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Galileo High Gain Antenna Anomaly Workarounds

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Abstract—This paper\textsuperscript{1, 2} discusses the Galileo (GLL) High Gain Antenna (HGA) anomaly that occurred in the operations phase of the mission in April 1991. The spacecraft was scheduled to deploy its 4.8-meter-diameter (16-foot) high-gain antenna as Galileo moved away from the Sun and the risk of overheating ended. The antenna, however, failed to fully deploy. A special team performed extensive tests and determined that a few (probably three) of the antenna’s 18 ribs were in the closed position. Despite exhaustive efforts to free the ribs, the antenna would not fully deploy. From 1993 to 1996, extensive new flight and ground software was developed, and ground stations of NASA’s Deep Space Network were enhanced in order to perform the mission using the spacecraft’s low-gain antennas \textsuperscript{19}. This paper serves as a systems engineering case study that provides highlights of the GLL mission, overviews of the hardware, software, and aspects of the systems engineering and operations approaches. It then describes the approach to develop several workarounds to accomplish the GLL mission objectives despite the HGA anomaly.

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1. MISSION OVERVIEW

Jupiter is the giant of our solar system, 1400 times the volume of the Earth, and over half a billion kilometers (310 million miles) away. It is made mostly of light elements, principally hydrogen and helium. Its atmosphere and clouds are deep and dense, and a significant amount of energy is emitted from its interior. It has no solid surface. Its gases become hotter and denser with increasing depth. It is surrounded by a thin ring system made of dust-sized particles, has at least 16 moons, and its dense fluid core generates a powerful magnetic field -- the strongest planetary magnetic field known. The resulting region of its influence, called the magnetosphere, is a huge teardrop-shaped bubble in the solar wind pointing away from the Sun. The inner part of the magnetically-constrained charged-particle belt is doughnut-shaped, but farther out it flattens into a disk. The magnetic poles are offset and tilted relative to Jupiter’s axis of rotation, so the field appears to wobble around with Jupiter’s rotation (about every 10 hours), sweeping up and down across the inner satellites and making waves throughout the magnetosphere. The primary Galileo science objectives were to investigate three broad aspects of the Jovian system: the planet’s atmosphere, the satellites and the magnetosphere. A secondary mission objective was to fly by an asteroid as a target of opportunity.

Science Objectives

The science objectives for the Galileo Project were \textsuperscript{3}:

1. Atmospheres
   a. Determine the chemical composition of the atmosphere
   b. Determine the structure of the atmosphere to a pressure depth of at least 10 bars
   c. Determine the nature of the cloud particles and the location and structure of the cloud layers
   d. Investigate the circulation and dynamics of the atmosphere
   e. Investigate the upper atmosphere and ionosphere

2. Magnetospheres
   a. Characterize the absolute energy spectra, composition, and angular distribution of energetic charged particles as a function of position (to 150 Rj) and time,
   b. Characterize the vector magnetic fields as a function of position (to 150 Rj) and time
   c. Characterize the absolute energy spectra, composition, and angular distribution of plasma, including plasma wave phenomena, as a function of position (to 150 Rj) and time
   d. Investigate satellite-magnetosphere interactions

\textsuperscript{1} 978-1-4244-7351-9/11/$26.00 ©2011 IEEE.
\textsuperscript{2} IEEEAC paper #1045, Version 4, Updated January 11, 2011
3. **Satellites**  
   a. Characterize the geology, morphology, and physical state of the satellite surfaces  
   b. Investigate the surface mineralogy of the satellites, and determine the distribution of the compositional units  
   c. Determine the gravitational fields, magnetic fields, and dynamic properties of the satellites  
   d. Study the atmospheres and ionospheres, extended gas clouds arising from the satellites, and interactions with the magnetosphere.

4. **Asteroids**  
   a. Characterize global properties, including size, shape and mass  
   b. Characterize surface morphology  
   c. Characterize regolith properties  
   d. Conduct a study of the comparative processes on small bodies.

Highlights of the GLL mission are given in Table 1 below.

<table>
<thead>
<tr>
<th>Table 1 Galileo Mission Highlights</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission</strong></td>
</tr>
<tr>
<td>Life-Cycle Phase</td>
</tr>
<tr>
<td>Mission Type</td>
</tr>
<tr>
<td>Competed vs. Directed</td>
</tr>
<tr>
<td>JPL Role</td>
</tr>
</tbody>
</table>
| Partners/Contractors | Ames Research Center and Hughes Aircraft Company: atmospheric probe  
Germany: Spacecraft propulsion system, 2 science experiments |
| Primary Science Objectives | Investigate the structure, physical state, chemical composition, physical dynamics and interactions of Jupiter and its magnetosphere, rings and satellites |
| Cost | Development: $892 M  
Primary/Extended Mission Ops: $525 M for total of $1.417 B  
International Contrib.: + $110 M |
| Inception Launch | November 1977  
Oct. 18, 1989  
Dec. 15, 1997 - Jan. 1, 2000  
Jan. 1, 2000 - Sept. 21, 2003 |
| Interplanetary Cruise Prime Mission |  |
| Europa Mission |  |
| Millennium Mission |  |
| Launch Vehicle | Space Shuttle Atlantis and two-stage Inertial Upper Stage (IUS)  
Cape Canaveral Air Force Stn |
| Launch Site |  |
| Project Manager(s) | John Casani, Richard Sphalski, Bill O’Neil, Bob Mitchell, Jim |
| Probe Manager(s) | Erikson, Eileen Theilig, and Claudia Alexander  
Joel Sperans, Benny Chinn and Marcie Smith |
| GLL System Dev. Office Manager for S-Band Mission | James Marr IV |
| Project Scientist Probe Scientist | Torrence V. Johnson  
Richard E. Young |
| Galileo Mission Director, Galileo Deputy Mission Director & Flight System SE | Neal E. Ausman, Jr.  
Matt Landano |
| Hardware | Spacecraft, Atmospheric probe |
Magnetometer (MAG)  
Dust Detector Subsystem (DDS)  
Energetic Particles Detector (EPD)  
Plasma Subsystem (PLS)  
Photopolarimeter-Radiometer (PPR)  
Plasma Wave Subsystem (PWS)  
Spectrometers: Near Infrared Mapping Spectrometer (NIMS)  
Extreme Ultraviolet Spectrometer (UVS)  
Spectrometer (EUV)  
Heavy Ion Counter (HIC)  
Radio Science |
| Probe Instruments | Atmospheric Structure Instrument (ASI)  
Neutral Mass Spectrometer (NMS)  
Neutral Helium Spectrometer (NEP)  
Lightning and Radio Emissions Detector (LRD)  
Energetic Particles Instrument (EPI)  
Helium Abundance Detector (HAD)  
Net Flux Radiometer (NFR)  
Doppler Wind Experiment (DWE) |
| GLL Website | http://www2.jpl.nasa.gov/galileo/indexold.html |

**Programmatic, Technical and Engineering Challenges**

After the start of the Galileo Project, there followed what has been described as a twisted tale of politics, technology, and science. Launch was to be in January 1982 with arrival at Jupiter in 1985. The Space Transportation System (STS), called the space shuttle, had been approved for development in 1972, and it was chosen as the (only) launch platform for Galileo. Galileo thus became the first deep-space mission to use the shuttle. The space shuttle fell behind schedule with many technical and programmatic issues. The choice of the Galileo upper stage flip-flopped several times between the Inertial (Interim) Upper Stage (IUS) and the more powerful Centaur. The launch date slipped from 1982 to 1984 to 1985 and finally firmed on May 20, 1986, with the use of the Centaur G upper stage providing a flight time to Jupiter of about two and one-half years. In December 1985, damaged...
memory chips were discovered in the finished spacecraft, and a maximum effort had the spacecraft ready again in early 1986, with delivery to the launch site shortly thereafter [15].

On January 28, 1986, the Challenger space shuttle disaster occurred. The NASA Space Shuttle Program was suspended, the Galileo May 20, 1986, launch date was cancelled, and Galileo was trapped in the delay of the shuttle reevaluation process. Also, as fallout of the Challenger disaster, it was determined for safety reasons that a liquid fuel upper stage would not be used in future shuttle operations. The Galileo upper stage once more became the less powerful two-stage IUS, however, this made it impossible for the spacecraft to fly directly to Jupiter. To save the project, Galileo engineers designed a new and remarkable interplanetary flight path using three planetary gravity assists (one at Venus and two at Earth). However, the trajectory, which became known as the Venus-Earth-Earth Gravity Assist (VEEGA), required a flyby of Venus and a close approach to the Sun resulting in a thermal environment for which the spacecraft had not been designed. Hence, additional shielding of the spacecraft was required. Also, the VEEGA trajectory resulted in an increase of Galileo flight time to Jupiter from two to one-half years to six years as shown in Figure 1. The launch date again slipped more than three years to October 18, 1989, with arrival at Jupiter scheduled for December 1995, some 18 years after the beginning of the project. As one of the Project leaders has said, "One of the more unique aspects of Galileo has been its very rocky history." James Van Allen has referred to the Galileo Project as "the perils of Pauline."

Galileo's primary mission at Jupiter began when the spacecraft entered into orbit around Jupiter in December 1995, and its descent probe, which had been released five months earlier, dove into the giant planet's atmosphere. The primary mission included a 23-month, 11-orbit tour of the Jovian system, including 10 close encounters of Jupiter's major natural satellites, or moons. Galileo traveled around Jupiter in elongated ovals – each orbit lasted about two months as shown in Figure 2. By traveling at different distances from Jupiter, Galileo could sample different parts of the planet's extensive magnetosphere. The orbits were designed for close-up flybys of Jupiter's largest moons. To keep track of Galileo's journey, each orbit was numbered, and named for the moon that the spacecraft encountered at closest range. During orbit "C-3" for example – the third orbit around Jupiter – Galileo flew near the moon Callisto.

Galileo was the first spacecraft ever to measure Jupiter's atmosphere directly with a descent probe, and the first to conduct long term observations of the Jovian system from orbit around Jupiter. It found evidence for subsurface liquid layers of saltwater on Europa, Ganymede and Callisto, and it documented extraordinary levels of volcanic activity on Io. During the interplanetary cruise, Galileo became the first spacecraft to fly by an asteroid and the first to discover the moon of an asteroid. It was also the only direct observer as fragments from the Shoemaker-Levy 9 comet slammed into Jupiter in July 1994 [16].

2. HARDWARE OVERVIEW

The Galileo hardware consists of the orbiter with 11 instruments and the atmospheric probe with 7 instruments. JPL managed, designed and built the orbiter. The probe was managed by NASA’s Ames Research Center (ARC), and
The GLL Telecom system enabled the orbiter to provide:

- Radio Frequency Subsystem (RFS)
- Modulation Demodulation Subsystem (MDS)
- Power Subsystem
- Telecommunications System

Orbiter

The Galileo orbiter, built at JPL, combined features of spinner spacecraft (e.g., the Pioneers and Ulysses) and three-axis stabilized spacecraft (e.g., the Voyagers). The orbiter was an innovative “dual-spin” design. Part of the orbiter (containing the antennas, fields and particles instruments, and some instrument booms) rotated at \( \sim 3 \) rpm in a controlled spin while another part (containing an instrument platform and remote sensing instruments) remained fixed in inertial space. This means that the orbiter was a good platform for fields and particles experiments; they perform best when rapidly gathering data from many different directions. The orbiter was also a good platform for remote sensing experiments that require very accurate and steady pointing. At launch, the orbiter weighed 2223 kilograms, including 118 kilograms of science instruments and 925 kilograms of usable rocket propellant. The overall length from the top of the low-gain antenna to the bottom of the probe measured 5.3 meters; the magnetometer boom extended 11 meters from the center of the spacecraft. See Figure 12 at the end of the paper for a diagram of the GLL spacecraft and instruments.

Power Subsystem

Galileo used two radioisotope thermoelectric generators (RTGs) to supply electrical power to run the spacecraft’s devices. The radioactive decay of plutonium produces heat that is converted to electricity. The RTGs produced about 570 watts at launch. The power output decreased at the rate of 0.6 watts per month and was 493 watts when Galileo arrived at Jupiter. Unlike other power sources, RTGs are insensitive to the freezing cold of space, and are virtually invulnerable to high radiation fields.

Telecommunications System

The GLL Telecom System was on the spin section of the orbiter. The system consisted of four hardware subsystems:

1. Radio frequency subsystem (RFS)
2. Modulation demodulation subsystem (MDS)
3. S-/X-band antenna (SXAS) subsystem
4. X- to S-band downconverter (XSDC).

The GLL Telecom system enabled the orbiter to provide:

- a) uplink carrier tracking and downlink carrier generation,
- b) command detection,
- c) telemetry encoding and modulation, and
d) radiometric communications with the DSN.

Radio Frequency Subsystem: The GLL RFS had the following major components [14]:

- 2 S-band receivers (S-RCVR)
- 2 S-band exciters (S-EXC)

Modulation Demodulation Subsystem: The GLL MDS consisted of two Telemetry Modulation Units (TMUs) and two Command Detector Units (CDUs), with one CDU and one TMU powered at a time. The CDU was responsible for the detection (demodulation) of uplink command data for decoding by the CDS, and the TMU was responsible for the modulation of telemetry data for down-link transmission. Because of the critical functions performed by the CDU and TMU, each had a large amount of hardware redundancy and cross-strapping with the interfacing RFS elements.

S-/X-band Antenna Subsystem: The GLL SXA consisted of one high gain antenna (HGA) and two low gain antennas (LGAs). The two LGAs worked at S-band only. The HGA was designed to work at S-band and X-band.

The GLL HGA was largely inherited from an antenna developed for Earth orbital missions for the Tracking Data Relay Satellite (TDRS) system. The surface of the antenna dish was constructed of a gold-plated molybdenum wire mesh stretched across 18 graphite-epoxy support ribs. The HGA’s reflecting dish was designed to unfurl in a parabolic shape which would focus the HGA’s energy into a tight beam directed toward Earth. Each graphite/epoxy rib had two titanium restraint pins. The titanium pins were finished with a ceramic anodized coating and then coated with a molybdenum disulfide dry lubricant. This material had been used successfully on many different spacecraft. The function of the restraint pins was to hold the antenna in a closed position while inside the Shuttle’s cargo bay and during parts of the VEEGA trajectory. JPL design changes to the antenna included substitution of two conical Inconel pin sockets with one conical and one V-groove Inconel socket. The HGA was capable of transmitting data at 134,000 bits per second (bps).

Because of the VEEGA trajectory, steps had to be taken to protect the GLL spacecraft and particularly the HGA from thermal damage. The HGA was kept folded up like an umbrella, and also had to stay pointed toward the Sun so that a sun shield mounted at its tip remained in the right position to keep the HGA shaded and cool. This also meant that the first LGA which was mounted near the feed of the HGA would be pointed away from the earth, so a second LGA was added [7]. The second LGA was mounted...
on one of the Radioisotope Thermoelectric Generator (RTG) booms, and when deployed, pointed in the aft direction. The LGAs communicated at only 10 bps [16].

**X- to S-band Downconverter:** The Galileo Project always considered the orbiter’s single XSDC as an experimental subsystem, meaning that use of an X-band uplink wasn’t essential for receiving commands or other critical mission functions [14].

**Command and Data Subsystem**

The Command and Data Subsystem (CDS) had several functions. First, it carried out instructions from the ground to operate the spacecraft and gather science data. Second, some portions of the CDS memory served as a storage place for science data. Third, the CDS packaged the data for transmission to Earth. The final crucial function of the CDS was fault protection activation. The CDS was alert for and responded to any problems with any of the spacecraft subsystems. Fault-protection algorithms made the spacecraft semi-autonomous and able to act quickly to protect itself. Commands sent from Earth could be in the form of real-time (do this now) commands or as a sequence, a set of instructions for operating the spacecraft. Sequences were carefully constructed (with input from many scientists and engineers) and thoroughly checked before being radioed to the spacecraft. On Galileo, a sequence could control spacecraft operations for a period of hours to several months, depending upon how busy the period was.

The CDS was originally designed to be dual string with three computers in each string as shown in Figure 3. Prior to launch a decision was made to double the amount of RAM in the CDS because of a late change in the type of RAM being used. Since there wasn’t much history on them or confidence that they would last for the duration of the 8 ½ year VEEGA mission, the amount of RAM was doubled for risk mitigation purposes. The extended memory was not accessible to any single CDS processor, but was instead distributed in the memory space of the six 1802 processors which comprised the dual string CDS or was available as a bulk memory device on the CDS data bus. The High Level Module controlled all bus transactions, and thus controlled movement of all data and commands between memories and processors [8].

**Science Instruments and Payload**

Galileo’s scientific instruments represented the most capable payload of experiments ever sent to another planet at the time. As mentioned earlier, the part of the orbiter that contained the antennas and some instrument booms rotated in a controlled spin while another part that contained an instrument platform remained fixed in inertial space. See Figure 4 for a simplified block diagram of the GLL Orbiter [8] and Table 2 for a summary of the orbiter instruments [16]. More details about the instruments are provided below [17].

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**Table 2 Summary of Orbiter Scientific Experiments**

<table>
<thead>
<tr>
<th>Orbiter Instruments</th>
<th>Object of Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid State Imaging Camera</td>
<td>Galilean satellites, high resolution, atmospheric small scale dynamics</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>Strength and fluctuations of magnetic fields</td>
</tr>
<tr>
<td>Dust Detector Subsystem</td>
<td>Mass, velocity, charge of particles smaller than a micrometer in size</td>
</tr>
<tr>
<td>Energetic Particles Detector</td>
<td>Electrons, protons, heavy ions in atmosphere</td>
</tr>
<tr>
<td>Photopolarimeter-Radiometer</td>
<td>Atmospheric particles, thermal/ reflected radiation</td>
</tr>
<tr>
<td>Plasma Subsystem</td>
<td>Composition, energy, distribution of ions</td>
</tr>
<tr>
<td>Plasma Wave Subsystem</td>
<td>Electromagnetic waves and wave-particle interactions</td>
</tr>
<tr>
<td>Near Infrared Mapping Spectrometer</td>
<td>Surface/atmospheric composition, thermal mapping</td>
</tr>
<tr>
<td>Ultraviolet Spectrometer, Extreme Ultraviolet Spectrometer</td>
<td>Atmospheric gases, aerosols</td>
</tr>
<tr>
<td>Heavy Ion Counter</td>
<td>Spacecraft’s charged-particle environment</td>
</tr>
<tr>
<td>Radio Science</td>
<td>Celestial Mechanics; masses and motions of bodies from spacecraft tracking; Propagation: size and atmospheric structure of Jupiter’s moons from radio propagation</td>
</tr>
</tbody>
</table>
Remote Sensing Instruments on Despun Platform

Solid State Imaging (SSI) Camera — The SSI was used to determine structure, motions, and radiative properties of the atmosphere of Jupiter. It measured wind profiles by tracking how fast clouds move at various altitudes. Radiative properties of the atmosphere, which are important for understanding energy management, were determined by measuring the scattering of light from specific features at various wavelengths and at various angles of illumination. The SSI was an 800- by 800-pixel solid-state camera consisting of an array of silicon sensors called a "charge-coupled device" (CCD).

Near Infrared Mapping Spectrometer (NIMS) — NIMS combined spectroscopy and imaging in one instrument. Since NIMS measured infrared radiation from the atmosphere of Jupiter, and contributed to compositional studies, the nature of clouds, motions, and energy balances. NIMS monitored ammonia, water vapor, phosphine, methane, and germane and looked for previously undetected molecules. The goal was to understand the major deep-seated circulation patterns that power the "near-surface" meteorology (planet-girdling cloudy zones, drier belts, and localized cyclonic storm systems such as the Great Red Spot).

Ultraviolet Spectrometer (UVS)/Extreme Ultraviolet Spectrometer (EUV) — The Galileo ultraviolet spectrometer investigation consisted of two instruments: the ultraviolet spectrometer and the extreme ultraviolet spectrometer. The UVS worked on the wavelengths just shorter than visible light, operating from 113 to 432 nanometers. The EUV/EUV studied properties of Jupiter’s atmosphere and aurora, the surfaces and atmospheres of the Galilean satellites, and the doughnut shaped cloud of ionized plasma in Io’s orbit. The UVS was mounted on the scan platform and could be pointed to an object in inertial space. The EUV was mounted on the spun section of the spacecraft. As Galileo was spinning, the EUV observed a narrow ribbon of space perpendicular to the spin axis.

Photopolarimeter-Radiometer (PPR) — The photopolarimeter/radiometer measured the intensity and polarization of sunlight, in the visible portion of the spectrum, that was reflected from—the Jovian satellites and Jupiter. The PPR was in many respects three instruments combined into one: a polarimeter, a photometer, and a radiometer. The polarimeter detected three spectral bands. The photometer used seven narrow spectral bands in the visible and near infrared wavelengths. The PPR had seven radiometry bands. One of these used no filters and observed all the radiation, both solar and thermal. Another band let only solar radiation through. The PPR also measured in five broadband channels that span the spectral range from 17 to 110 micrometers. The radiometer provided data on the temperatures of the Jovian satellites and Jupiter’s atmosphere.

Magnetometer (MAG) — A basic set of measurements for fields and particles science is the determination of the strength and direction of the magnetic field within the magnetosphere. The magnetometer used two sets of three sensors. The three sensors allowed the three orthogonal components of the magnetic field section to be measured. One set was located at the end of the magnetometer boom and, in that position, was about 11 meters from the spin axis of the spacecraft. The second set, designed to detect stronger fields, was 6.7 meters from the spin axis. The boom was used to remove the MAG from the immediate vicinity of the spacecraft to minimize magnetic effects from the spacecraft. The strength of a magnetic field was measured in units of “tesla.”

Dust Detector Subsystem (DDS) — “Dust” is a term used by astronomers to describe small grains of matter found not only in planetary systems but also in interstellar space, often mixed in with interstellar clouds of gas. The Dust Detector Subsystem (DDS) was used to measure the mass, electric charge, and velocity of incoming particles. The masses of dust particles that the DDS could detect went from $10^{-16}$ to $10^{-7}$ grams. The speed of these small particles could be measured over the range of 1 to 70 kilometers per second. The instrument could measure impact rates from 1 particle per 115 days to 100 particles per second. These particles help determine dust origin and dynamics within the magnetosphere.
Energetic Particles Detector (EPD) — The energetic particles detector was designed to measure the numbers and energies of ions and electrons whose energies exceed about 20 keV. The EPD could also measure the direction of travel of such particles and, in the case of ions, could determine their composition. The EPD used silicon solid-state detectors and a time-of-flight detector system to measure changes in the energetic particle population at Jupiter as a function of position and time.

Plasma Subsystem (PLS) — The plasma instrument measured the energies and directions of approach of ions and electrons comprising the plasma. PLS used a mass spectrometer to identify the composition of the ions. Information from PLS helped determine the temperature of the plasma and the manner in which the particles are distributed in space. This information in turn helped scientists understand particle dynamics in the magnetosphere. The PLS used seven fields of view (FOVs) to collect charged particles for energy and mass analysis. These FOVs covered most angles from 0 to 180 degrees, spanning the rotation of the spacecraft carried each FOV through a full circle.

Plasma Wave Subsystem (PWS) — Particles of plasma are bound to the magnetic field. Motions within the plasma can perturb the surrounding magnetic and electric fields. Changes with time of the electric and magnetic fields within plasma are called “plasma waves.” The Plasma Wave Subsystem was designed to measure the properties of varying electric fields over the frequency range from 5 hertz to 5.6 megahertz and of varying magnetic fields from 5 hertz to 160 kilohertz—and to identify the plasma waves present. An electric dipole antenna studied the electric fields of plasma, while two search coil magnetic antennas studied the magnetic fields. The electric dipole antenna was mounted at the tip of the magnetometer boom. The search coil magnetic antennas were mounted on the high-gain antenna feed.

Heavy Ion Counter (HIC) — The heavy ion counter experiment was originally included on the payload as an engineering experiment. It was to measure and monitor very high-energy heavy ions (such as the nuclei of oxygen atoms) hitting the spacecraft. These measurements would then provide basic information on a form of radiation that can cause random changes in a spacecraft’s electronics and perhaps provide the basis for the design of better radiation-resistant electronics for future missions. However, HIC data would be useful to scientists as well. For example, the heavy ions observed by the HIC during solar flares were analyzed to determine the composition of the Sun. The HIC detected heavy ions using stacks of single-crystal silicon wafers. The HIC could measure heavy ions with energies as low as 6 MeV and as high as 200 MeV per nucleon. This range includes all atomic substances between carbon and nickel.

Radio Science — There were two scientific experiments that used Galileo’s radio telecommunications system. The two categories of radio science done at Jupiter were celestial mechanics and radio propagation.

The celestial mechanics experiments used the radio system to sense small changes in the trajectory of the spacecraft. The spacecraft’s radio transmitter sent a signal at a well-known stable frequency. Any change in speed that the spacecraft experienced would cause the frequency of the radio signal received on Earth to change. The amount of change was dependent on the change in speed of the spacecraft, relative to Earth. Thus, by measuring the change in frequency of the Earth-received radio signal, the mass and internal structure of Jupiter or one of the Galilean satellites could be estimated.

The spacecraft radio signal was used to investigate Jupiter’s neutral atmosphere and ionosphere, Io’s ionosphere, and to search for ionospheres on the other Galilean satellites (Europa, Ganymede, and Callisto). This was done during radio occultation experiments, when the Galileo orbiter passed behind the planet or satellite as viewed from Earth. The radio signal propagating from the spacecraft to Earth experienced both refraction and scattering in the atmosphere of the occulting body. This caused changes in the frequency and amplitude of the signal received at a DSN tracking station on Earth. Analysis of these changes yielded information about the atmospheres and ionospheres of the Jovian system.

Probe

The probe consisted of two main parts, the deceleration module and the descent module. The deceleration module was required for the transition from the vacuum and cold of interplanetary space to the intense heat and structural loads to be incurred during a hypersonic entry into a planetary atmosphere — and from a speed of tens of kilometers per second to a relatively placid descent by parachute. The descent module carried the scientific instruments and supporting engineering subsystems that collected and transmitted priceless scientific data to the orbiter flying overhead. Figure 6 shows the descent of the Galileo probe into the Jovian atmosphere [17]. Table 3 summarizes the scientific experiments aboard the probe [18].

Atmospheric Structure Instrument (ASI) — The primary purpose of the atmospheric structure instrument was to determine how the temperature, pressure, and density of the atmosphere vary with altitude. The ASI was designed to take measurements from about 1000 kilometers above the clouds down to the end of the probe mission. The instrument package consisted of acceleration, temperature, and pressure sensors and associated electronics. The pressure sensor had a range from 0 to 500 kelvin. The pressure sensor was designed to cover a wide range of pressures from 0.1 to 28 bars. The third type of sensor in the
ASI, accelerometers, covered a wide range of measurements: from one millionth of a g to 400 g. Accelerations were sensed in three dimensions so that the total acceleration of the package was known. Acceleration data yielded information about the effect of atmospheric turbulence on the probe.

**Table 3 Galileo Descent Probe Scientific Experiments**

<table>
<thead>
<tr>
<th>Descent Probe Instrument</th>
<th>Object of Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric Structure Instrument</td>
<td>Temperature, pressure, density, molecular weight profiles</td>
</tr>
<tr>
<td>Neutral Mass Spectrometer</td>
<td>Chemical composition</td>
</tr>
<tr>
<td>Doppler Wind Experiment</td>
<td>Measure winds, learn their energy source</td>
</tr>
<tr>
<td>Net Flux Radiometer</td>
<td>Thermal/solar energy profiles</td>
</tr>
<tr>
<td>Helium Abundance Detector</td>
<td>Helim/hydrogen ratio</td>
</tr>
<tr>
<td>Energetic Particles Instrument</td>
<td>Energetic particles</td>
</tr>
<tr>
<td>Lightning and Radio Emissions Detector</td>
<td>Lightning detection</td>
</tr>
<tr>
<td>Helium Abundance Detector</td>
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<tr>
<td>Doppler Wind Experiment</td>
<td>Measure winds, learn their energy source</td>
</tr>
</tbody>
</table>

**Neutral Mass Spectrometer (NMS)** -- The neutral mass spectrometer was designed to provide a detailed analysis of the chemical composition of the atmosphere and aid in understanding the processes responsible for the complex, colorful clouds. The Galileo probe used a quadrupole mass spectrometer. In this device the ions were passed between four parallel rods. These rods had a combination of DC and AC voltages that allowed ions of a certain mass to pass through, while rejecting the rest. During descent, the voltages were adjusted to allow different masses to pass through.

**Helium Abundance Detector (HAD)** -- The atmosphere of Jupiter is composed primarily of hydrogen and helium. The HAD measured the abundance ratio of helium to hydrogen. The HAD measured the abundance ratio by determining the refractive index of the Jovian atmosphere over a range of pressures from 2.5 to 10 bars. The measurements were done using an optical interferometer.

**Lightning and Radio Emissions Detector (LRD)** -- The LRD searched for lightning during its descent through the atmosphere of Jupiter and also measured the radio-frequency noise spectrum of the atmosphere. In addition, the LRD made radio-frequency measurements as the probe approached Jupiter, at about 4, 3, 2, and 1 planetary radii. The LRD hardware consisted of three basic sensors. One sensor was a radio-frequency antenna that measured in the frequency range from 10 hertz to 100 kilohertz. The lightning sensors operated in the optical range. Two sensitive photodiodes were placed behind two fisheye lenses that looked out perpendicular to the spin axis of the probe, 180 degrees apart, to give full coverage.

**Energetic Particles Instrument (EPI)** -- The EPI experiment studied the inner portion of the magnetosphere (the region within 5 radii of the planet) and the outer reaches of the Jovian atmosphere. The objects of this study were four species of particles: electrons, protons, alpha particles, and heavy ions. The EPI made omnidirectional measurements of particles. Samples were taken at 5, 4, and 3 Jupiter radii, then continuously from 2 radii to entry of the atmosphere. The EPI could count up to as many as 3 million particles per second. The EPI’s silicon detectors were mounted at the end of a telescope tube.

**Nephelometer (NEP)** -- The nephelometer investigated the structure of clouds and the characteristics of particles in the atmosphere of Jupiter. The detailed scientific objectives of the NEP were tied to altitude, as measured by pressure, within the atmosphere. The NEP was designed to map cloud structures to a resolution of 1 kilometer from 0.1 to 10 bars. Also, the NEP measured the numbers and dimensions of particles and determined, by their shape, whether they were in the liquid or solid (ice) state. The NEP fired a laser beam from the probe through cloud particles adjacent to the probe. A reflector on an arm extended away from the probe reflected the scattered light back into the instrument detector.

**Net Flux Radiometer (NFR)** -- The net flux radiometer in the probe was designed to directly sample the local energy flows within and below the Jovian cloud layers. As the probe descended through various atmospheric layers, observable changes in the net radiation flux were anticipated. During the descent into a continuously hotter and denser atmosphere, the NFR rapidly alternated between looking upward and looking downward. Measuring the difference in radiation intensity between these two views would determine the amount and direction of the net flow of radiative energy. Radiation from the Jovian atmosphere entered the instrument through a diamond window. The NFR had six lithium tantalate pyroelectric detectors viewing through filters extending from the visible to infrared wavelengths.
Doppler Wind Experiment (DWE) -- The Doppler Wind Experiment measured the winds in the atmosphere of Jupiter by using the Doppler effect. As the probe was carried by winds during the descent, the frequency of its radio signal changed, indicating the probe’s velocity and providing data about the winds.

3. SOFTWARE OVERVIEW

Flight Software

GLL on-board flight software (FSW) consisted of guidance and control software (AACS), command and data handling software (CDS), payload interface, instrument control, onboard data processing, and a real-time operating system. The FSW also included fault protection sequences designed to automatically put Galileo in a safe state in case of computer glitches or other unforeseen circumstance. The original GLL FSW was developed for the 1986 launch and then updated for the 1989 launch and VEEGA trajectory with its sun-pointed cruise and trajectory correction maneuvers (TCMs). The 1989 “launch only” FSW did not include the JOI or Gaspra encounter capabilities [1].

The CDS code was written in structured assembly language with size of 15K non-comment source lines (NCSL), and the AACS code was written in HAL/S with code size of 7K NCSL [33]. Note that most of the GLL FSW was developed in the late 1980s and early 1990s before the current JPL institutional standards were developed, i.e., the JPL Software Development Requirements (SDR) [23] and the JPL Software Development Standard Processes (SDSPs) [24].

Ground Data System

The GLL Ground Data System (GDS) was made up of the GLL project-specific GDS (PGDS), the Multi-mission GDS (MGDS), and the Deep Space Network (DSN). GLL was originally designed to use the standard DSN configuration. The GDS software included uplink (command), downlink (telemetry), tracking, DSN Monitor & Control, data acquisition, tracking & navigation. The MGDS software included mission planning, DSN scheduling, sequence design and science data distribution.

Note that both the flight and ground software were modified extensively in response to the HGA anomaly and these modifications are discussed in detail in Section 6.

4. SE APPROACH AND PRACTICES

Systems Engineering Management Plan (SEMP)

There was no formal Galileo SEMP delineating the GLL SE approach, but many aspects were defined in various other project documents such as the GLL Project Implementation Plan, GLL LGA Mission Project Development Plan, GLL Spacecraft Test Plan, GLL Test Procedures, GLL Software Management Plan, etc. The SE Team produced the System Design as well as the GLL CMD/TLM Dictionary. Note that GLL was developed before the current JPL institutional and SE standards [20], [21], [28] were developed.

Also, a number of teams were put in place to provide valuable insight, coordination and evaluation of tradeoffs. The GLL teams included the GLL Flight Team, GLL Ops Team, GLL Science Team, and GLL Engineering Team. In addition, there were several Tiger Teams such as the GLL HGA Anomaly Resolution Team, the GLL LGA Mission Study Team, the GLL DMS (Tape Recorder) Tiger Team, etc. There was also a DSN Implementation Task Team. A key factor in the success of the GLL mission was the cooperative and collaborative interactions of these teams in the face of daunting problems. Since there was no Project Systems Engineer “in those days”, the Deputy Mission Director and GLL Flight System SE played a key role in system coordination.

Architecture

The Galileo spacecraft was characterized by its highly integrated design. Its diverse subsystems, developed by different project teams, needed to interface flawlessly with each other over many years. Subsystem dependencies needed to be fully understood and controlled because the environment experienced by a typical subsystem was strongly affected by the behavior of other connected subsystems. For example, the limited electric power that was available aboard GLL had to be shared by temperature control and many other spacecraft systems in a manner that minimized energy use. Large temperature swings inside the spacecraft could result from this situation, and this placed stringent design requirements on the subsystems that had to withstand those swings. [11] As noted in Sec. 2, the GLL spacecraft had three segments: the atmospheric probe, the spun section for fields and particles instruments, and the nonspinning or “despun” section for remote sensing instruments such as cameras and spectrometers.

After the HGA anomaly, the majority of the GLL system design/architecture changes were completed during the contingency studies (before the project gave up on freeing the HGA). What was implemented was essentially what came out of those studies. Note that working with the GLL science team throughout the study process was essential to achieving a design that could actually be implemented. The CDS Software Lead did a remarkable job of working with the individual Principal Investigators to define what would be possible for each instrument and to help them stick with the agreements made.

Verification and Validation (V&V)

The GLL Project developed a very thorough approach to testing, defined in the GLL Spacecraft Test Plan and GLL Test Procedures, and the GLL GDS Integration and Test
Plan. These tests spanned the range from unit testing, to subsystem testing, integration testing and system testing. Types of tests included functional tests, timing tests, fault protection tests, sequence tests, and regression tests. In addition, there was extensive testing of the in-flight FSW loading process that involved "ground in the loop" verification. GLL had a very high fidelity flight system testbed (FST) and Minimum Capability Hybrid Simulator (MCHS) for use throughout the testing process. Considerable regression testing was done for each new capability added.

Three special tools were developed to aid in the development of the GLL Phase 2 capabilities: an end-to-end model, a ten-times real-time CDS bit-level simulator, and specialized support equipment needed to provide CDS test capability. [8]

1. An end-to-end model was developed using the commercial modeling tool SES Workbench. This tool modeled both the spacecraft processes from instruments to downlink telemetry and the ground system out to the Project Database (the received data archive). This module executed real spacecraft sequences and provided a variety of outputs to evaluate the performance of all elements of the system under both normal and simulated fault (including data dropout) conditions. Using this tool to simulate a modified orbit sequence developed for the C3 orbit, designers were able to make tradeoffs and to look for surprises in the operation of the system.

2. The ten-times real-time bit-level simulator, known as FASTSIM, was developed to allow CDS software developers to have a platform for troubleshooting their code. This tool was required in order to off-load the spacecraft Test Bed and the Minimum Capability Hybrid Simulator (MCHS) systems which were heavily used for normal spacecraft operations.

3. Existing GLL Test Bed and MCHS capabilities were expanded to allow testing of the new Phase 2 capabilities. New equipment was developed to simulate science instrument outputs and to evaluate CDS editing, compression, packetizing, VCDU & R-S encoded Frame building, and software convolutional encoding. This equipment generated predicts for the CDS processed data and was used in to compare the data which left the CDS.

Risk Management

Risk management on GLL was always done through operational options and capability descopes. Operationally, if the probe data wasn't fully returned by the time Phase 2 software was to be loaded for the first encounter, then the Phase 2 software load would be delayed to enable completing the Probe data playback. Phase 2 software had a list of descope options with capabilities that could be descoped if needed; however, none were ever taken.

Resource and Margin Management

Resource and margin management was accomplished by each of the development leads. This was much simpler than usual since there was no requirements creep during the recovery implementation. The plan was, however, to pack as much capability as the system would allow, utilizing both strings of the CDS as a single string system (except for Fault Protection, which remained dual string).

5. Problem Description

On April 11, 1991, after Galileo had completed the Venus flyby and was outside 1.0 AU, far enough from the heat of the Sun, the spacecraft executed stored computer commands designed to unfurl the large high-gain antenna. But telemetry received minutes later at JPL showed that something went wrong. The motors designed to open the HGA obeyed the commands and turned on, but they operated at higher-than-expected power levels for nearly eight full minutes, as if they were laboring to open the antenna. The motors were supposed to turn a worm gear, which in turn was supposed to push a ring up the axis of the antenna. This ring was connected to levers that were to open the antenna by spreading its ribs. The team expected a signal from GLL confirming that the antenna had opened, but the signal never came [11].

That same day, an HGA deployment anomaly team of more than 100 technical experts from JPL and industry was formed, consisting of mechanical, electrical, thermal, materials design, reliability, and flight operations specialists, as well as personnel from Harris Corp. which had built the HGA. In a crash effort over the next several weeks, the team analyzed Galileo's telemetry and conducted ground testing with an identical spare antenna, noting the following:

1. Output from one of the GLL Sun Gate Sensors, as shown in Figure 7, was reduced at certain "clock angles". The clock angle measured angular position on the spacecraft, with the origin at the craft’s rotational axis.
2. The spacecraft spin detector output spiked 8 seconds after the HGA deployment attempt, indicating a sudden acceleration and deceleration of the spacecraft spin rate.
3. The spacecraft spin rate further decreased over the remainder of the deployment attempt.
4. Electric current data from the two motors designed to open the HGA indicated that they stalled 56 seconds after the start of the deployment sequence.
5. The wobble of the spacecraft had increased. [11]

They deduced that the problem was due to the sticking of a few antenna ribs to the control tower, most likely caused by friction between their standoff pins and sockets. The excessive friction between the pins and sockets has since been attributed to etching of the surfaces that occurred after the loss of a dry lubricant that had been bonded to the
standoff pins during the antenna's manufacture in Florida. The antenna was originally shipped to JPL in Pasadena, CA, by truck in its own special shipping container. In December 1985, the antenna, again in its own shipping container, was sent by truck to NASA's Kennedy Space Center (KSC) in Florida to await launch. After Challenger, Galileo and its antenna had to be shipped back to JPL in late 1986. Finally, they were reshipped to KSC for integration and launch in 1989. Some believe the loss of lubricant occurred due to the vibration that the antenna experienced during those cross-country truck trips. Preloading of the ribs when the antenna was stowed at the factory damaged the ceramic coating on the pin engaged by the V-groove socket; the coating served to retain the molybdenum disulfide dry lubricant. Accumulated stresses from vibration testing, rib preloading, four cross-country trips, and the post-launch ignition of the upper stage further dispersed the lubricant film. The resulting friction caused asymmetrical deployment, resulting in restraining forces which further reduced the torque available from the deployment drive system. Extensive analysis has shown that, in any case, the problem existed at launch and went undetected; it was not related to sending the spacecraft on the VEEGA trajectory or the resulting delay in antenna deployment [18].

![SG RAW DATA PRIOR TO DDA ON ACTIVITY](image)

**Figure 7 GLL sun gate sensor data indicating stuck ribs**

Galileo illustrates the difficulty of reproducing the spaceflight environment in the ground test of large and complex mechanisms, even when full design review and environmental testing are undertaken. Flight antenna deployment test failed to disclose the problem because (1) vacuum test was performed without the vibration-induced relative motion between the pins and sockets and (2) oxides and contaminants present during ground test on the bare titanium pins lubricated the mechanism. Similarly, ambient ground tests did not reveal the failure mode due to the lower coefficient of friction of the titanium pin/socket interface in air. Additional testing of the deployment mechanism would only have worn out the deployment drive system [6].

The selection of an Earth orbital antenna design for Galileo, even though proven in that application, was not fully consistent with the Galileo mission. Inheritance and other design reviews failed to reveal the existence of high surface stresses. In addition, a lessons learned on Voyager II to use spring assisted mechanical deployments was not followed. The GLL deep space mission subjected the redesigned antenna to environmental conditions not encountered by TDRS in Earth orbit, and the VEEGA mission profile instituted after Challenger extended both the duration of those conditions and the time to deployment [6]. An important lesson learned is that design changes intended to improve the reliability of inherited hardware may introduce new failure mechanisms. The mission impact of such design changes may best be understood through a "physics of failure" approach to reliability analysis. Failure physics issues relevant to antenna support bearings, for example, may include oxidation, cold welding, galling, static and sliding friction, lubrication transfer, Hertzian contact stresses, and plastic deformation, as well as operational issues such as long-term storage, ground handling, the mission environment, and mission duration [6].

**Attempts to Free the Antenna**

While diagnosis of the problem continued, the Galileo team sent a variety of commands intended to free the antenna. Most involved turning the spacecraft sideways and away from the Sun, in the hope that warming and cooling the apparatus would free the stuck hardware through thermal expansion and contraction. None of these attempts succeeded in releasing the ribs. Further engineering analysis and testing suggested that "hammering" the antenna deployment motors -- turning them on and off repeatedly -- would increase the torque from the motors by a factor of two and would deliver the force needed to free the stuck pins and open the antenna. After more than 13,000 hammerings between December 1992 and January 1993, engineering telemetry from the spacecraft showed that additional deployment force had been generated, but it had not freed the ribs. Other approaches were tried, such as spinning the spacecraft up to its fastest rotation rate of 10 rpm and hammering the motors again, but these efforts also failed to free the antenna. Note that the Galileo engineers working on the antenna anomaly were guided by two basic principles:

1. The health and safety of the spacecraft must be safeguarded.
2. Nothing shall be done that may seriously threaten Probe Relay, Jupiter Orbit Insertion (JOI), or the Orbital Tour.

Project engineers believe the state of the antenna has been as well-defined as long-distance telemetry and laboratory tests will allow. After the years-long campaign to try to free
the stuck hardware, the project determined that there was no longer any significant prospect of the antenna ever being deployed. Laboratory tests verified that holding ribs 9, 10, and 11 in the stowed position, as shown in Figure 8, most nearly modeled the spacecraft telemetry.

Nevertheless, one last attempt was made in March 1996, after the orbiter's main engine was fired to raise Galileo's orbit around Jupiter. This "perijove raise maneuver" delivered the largest acceleration the spacecraft had experienced since launch, and it followed three other mildly jarring events: the release of the atmospheric probe, the orbiter deflection maneuver that followed probe release, and the Jupiter orbit insertion engine firing [18]. All these efforts were to no avail, however.

Without further remedies, the planned downlink data rate from Jupiter of over 100,000 bps would be reduced to about 10 bits per second using the spacecraft low-gain antenna at S-band. If left unmitigated, such a four-orders-of-magnitude decrease in data return would be disastrous for the scientific goals of the mission.

6. RECOVERY APPROACH

From 1993 to 1996, extensive new flight and ground software was developed, and ground stations of NASA's Deep Space Network (DSN) were enhanced in order to perform the mission using the spacecraft's LGAs.

Not long after the initial failure of the high-gain antenna, the DSN Advanced Systems Program, against the possibility that the problem could not be solved, reviewed the reservoir of its advanced technologies to see what might be applied to materially increase the 10 bps provided by the spacecraft S-band low-gain antenna. This reservoir of advanced technologies included not only devices, but also the outstanding people who had developed the technology over an extended period. Four of the advanced technology areas had evident promise, as follows [15]:

1. **Increase the S-band signal-to-noise ratio** of the DSN S-band antennas; that is, increase $A_e/T_{op}$ where $A_e$ is the effective area of the antenna(s) and $T_{op}$ is the operating noise temperature of the antenna/receiver system. $A_e$ can be increased by antenna arraying, and $T_{op}$ can be decreased with ultralow noise amplifiers and feeds.

2. **Improve the efficiency of the modulation of the radio signal**, such as with a suppressed carrier. The new Block V Receiver (BVR) has fully suppressed carrier capability.

3. **Use improved channel codes** so that the desired bit-error probability requires less energy per bit; that is, reduce $E_b/N_0$. New high-performance concatenated codes and hardware have been designed and tested.

4. **Aggressively apply data compression techniques** to the various science, engineering, and optical navigation data from the spacecraft to Earth to provide an increase in the effective data rate. This required reduced bit-error probabilities for the compressed data, which also could be provided by the improved codes of (3).

It was estimated that the combination of areas (1), (2), and (3) above would increase the 10-bps data rate by an order of magnitude, and the application of (4) would provide at least another order-of-magnitude increase. The resulting equivalent data rate of at least 1000 bps, coupled with careful editing and choice of science and other data, could provide a viable mission fulfilling much of the original Galileo science objectives. [15]

However, it is one thing to discuss technology capabilities and quite another to move the technology into a constrained engineering application in a relatively short time. The improvements of (1) and (2) would involve mainly DSN systems with little interaction with the spacecraft. However, the improvements of (3) and (4) would strongly interact with the spacecraft, requiring reprogramming and reallocating of spacecraft computer resources within the constraints of spacecraft operability and safety. Also, the compression of science data would extensively involve science team members in evaluating and choosing data compression algorithms. An early report was conducted in November 1991 [17] primarily by ground systems people with small participation from Galileo engineers and science team members, who were busy with the high-gain antenna problem, the Gaspra encounter, etc. [15]

With the positive results of the TDA Technology Development early report [4] and the probability of repairing the high-gain antenna fading, a major Galileo S-band Mission study was jointly chartered by TDA and the Flight Projects Office (FPO), with the report issued on March 2, 1992 [5]. The study was divided into four...
subtasks: science/mission design; telecommunication systems; ground systems; and spacecraft systems. The basic conclusion of this more detailed study was that by using the technology identified in the initial report, a viable Galileo S-band Low Gain Antenna Mission would be feasible. A design was provided that would meet a somewhat reduced, but very palatable, set of science objectives. [15]

On January 7, 1993, the Galileo S-band LGA Mission was formally approved and funded. Some details of the technologies used in this rescue follow [15].

1. **Antenna Arraying and Noise Temperature Reduction.**
   The antenna-arraying capability developed by the Advanced Systems Program was made available for up to six antennas — the 70-m and three 34-m antennas at Canberra, the 64-m antenna at Parkes, and the 70-m antenna at Goldstone. This increased the effective area, $A_e$, for Galileo signal reception to the sum of the effective areas of the antennas, which could exceed that of three 70-m antennas. See Figure 9 to see how the high data rate profile was improved by the arraying.

   The antenna that could make the greatest contribution from reduction in operating noise temperature was the 70-m antenna at Canberra. Its southern hemisphere location gives it more time at higher elevation (less atmosphere noise contribution) when tracking Galileo, and none of the other antennas has a higher $A_e$. When arraying antennas, the contribution to the overall array signal-to-noise ratio is greatest by the antenna with the greatest $A_e/T_{op}$. Accordingly, the Canberra 70-m antenna was equipped with the receive-only "ultracone" feed and low-noise amplifier that previously had been developed. It provided a receive-only very low $T_{op}$ of 11.8 K, compared to a receive-only $T_{op}$ of 15.6 K provided by the regular operational system [15].

2. **Improved Modulation Efficiency.**
   Once the Block V Receiver (BVR) was available with its capability of tracking and processing fully suppressed carrier signals, the increase in modulation efficiency was essentially without cost. It was only necessary to program the spacecraft transmitter for an appropriate increase in phase modulation to obtain the increased efficiency. An increase of modulation index from 43 deg to 90 deg (fully suppressed carrier) approximately doubled the available data power. The BVR was based on the prototype Advanced Receiver (ARX) developed by the Advanced Systems Program over the better part of a decade. This prototype utilized flexible digital implementation of carrier, subcarrier, and symbol tracking loops, which allowed very narrow loop bandwidth. A Costas loop allowed recovery and tracking of a fully suppressed carrier [15].

3. **Channel Coding.**
   The built-in channel coding available to the Galileo S-band transmitter was a hardware $(7,1/2)$ convolutional code, primitive by today's standards—particularly for highly compressed data. By programming a software $(11,1/2)$ convolutional code on a Galileo computer (possible because of low bit rates) and concatenating it with the hardware $(7,1/2)$ code, a $(14,1/4)$ code was produced. This was used with a software Viterbi decoder (permitted by low bit rates) as the inner code of a novel concatenated $(255, k)$ variable redundancy Reed–Solomon (RS) coding scheme. The feedback concatenated decoder was implemented in software and provided a bit-error rate of $10 \times 10^{-7}$ at an exceptionally low signal-to-noise ratio [15].

   In addition to this code, the processing of the received signals included predetection recording and noncausal processing to eliminate acquisition delay and minimize dropout intervals. Noncausal processing involved using future as well as past values of the signal for estimation at a given time instead of being limited to the use of past and present values, as required by real-time (without delay) processing. Noncausal processing can eliminate the usual acquisition delay by phase-lock and symbol loops (and the resulting loss of data) by processing the signal in reverse time, where the beginning of the signal becomes the end of the signal and future signal becomes past signal [15].

4. **Revised Downlink Telemetry Approach.**
   GLL was originally designed to use Time Division Multiplexed (TDM) downlink, meaning that each data-generating element on the spacecraft had its own dedicated time slot for downlinking data, regardless of whether or not it actually had any data to send. This was redesigned to become a priority-based packet telemetry scheme, ensuring that there would always be valid data on the downlink channel and that the most important data would be downlinked first.
5. **Data Compression Algorithms.** In a mission such as Galileo, the majority of the downlink data was assigned to images and, thus, the maximum acceptable compression of image data was most important. The Galileo SSI camera provided 800 X 800 pixel images with 8-bit digitization of each pixel, thus producing 5.12 megabits per full image. In order to obtain a large factor of data compression for images, it was necessary to use compression algorithms, which introduced error. This error increases with the factor of compression. In order to determine the maximum acceptable error in images, the scientists and the Galileo SSI team conducted an extensive investigator-in-the-loop evaluation of compression algorithms. It was determined that an integer approximation of the discrete cosine transform, previously studied by the DSN Advanced Systems Program, would provide generally acceptable images. The acceptable compression factor may vary from image to image, but on the average, a compression factor of at least 10 resulted. The integer approximation did not significantly degrade the compression and made it possible to carry out the discrete cosine transform on a spacecraft computer of limited capability. The decompression operation included post-processing techniques in the frequency and spatial domains to remove compression artifacts without increasing distortion [15].

With the improved S-band downlink having a maximum data rate in the neighborhood of 160 bps, the spacecraft tape recorder had an additional critical function. In addition to storing data for later transmission, the recorder must "convert" high-rate data produced by some of the instruments to low-rate data for subsequent playback over the improved S-band downlink, which still was a factor of about 1000 slower than the failed original X-band downlink around which the mission was designed. Some further recovery of Galileo's data volume was accomplished by simply allocating a large amount of DSN antenna time to "convert" high-rate data produced by some of the instruments to low-rate data for subsequent playback over the improved S-band downlink, which still was a factor of about 1000 slower than the failed original X-band downlink around which the mission was designed. Some further recovery of Galileo's data volume was accomplished by simply allocating a large amount of DSN antenna time to the mission [15].

**Flight Software Modifications**

Both the flight and ground software were modified extensively in response to the HGA anomaly, with three major phases and multiple builds within each phase as shown in Table 4.

Two sets of new flight software were critical to the success of the GLL mission. The first set, called Phase 1, began operating in March 1995 and was designed expressly to partially back-up and ensure receipt of the most important data collected from the atmospheric probe. This was accomplished by modifying the software in the spacecraft CDS, through in-flight patching, to provide a means of storing Probe data in CDS memory to backup the flight tape recorder storage. Patches were also sent to the Attitude and Articulation Control Subsystem (AACS) software to support Probe relay and JOI.

### Table 4 GLL Software Phases and Timeframes

<table>
<thead>
<tr>
<th>Phase</th>
<th>Timeframe</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mar. 1995 - Mar. 1996</td>
<td>Protect Jupiter Orbit Insertion (JOI) and the Probe Relay mission – minimal changes needed to ensure successful return of Probe data</td>
</tr>
<tr>
<td>2</td>
<td>Mar. 1996 - Sept. 2003</td>
<td>Support the orbital tour of the Jovian system – very substantial changes in the way the spacecraft and ground systems were to operate</td>
</tr>
<tr>
<td>3</td>
<td>Never uploaded</td>
<td>Provide some basic science data return should the single-string spacecraft tape recorder fail – done for contingency as risk mitigation</td>
</tr>
</tbody>
</table>

The inflight load process was extra-ordinarily complex, requiring an address by address verification of the functionality of the AACS flight memories, the uplink of the flight software to the primary of the two redundant memories, switching operation to the new flight software, and then finally loading the other memory. This entire process took approximately 96 hours of continuous operations. Prior to being accepted for uplink to the spacecraft, the AACS flight software was carefully and thoroughly tested using the Galileo Test Bed, a hardware and software replica of the essential flight spacecraft subsystems. Following subsystem testing, a system-level test program was undertaken for almost three months. In addition, the inflight load sequence was tested at both the subsystem and system level. This FSW test program was even more thorough than the prelaunch test program [8].

Once the critical scientific data from the probe was safely returned to Earth, a second set of new software called Phase 2 was radioed and loaded onto the spacecraft in March 1996. Phase 2 software consisted of a much larger change to the CDS, additional changes to the AACS, and changes to eight out of eleven science instruments so that their functionality was compatible with the new spacecraft capabilities. The new capability in the CDS and AACS provided the capability to collect data from each of the modified science instruments, to edit each data stream, to assemble the data into packets, to assemble packets into Virtual Channel Data Units (VCDUs), and to store those VCDUs in a multi-use buffer for later downlink [8]. Hence, this software was used to shrink the voluminous science data the Galileo orbiter collected and store it on its tape recorder during its mission (using compression algorithms), while retaining the scientifically important information, and return that data at the lower data rate [18]. See Figure 10 to see when each FSW Phase was active during the GLL Mission. See Table 5 for specific changes to the flight and ground segments for Phases 1 and 2. The innovative Phase
2 software changes, when coupled with hardware and software adaptations at Earth-based receiving stations, increased the data rate from Jupiter by as much as 10 times, to 160 bps.

![Mission Events Diagram](image)

**Figure 10 Galileo Mission with FSW Phases [8]**

See Figure 13 for a diagram of GLL spacecraft onboard telemetry processing for Orbital Operations using Phase 2 capabilities. By introducing the packetized telemetry concept, the connection between the data acquisition processes and the data downlink processes could be broken. Using packets as the fundamental data unit, and with data buffering onboard the spacecraft, the data acquisition could be optimized independent of the downlink rate [12].

These major FSW changes were enabled by the fortuitous decision to double the amount of RAM in the CDS pre-launch. Without this extra memory, the Phase 1 and 2 changes could not have been made without significantly compromising the reliability of the spacecraft since redundancy in fault protection would be sacrificed [10].

A big advantage that the recovery software team had was a stable, well-characterized hardware configuration, something not enjoyed by most pre-launch software teams. This helped immensely since the team didn’t need to spend any time trying to track moving hardware performance or figuring out whether an anomaly was caused by hardware or software.

**Data Compression Methods**

Two different methods of data compression were used. In both methods, the data were compressed onboard the spacecraft before being transmitted to Earth. The first method, called "lossless" compression used the Rice algorithm which allowed the data to be reformatted back to their original state once on the ground. This technique is routinely used in personal computer modems to increase their effective transmission rates. The second compression method was called "lossy," since it referred to the loss of some original data through mathematical approximations used to abbreviate the total amount of data to be sent to the ground. Lossy compression used an Integer Cosine Transform (ICT) compression algorithm and was used to shrink imaging and plasma wave data down to as little as 1/80th of its original volume. The AACS was used as a math co-processor to accomplish the ICT compression since the CDS was incapable of doing the required math with its 8-bit 1802 processors. The AACS had math-capable ATAC-16MS CPUs and the time to do the compression during orbital cruise. These data compression methods allowed retention of the most interesting and scientifically valuable information, while minimizing or eliminating less valuable data (such as the dark background of space) before transmission. See Figure 11 for a diagram showing Galileo imaging playback via the Low Gain Antenna (LGA).

![Imaging Playback Diagram](image)

**Figure 11 GLL Imaging Playback via LGA [18]**

**Ground Software Modifications**

All elements of the GLL GDS (PGDS, MGDS and DSN) had to accommodate the new data rates and the new packet telemetry variable length format which replaced the Time Division Multiplexed (TDM) fixed length formats that were used until Phase 2 was uploaded. All elements also had to accommodate a guaranteed delivery system of data transfer through the GDS network elements.

The PGDS provided tools and procedures to operate the new spacecraft capabilities. These included new prediction tools which allowed sequence designers to predict the condition of the multi-use buffer and to manage the DMS recorder tape allocation. The PGDS also provided the commands necessary to operate the new spacecraft capability and to provide the downlink software necessary to process and distribute the data to the end users of that information. Originally very little "real time" commanding was envisioned when the ground software was developed and the size of the Flight Team was established. The HGA recovery efforts dramatically increased the number of real-time commands sent to the spacecraft, with nearly 60,000 of those associated with the Dual Drive Actuator (DDA) "motor hammering" done in an effort to release the stuck HGA ribs. The MGDS implemented the decoders and decompressors needed to invert the processes used on the spacecraft, i.e., a convolutional decoder, a Reed-Solomon decoder, and a decompressor for the ICT and Rice compressors [8].
The accomplishments of the Galileo Mission after arrival at Jupiter indicate that application of the new technology for the Galileo S-Band LGA Mission was entirely successful. On December 7, 1995, the Galileo Probe entered the Jupiter atmosphere and functioned as planned. The Probe data were received and stored on the Orbiter just prior to its Jupiter orbit insertion. The stored Probe data were transmitted to Earth over an extended period via the S-band downlink. The advanced coding and other improvements of the Galileo S-Band LGA Mission were activated later in 1996. The first satellite encounter after Jupiter orbit insertion was that of Ganymede on June 27, 1996, at a distance of 832 km. All of the enhancements provided (except for antenna arraying, scheduled for later) functioned as planned for imaging and other data. On September 6, 1996, there was a second Ganymede encounter at a distance of 262 km [15].

On November 4, 1996, there was the first encounter with Callisto, at a distance of 1104 km. At this encounter, the spacecraft was at one of its most distant points from Earth, and the DSN antenna arraying capability was used for the first time on the mission. The array included the 70-m and 34-m antennas at Canberra, the 64-m antenna at Parkes, and the 70-m antenna at Goldstone. At this maximum distance, the spacecraft downlink data rate was programmed among 120, 80, 40, 32, and 20 bps, depending on the combination of arrayed antennas and their tracking elevation angles. This arraying capability had been tested successfully in September at spacecraft telemetry bit rates up to 160 bps.

On December 18, 1996, the Europa encounter occurred at a distance of 692 km. All communication enhancements continued to operate as planned. There is every indication that the vital technology contributions described above contributed to the success of the Galileo Mission during the remainder of its operation [15].

Although the primary mission was completed in December 1997, the mission was extended three times to take advantage of the spacecraft's durability with 24 more orbits. The extensions enabled additional encounters with all four of Jupiter's major moons: Io, Europa, Ganymede and Callisto. Galileo flew near a small inner moon, Amalthea, before making a planned mission ending plunge into Jupiter's atmosphere. In total, Galileo had 35 encounters of Jupiter's major moons – 11 with Europa, 8 with Callisto, 8 with Ganymede, 7 with Io and 1 with Amalthea – and returned more than 30 Gigabytes of data, including 14,000 images.

On September 21, 2003, the GLL spacecraft was purposely put on a collision course with Jupiter to eliminate any chance of an unwanted impact between the spacecraft and Jupiter’s moon Europa, which Galileo discovered was likely to have a subsurface ocean. The long planned impact was necessary once the onboard propellant was nearly depleted. Without propellant, the spacecraft would not have been able to point its antenna towards Earth nor adjust its trajectory, so controlling the spacecraft was no longer possible [19].

In conclusion, in the face of adversity, the Galileo Project team succeeded in developing extraordinary means to ensure that the mission's most important science was obtained. In fact, very few of Galileo's original measurement objectives had to be completely abandoned as a result of the HGA problem. For the most part, science investigations on the spacecraft adapted to the lower data rates using a variety of techniques, depending on the nature of the experiment. Thus, despite a failed high-gain antenna and a fussy tape recorder, more than 70% of the original Galileo Prime Mission science objectives were accomplished using the low gain antenna.

8. ACKNOWLEDGEMENTS

Many people have contributed to the success of JPL’s Systems Engineering Advancement Project, especially the JPL SE Workshop, and deserve recognition.

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- David Nichols – Manager, Systems and Software Division (31)
- Chi Lin – Manager, Div. 31 Engineering Development Office
- Roger Diehl – SEA Project Manager

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- Erik Nilsen – former Galileo Systems Engineer
- Bob Barry – former Galileo FSW Test Engineer
- Dan Erickson – former Galileo FSW Developer/Tester

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of Technology.
9. ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AACS</td>
<td>Attitude and Articulation Control Subsystem</td>
</tr>
<tr>
<td>ARC</td>
<td>Ames Research Center</td>
</tr>
<tr>
<td>ASI</td>
<td>Atmospheric Structure Instrument</td>
</tr>
<tr>
<td>ARX</td>
<td>Advanced Receiver</td>
</tr>
<tr>
<td>bps</td>
<td>Bits Per Second</td>
</tr>
<tr>
<td>BVR</td>
<td>Block V Receiver</td>
</tr>
<tr>
<td>Caltech</td>
<td>California Institute of Technology</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
<tr>
<td>CDS</td>
<td>Command and Data Subsystem</td>
</tr>
<tr>
<td>CDU</td>
<td>Command Detector Unit</td>
</tr>
<tr>
<td>CMD</td>
<td>Command</td>
</tr>
<tr>
<td>CoP</td>
<td>Community of Practice</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial Off-the-Shelf</td>
</tr>
<tr>
<td>DDA</td>
<td>Dual Drive Actuator (motors to drive open HGA)</td>
</tr>
<tr>
<td>DDS</td>
<td>Dust Detector Subsystem</td>
</tr>
<tr>
<td>DMS</td>
<td>Data Memory Subsystem (Odetics Tape Recorder)</td>
</tr>
<tr>
<td>DOR</td>
<td>Differential One-way Ranging</td>
</tr>
<tr>
<td>DSN</td>
<td>Deep Space Network</td>
</tr>
<tr>
<td>DWE</td>
<td>Doppler Wind Experiment</td>
</tr>
<tr>
<td>EPD</td>
<td>Energetic Particles Detector</td>
</tr>
<tr>
<td>EPI</td>
<td>Energetic Particles Instrument</td>
</tr>
<tr>
<td>ESD</td>
<td>Engineering and Science Directorate</td>
</tr>
<tr>
<td>EUV</td>
<td>Extreme Ultraviolet Spectrometer</td>
</tr>
<tr>
<td>FPO</td>
<td>Flight Projects Office</td>
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<tr>
<td>FPP</td>
<td>Flight Project Practices</td>
</tr>
<tr>
<td>FSR</td>
<td>Full Spectrum Recorder</td>
</tr>
<tr>
<td>FST</td>
<td>Flight System Testbed</td>
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<tr>
<td>FSW</td>
<td>Flight Software</td>
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<tr>
<td>GDS</td>
<td>Ground Data System</td>
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<tr>
<td>GLL</td>
<td>Galileo</td>
</tr>
<tr>
<td>HAD</td>
<td>Helium Abundance Detector</td>
</tr>
<tr>
<td>HGA</td>
<td>High Gain Antenna</td>
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<tr>
<td>HIC</td>
<td>Heavy Ion Counter</td>
</tr>
<tr>
<td>JOI</td>
<td>Jupiter Orbit Insertion</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>ICT</td>
<td>Integer Cosine Transform</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IUS</td>
<td>Inertial (Interim) Upper Stage</td>
</tr>
<tr>
<td>KSC</td>
<td>Kennedy Space Center</td>
</tr>
<tr>
<td>LGA</td>
<td>Low Gain Antenna</td>
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<tr>
<td>LRD</td>
<td>Lightning and Radio Emissions Detector</td>
</tr>
<tr>
<td>MAG</td>
<td>Magnemeter</td>
</tr>
<tr>
<td>MCHS</td>
<td>Minimum Capability Hybrid Simulator</td>
</tr>
<tr>
<td>MDS</td>
<td>Modulation Demodulation Subsystem</td>
</tr>
<tr>
<td>MGDS</td>
<td>Multi-mission GDS</td>
</tr>
<tr>
<td>MGSS</td>
<td>Multi-Mission Ground Systems and Services</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics &amp; Space Administration</td>
</tr>
<tr>
<td>NEP</td>
<td>Nephelometer</td>
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<tr>
<td>NFR</td>
<td>Net Flux Radiometer</td>
</tr>
<tr>
<td>NIMS</td>
<td>Near Infrared Mapping Spectrometer</td>
</tr>
<tr>
<td>NMS</td>
<td>Neutral Mass Spectrometer</td>
</tr>
<tr>
<td>NPR</td>
<td>NASA Procedural Requirements</td>
</tr>
<tr>
<td>PDMS</td>
<td>Project Data Management System</td>
</tr>
<tr>
<td>PGDS</td>
<td>Project-specific GDS</td>
</tr>
<tr>
<td>PLS</td>
<td>Plasma Subsystem</td>
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<tr>
<td>PPR</td>
<td>Photopolarimeter-Radiometer</td>
</tr>
<tr>
<td>PPS</td>
<td>Power Pyro Subsystem</td>
</tr>
<tr>
<td>PWS</td>
<td>Plasma Wave Subsystem</td>
</tr>
<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>RFS</td>
<td>Radio Frequency Subsystem</td>
</tr>
<tr>
<td>RS</td>
<td>Radio Science</td>
</tr>
<tr>
<td>RTG</td>
<td>Radioisotope Thermoelectric Generator</td>
</tr>
<tr>
<td>SBA</td>
<td>Spin Bearing Assembly</td>
</tr>
<tr>
<td>spacecraft</td>
<td>Spacecraft</td>
</tr>
<tr>
<td>SDR</td>
<td>Software Development Requirement</td>
</tr>
<tr>
<td>SDSP</td>
<td>Software Development Standard Processes</td>
</tr>
<tr>
<td>SE</td>
<td>Systems engineering</td>
</tr>
<tr>
<td>SEA</td>
<td>Systems Engineering Advancement</td>
</tr>
<tr>
<td>SEMP</td>
<td>Systems Engineering Management Plan</td>
</tr>
<tr>
<td>SEP</td>
<td>Systems Engineering Practices</td>
</tr>
<tr>
<td>SSI</td>
<td>Solid State Imaging</td>
</tr>
<tr>
<td>STS</td>
<td>Space Transportation System (Space Shuttle)</td>
</tr>
<tr>
<td>SXA</td>
<td>S-/X-band antenna (SXA) subystem</td>
</tr>
<tr>
<td>TDA</td>
<td>Tracking and Data Acquisition</td>
</tr>
<tr>
<td>TDM</td>
<td>Time Division Multiplexed</td>
</tr>
<tr>
<td>TDRS</td>
<td>Tracking Data Relay Satellite</td>
</tr>
<tr>
<td>TLM</td>
<td>Telemetry</td>
</tr>
<tr>
<td>TWTA</td>
<td>Traveling Wave Tube Amplifier</td>
</tr>
<tr>
<td>TMU</td>
<td>Telemetry Modulation Unit</td>
</tr>
<tr>
<td>USO</td>
<td>Ultra-stable Oscillator</td>
</tr>
<tr>
<td>UVS</td>
<td>Ultraviolet Spectrometer</td>
</tr>
<tr>
<td>VEEGA</td>
<td>Venus, Earth, Earth Gravity Assist</td>
</tr>
<tr>
<td>V&amp;V</td>
<td>Verification and Validation</td>
</tr>
<tr>
<td>XSDC</td>
<td>X- to S-band downconverter</td>
</tr>
</tbody>
</table>

REFERENCES


**BIOGRAPHY**

P. A. “Trisha” Jansma is the Lead for the Deployment Subgroup for the NASA Systems Engineering Working Group for the NASA Office of the Chief Engineer. She also supports training and deployment for the Systems Engineering Advancement Project at the Jet Propulsion Laboratory (in Pasadena, California. She served as the Case Study Coordinator for the JPL Systems Engineering Workshop. With over 30 years at JPL in both line and project management positions, she has a broad background in systems and software engineering in both engineering and scientific environments. Jansma has extensive experience in the management, design, development and delivery of cost-effective, software-intensive systems. She has experience in all facets of project life-cycle development, from initial feasibility analysis, proposal development and conceptual design through implementation, documentation, user training, enhancement and operations. Jansma has a B.A. in Mathematics from Point Loma Nazarene University, a M.S. in Computer Science from the University of Southern California, and an Executive M.B.A. from the Peter F. Drucker Graduate School of Management at Claremont Graduate University. In addition, she obtained both a California secondary teaching credential and a community college teaching credential, and has taught courses at the graduate level.
Figure 12 Galileo Orbiter and Instruments [8]

Figure 13 GLL Orbital Operations (Phase 2) Spacecraft Onboard Telemetry Processing
### Table 5 GLL Flight Software and Ground Segment Capabilities by Phase [9]

<table>
<thead>
<tr>
<th>Phase</th>
<th>Objectives</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Support original GLL pre-Probe Operations</td>
<td>Launch and Cruise FSW and GDS based on using HGA with real-time downlink</td>
</tr>
</tbody>
</table>
| 1     | Protect Jupiter Orbit Insertion (JOI) and the Probe Relay mission – minimal changes needed to ensure successful return of Probe data | **Flight Segment:**
- Maintain full redundancy to support JOI fault recovery
- Preserve saving a copy of full Jupiter Probe symbol data on the spacecraft tape recorder
  - Backup mode in the original design; primary mode in Phase 1
- Provide the ability to store a backup partial copy of Jupiter Probe symbol data in spacecraft Command and Data System (CDS) Random Access Memory (RAM) to protect against a tape recorder failure
  - Replaces what was originally intended to be real-time downlink via the HGA
**Ground Segment:**
- Enhanced digital receivers (Block V) at DSN stations enabled using suppressed carrier downlink, allowing all transmit power to go into the data instead of being wasted in a carrier |
|       | Uploaded March 1995 | |
| 2     | Support the orbital tour of the Jovian system – very substantial changes in the way the spacecraft and ground systems were to operate | **Flight Segment:**
- Required reprogramming of the entire Command and Data Subsystem (CDS), part of the Attitude and Articulation Control Subsystem (AACS) and eight of the eleven science instruments on board the spacecraft
- Completely changed the way data was collected, stored, processed and sent to the ground
  - Substantial new on-board data editing capabilities to enable selection of only the most important parts of data sets collected from instruments
  - Data compression of all data
    - Variable (1:1 up to 80:1) “lossy” compression for imaging and plasma wave data and lossless compression for all other data
- Inefficient Time Division Multiplexed (TDM) telemetry changed to an efficient prioritized and channelized packet telemetry scheme
- Variable downlink rate (up to 6 data rate levels per 8 hour DSN pass) to match Deep Space Network (DSN) data rate capability profile
- Two levels of error control coding to improve downlink bit error rate four orders of magnitude in order to ensure compressed packets arrived intact
**Ground Segment:**
- Deep Space Network (DSN):
  - Enhanced performance of the Canberra 70m antenna in S-band
  - Advanced digital receivers at all three DSN stations
  - Full-spectrum recorders and combiners at all DSN stations
  - Combined the signals from many geographically separated antennas to form an effective aperture much larger than any single antenna
  - Error correction decoders to match spacecraft coding
  - Accommodation for up to 6 data rates per 8-hour DSN pass to make efficient use of available antenna bandwidth at all elevation angles
- Ground Data System:
  - Handle new packetized telemetry
  - Data decompression capability for spacecraft compression modes
  - Support for new telemetry modes and operational commands
  - New science observation planning tools to enable the complex observing sequences required by new spacecraft operational modes |
|       | Uploaded March 1996 | |
| 3     | Provide some basic science data return should the single-string spacecraft tape recorder fail – done for contingency as risk mitigation | This was a contingency load that was never used. |