-out and characterize HGA performance prior to real-time downlink of Gaspra science data on 29 October 1991.[12]

2. Deployment Anomaly

On 11 April 1991, the Orbiter executed stored commands to power dual-redundant deployment motors. Nominally, the motors should have needed only a fraction of their full torque to unfurl the HGA fully within a few minutes. Almost immediately they drew their full torque and sustained it for the full eight minutes programmed to assure full deployment.[12]

Stalling both motors indicated a mechanical obstruction somewhere in the deployment chain. From shadows cast by the HGA ribs onto a Sun Detector below, investigators determined that while most ribs had partially deployed, three adjacent ribs were stuck to the central mast. The most likely scenario was that alignment pins near the ribs' tips had wedged into their sockets.[12]

The HGA deployment system had no means to reverse the deployment motors in flight. The pins would need to be released by some other means. The first approach attempted was thermal expansion and contraction of the HGA structure. The HGA had no heaters -- the only way to warm or cool its structure significantly was to expose antenna to sunlight or shadow it from sunlight over a period of days.[13]

Either way, enough sunlight would strike the RPM central body for propellant to warm.

3. Warming / Cooling Turns

Figure 9 illustrates propellant temperatures and pressures during the warming / cooling turn campaign between May 1991 and January 1993. It provided the most extreme variations in propellant temperatures and pressures encountered in the missions. The thermal ratchets resulting from the first turns would later impact operations following the flyby of asteroid Gaspra.

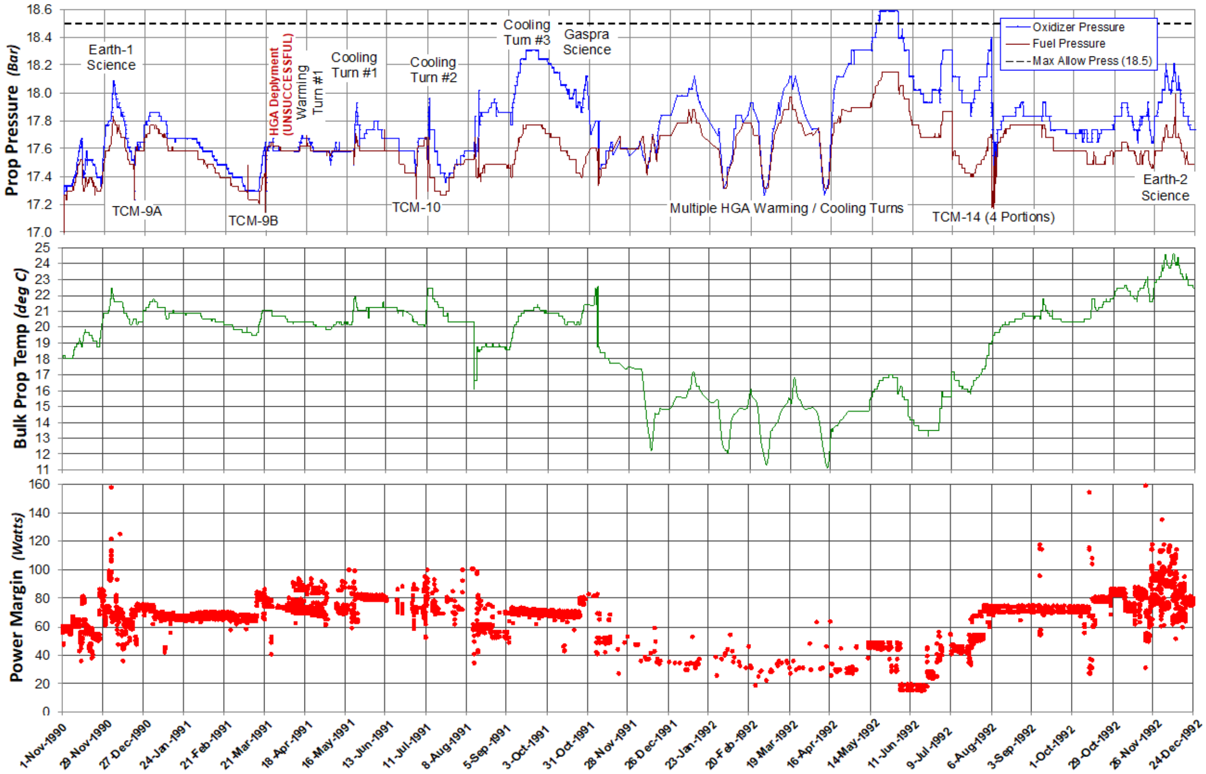

Figure 9. Propellant Pressures, Bulk Temperature, and Power Margin *(Earth-1 to Earth-2)*

On 20 May 1991, the first warming turn placed the Orbiter about 45 degrees off sun for nearly two days. Some of the usual heaters for RPM temperature control were on equipment that would receive additional sunlight. Extensive thermal analysis determined which could be powered while keeping their parent hardware within allowable temperatures. In addition, contingency commands were prepared for emergency uplink if trends showed temperatures limits might be violated. In the end, no real-time intervention was required and propellant temperatures and pressures behaved per predicts.[13]

The warming turn did not release the HGA. For a more extreme thermal cycle that might unstick the pins, a cooling turn to 165 degrees off-Sun was performed that completely shadowed the HGA with the shade for the Spun Bus. This, too, was unsuccessful.

Next a more extreme cooling turn was performed. Beyond shadowing the HGA, its interface with the Spun Bus was pre-cooled to minimize antenna temperatures during shadowing. This required removing power temporarily from all non-essential equipment in the Spun Bus, including the radio transmitter providing real-time spacecraft telemetry. Since the RPM was thermally coupled to the Spun Bus, it needed to be cooled as well. Power was diverted away from the RPM by powering on loads on the spacecraft's despun side. When pre-cooling was complete, the transmitter was turned back on and the spacecraft commanded to perform another, more extreme cooling turn. This, too, failed to release the stuck ribs.

4. Gaspra

On 29 October 1991 Galileo successful flew by Gaspra, collecting the first high-resolution images of an asteroid.[1] Like Venus and Earth flybys, heaters on calibration targets and remote sensing instruments were unavailable for RPM temperature management, so extra power flowed into the RPM shunt heaters. The flyby's short duration kept RPM temperature and pressure changes small.

Warming / cooling turns resumed after Gaspra. Without a functional HGA, Gaspra data was recorded on Galileo's Data Management System (DMS) -- a reel-to-reel tape recorder like ones on Voyagers 1 and 2 -- to be trickled to

Earth over the primary LGA. Post-flyby, only 10 bps downlink was supportable; DMS playback was delayed until May 1992 when Galileo's signal strength could support a 40 bps downlink. This activity provided another challenge for managing propellant temperatures and pressures.

To minimize even the small risk of undervoltage during playback, the sequence was designed with 40 watts power margin. The previous cooling turn had ratcheted down the lock-up temperature to 11 degrees C – the lowest level of the mission until that time. Even so, temperature / pressure models predicted oxidizer pressures would remain below 18.5 bar during playback. Instead, they equilibrated at 18.6 bar – above the Project's limit for thruster safety.

To lower pressures, commands were sent to reduce power margin significantly – ultimately sending it to less than 20 watts. This was sustained for the duration of playback without incident. In August, TCM-14 repressurized the propellant tanks at a temperature that enabled higher power margins for Galileo's successful Earth-2 flyby on 8 December 1992. RPM pressures / temperatures followed their usual encounter profile.

D. Earth-Jupiter Cruise

Power margins were adjusted to precondition the propellant tanks for the Ida Encounter on 28 August 1993. TCM-22 two months later, and observations of Comet Shoemaker-Levy 9's impacts of Jupiter in July 1994. Prior to reaching the vicinity of Jupiter, propellant temperatures and pressures behaved nominally.

E. Operations Around JOI

1. Probe Release and Orbit Deflection Maneuver (ODM)

On 13 July 1995, Probe Release exposed much of Galileo's Despun Section to space for the first time. This new thermal balance changed operating constraints on Despun heaters, with impacts to RPM temperature management.

Two weeks later, the ODM successfully performed a mission-critical trajectory change and demonstrated nominal 400-N engine performance in preparation for JOI. Based on conditions at ODM start, analysis predicted that propellant consumption would only open the fuel check valve. Instead, fuel and oxidizer check valves opened. Telemetry suggested that oxidizer check valve may have reseated only partially; unfortunately drift of the pressure transducers delayed this determination. Propellant pressures crept higher as leakage through one check valve kept pressurant flowing through the regulator and into all tanks (see Figure 10).

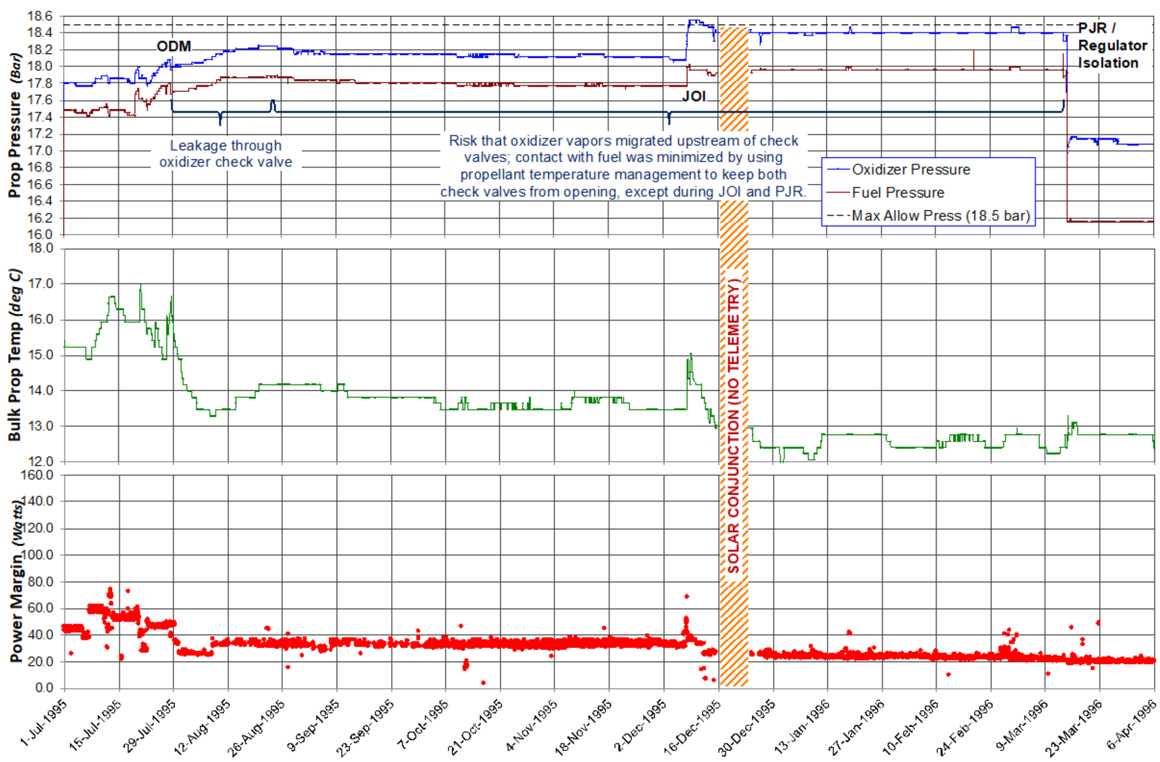

Figure 10. Propellant Pressures, Bulk Temperature, and Power Margin *(Probe Release to PeriJove Raise Maneuver)*

2. Check-Valve Leak

Operators watched tensely to see if the check valve would seal completely. Meanwhile oxidizer pressure slowly climbed. If the regulator stopped flowing gas while the check valves remained open, propellant vapors might mix -- a risky scenario.

Ultimately, both check valves reseated. Unfortunately, the regulator's repressurization temperature had shifted upward. To keep check valves from opening prior to JOI, average power margins had to remain nearly constant.

This posed a very serious impact to Jupiter approach activities. Remote sensing instruments were about to begin observations of the planet. Per plan, turning off decontamination heater would have raised power margin. Had check valve operation been nominal, propellant pressures were predicted to remain below 18.5 bar. Now, to keep within this limit, power margin needed lowering using loads that would not interfere with remote sensing. Few suitable heaters met this criteria, so the OET began searching for alternatives.

3. DMS Anomaly

While operators evaluated heater options, Galileo began collecting its first Jupiter approach images. While doing so, the DMS's magnetic tape stopped unexpectedly. A switch, designed to detect when the tape reaches the end of a track, should have triggered automatic transfer of the tape head onto the next track and reversed tape direction. Instead, DMS motors stalled trying to move the tape past its stop. Real-time commands were sent to pause the motors.[14]

Later, in-flight testing demonstrated that the DMS was operable at its lowest tape speed -- one sufficient to store data received from the Galileo Probe as it descended through Jupiter's atmosphere. There was little time for more tests. From the information available, there was a risk that higher speeds to collect faster data (remote sensing data, for example) might jam the tape again before Probe data could be collected. By limiting DMS to its lower speed, Galileo would miss close observations of Io -- the only opportunity planned for the nominal mission.[14]

Probe data was the Project's highest priority. The DMS would be operated only at its lowest speed until the Probe data could be sent to Earth post-JOI; until then, remote sensing activities were cancelled. Later, ground operators would test the tape recorder at higher speeds, but commanding it to stop and change tracks rather than relying on a mechanical switch. In the future, perhaps, an extended mission might enable another Io flyby.

Meanwhile, remote sensing instruments were powered off. This engineer had the sad duty of selecting heaters to adjust power margin due to the lack of remote sensing activities.

4. Relay / JOI

On 7 December 1995, Galileo flew by Io, but took no images. Galileo's Probe entered Jupiter's atmosphere and transmitted its science data; overhead, the Orbiter received and stored the data without incident. Upon completing its 49-minute JOI burn, Galileo became a satellite of Jupiter.[11]

5. Peri-Jove Raise Maneuver (PJR)

Check valve leakage remained a concern through PJR -- the final 400-N engine burn of the mission. After its successful execution on 14 March 1996, commands were sent to isolate the prime regulator.[11] Thereafter, the RPM would be operated in blow-down mode, using only pressurant already in the propellant tanks. Thanks to the large ullage volumes post-PJR, propellant pressures would remain above minimum operational levels for the 10-N thrusters. As an added benefit, isolating the regulator precluded thermal ratcheting.

F. Orbital Science Operations

With the regulator isolated, propellant pressures could not reach 18.5 bar with the power margin available. It was now safe to discontinue power management for propellant temperature and pressure control.

Meanwhile, tests of the DMS showed it could be operated at all tape speeds provided track changes were manually commanded without depending on end-of-track switches.[15] Remote sensing science resumed and provided many discoveries.

Through Galileo's 14 years of flight operations, comprising one prime and two extended missions, its 10-N thrusters operated failure-free. It is impossible to know the relative contributions to this success from propellant temperature / pressure management versus other protective measures, like firing the thrusters only in pulse-mode and imposing cool-down times between pulse strings. Galileo flight operations applied them all and the mission succeeded.

IX. Lessons*

The detail and variety of subtopics in this paper illustrates key lessons from Galileo's use of power margin to control propellant temperatures and pressures. Closely coupling key subsystems can affect many aspects of operation.

---

* On this topic, a very short lesson may be found in the NASA Public Lesson Learned online database as "Galileo Retro Propulsion Module and Pyro Power Subsystem Interaction, URL: http://llis.nasa.gov/lesson/364.

In Galileo's case, most spacecraft subsystems depend on electrical power and trajectories depend on propulsion. When technical obstacles developed, resolving them required consensus among many affected parties. Table 2 illustrates how daunting it could be to lower propellant temperatures and pressures by just "turning on a heater".

That said, interdependencies may offer unforeseen benefits. When, post-Challenger, the mission required Galileo to fly much closer to the sun, RPM temperatures could be controlled with the existing power/thermal/propulsion interface rather than extensively redesigning the central bodies temperature control. When a check valve began leaking during Jupiter approach, power margin adjustments successfully controlled pressures for the critical JOI burn.

There is no simple answer to avoiding the sort of operational complexities described in this paper. Bold interplanetary missions call for tightly integrated spacecraft to meet mission demands. Designs will evolve based on the experience of prior missions. To this end, Galileo applied an innovative design and made it work – albeit with unforeseen difficulties. Examining this history may help future missions avoid surprises from tightly integrated spacecraft designs.

The author offers these guidelines:

- When introducing interdependencies into a spacecraft design, closely regard operational consequences. Time pressures can encourage design solutions that address the problem at hand, but leave flight operations to be resolved later. Design teams should make operational impacts a priority for evaluating hardware design options.
- Use operational issues to derive hardware requirements with margin added to cover surprises. If a hardware design imposes an operational constraint, be sure there are hardware requirements to show limits to what mission operations can support. They may prompt a design trade to be reopened once new information is available.
- When in doubt, favor design solutions that impose fewer requirements on mission operations but still enable ground intervention for spacecraft anomalies.
- Seek developers with operational experience and operators with development experience. Cross-training benefits all sides.

Exploring Deep Space requires many partnerships. By coupling thermal control of its propulsion system with the spacecraft's power bus, Galileo demanded an unusual degree of cooperation among many teams, covering many disciplines, that were responsible for its operation. For the spacecraft to work properly, many people had to work together closely. There were many struggles. Surprises in flight, like failure to deploy Galileo's HGA, forced some difficult adjustments on the ground. In the end, teamwork prevailed and brought Galileo's mission many successes.

The author is proud to have played a part.

X. Acknowledgments

The following members of Galileo's Orbiter Engineering Team provided technical review of this paper — Todd Barber (propulsion), Jerry Millard (temperature control), and Barry Rein (spacecraft power). For the data used for pressure, temperature, and power diagrams Gary Smith provided CDs of Galileo telemetry while Cindy Lush, Jaime Cabrera, Kelly Clarke, and Betsy Wilson all helped convert the raw data into engineering units; JPL's Europa Project provided funds for this data processing. Danielle Medina helped me retrieve daily OET Spacecraft Reports from JPL Archival Storage; these logs helped fill in data missing from the telemetry CDs.

The RPM's success owes much to the operations leadership of Fritz Krug (1956 – 2009) and technical support of Bernard Froidevaux (1944 – 1993), both of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V.). They helped sail a great ship to distant worlds.

This paper is dedicated to Dr. Claudia Alexander (1959 – 2015). Alexander was the last of Galileo's seven Project Managers as well as Project Scientist for NASA's role in the European Space Agency's Rosetta mission to Comet 67P/Churyumov-Gerasimenko. Her erudition, eloquence, and enthusiasm inspired us all.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1]Meltzner, M., "Mission to Jupiter: A History of the Galileo Project", NASA SP-2007-4231, 2007

[2]Jones, C.P.and Landano, M.R., "The Galileo Spacecraft System Design," AIAA Paper 93-0097, January 1983.

[3]Bennett, G.L., et al. "Mission of Daring: The General-Purpose Heat Source Radioisotope Thermoelectric Generator." 4th International Energy Conversion Engineering Conference and Exhibit (IECEC), San Diego, California, AIAA. Vol. 4096. 2006.

[4]Stultz, J.W. "Thermal Design of the Galileo Bus and Retropropulsion Module." Journal of Spacecraft and Rockets 28.2 (1991): 146-151.

[5]Barber, T.J., Krug, F.A., and Froidevaux, B.M., "Initial Galileo Propulsion System In-Flight Characterization," AIAA Paper 93-2117, June 1993.
[6]Killinger, R., and Bohnhoff, K.. "The Galileo Propulsion System: Mission History and Long Term Performance." European Spacecraft Propulsion Conference. Vol. 398. 1997.
[7]Greenfield, M., et al. "Thermal Design of the Galileo Spun and Despun Science." (1989).
[8]Galileo Project Document (PD) 625-270, Spacecraft Flight Rules and Constraints, Rev. B., 1987.
[9]Galileo Project Document (PD) 625-270, Spacecraft Flight Rules and Constraints, Rev. D., 1989.
[10]Galileo PD 625-505, Vol. III, OET TP-121, "Spaceflight Operating Plan - Engineering Team Procedures - RPM Tank Temperature Maintenance", 1989
[11]Barber, T.J.; Krug, F.A., and Renner, K.P., "Final Galileo Propulsion System In-Flight Characterization," AIAA Paper 97-2946, July 1997.
[12]Johnson, M.R., "The Galileo High Gain Antenna Deployment Anomaly", The 28th Aerospace Mechanisms Symposium, p 359-377 (see N94-33291 09-15); 1995
[13]Jansma, P. A. "Open! Open! Open! Galileo High Gain Antenna anomaly workarounds." Aerospace Conference, 2011 IEEE. IEEE, 2011.
[14]Johnson, M.R. and Levanas, G.C., "The Galileo Tape Recorder Rewind Operation Anomaly", 1997
[15]Landano, M. R. "Galileo Spacecraft Operations." The Three Galileos: The Man, the Spacecraft, the Telescope. Springer Netherlands, 1997. 145-157.