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PROJECT GALILEO -- THE JUPITER M1SS1ON

Project Galileo is ecstatic to report that as of December 7, 1995, there are seventeen known satellites of Jupiter—the seventeenth being the first artificial satellite—the Galileo Orbiter!. Galileo Galilei discovered the first known moons of another planet. He discovered the four major moons of Jupiter in January 1610 with his newly fashioned telescope from his backyard in Padova, Italy. How delightful that the four major moons are called the Galilean satellites in his honor and now the first spacecraft to orbit Jupiter is named Galileo in his honor. And it is a further delight that this paper is presented at the *Three Galileos Conference* in the place of Galileo Galilei on some of the very days of the year that he discovered the satellites. Jupiter is by far the largest planet in the solar system. It contains two-thirds of the solar system mass outside the Sun--twice the mass of all the other planets combined. Earth's volume would fit inside Jupiter 1,400 times. Earth would fit nearly three times in Jupiter's Great Red Spot. The magnetosphere of Jupiter--the region of space controlled by Jupiter's magnetic field which traps ions and electrons—-is the largest object in the solar system at one-hundred times the volume of the Sun. The Jupiter System is a miniature solar system with sixteen known natural satellites.

Project Galileo has three co-equal objectives--to investigate the chemical composition and physical state of Jupiter's atmosphere, its satellites, and the structure and physical dynamics of its magnetosphere.

Project Galileo made a triumphant arrival at Jupiter on December 7, 1995 (Figure 1 see *color section*). The Galileo Atmospheric Entry Probe became the first object to penetrate and directly measure the atmosphere of an outer planet. The Orbiter mothership became the first spacecraft to orbit an outer planet.

Jupiter is by far the most difficult planetary entry in our solar system. The Probe hit the atmosphere of Jupiter at 170,000 km/hr. In less than two minutes atmospheric drag on the heat shield slowed the Probe to 1,700 km/hr with a peak deceleration of228 g's. The heat shield protected the interior from stagnation point temperatures as high as 25,000° F. Everything on the Probe survived the entry loads. The Descent Module descended on its parachute and radioed its scientific data to the Orbiter mothership without interruption for nearly 58 minutes. The Orbiter made a perfect overflight of the Probe at over 200,000 km altitude and captured literally every bit of data the Probe transmitted. The Probe mission ended when the second of the two redundant transmitters failed 10 minutes after the first. Both failed due to overheating. Because the Probe descended far beyond its mission requirement and atmosphere entered the vented Probe more rapidly than the design intended, equipment temperatures went over 100° C, which was far beyond the flight qualification temperature of 50° C. The Probe reached a pressure depth of 23 bars at 140 km below the 1 bar reference (O altitude) level, The engineering model instruments are now being calibrated in the investigators' laboratories for these higher temperatures in order to more accurately assess the scientific measurements near the maximum depth,

The parachute deployment was 53 seconds late, apparently due to cross-wiring of the quad-redundant accelerometers, which were the sole source of entry detection and the signals to the onboard computer to execute the deployment sequence. The shape of the entry deceleration pulse as implied by the four acceleration trip points was used by an onboard algorithm to determine when to deploy the chute. Six hours before entry, an onboard clock, initiated just before the Probe was released from the Orbiter five months earlier, started the sequence to collect limited pre-entry science. A clock was not suitable for initiating deployment because of the uncertainties in predicting entry time and, furthermore, it could not "sense" the atmosphere density to establish best deployment time.

The Probe's mission requirement was to obtain measurements to a pressure depth of 10 bars in order to measure bulk composition below the veiling clouds. As seen in Figure 2, it was expected that the Probe would operate to 20 to 25 bars, expiring 60 to 75 minutes after entry. It is marvelous that the Probe operated to 23 bars-more than twice the mission requirement! The last data point was transmitted 61 minutes after entry.

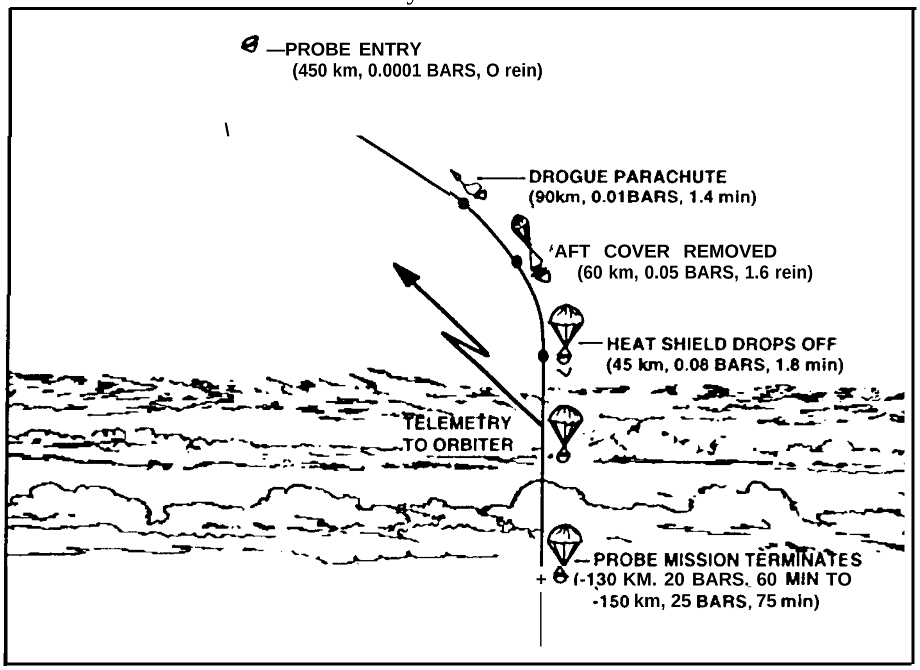

Figure 2: Probe Mission

The Probe carried seven scientific instruments (Figure 3): . . . Neutral Mass Spectrometer, Nephelometer (cloud particle measurements), Net Flux Radiometer, and Atmospheric Structure Instrument from the United States and, Lighming and Radio Emissions Detector, Energetic Particle Instrument, and Helium Abundance Detector from Germany. All the instruments provided excellent data.

The Probe was designed and built by Hughes Space and Communications Company in El Segundo, CA under contract to the NASA Ames Research Center in Mountain View, CA. The overall management of Project Galileo since inception has been the responsibility of the NASA/Caltech Jet Propulsion Laboratory in Pasadena, CA under the NASA Headquarters Office of Space Science in Washington, DC. JPL designed and built the Orbiter in-house. The Orbiter propulsion system. which supplies all propulsive velocity changes and all attitude control torques, was designed and built by Messerschmitt-Bölkow Blohm (now DASA) under contract to the German Space Agency (DARA). Germany provided three Probe instruments and one full and one half of Orbiter science instrument, as well as the Propulsion System to NASA free of charge as the major international partner in Project Galileo. JPL operates Galileo in partnership with Ames, Hughes, and DARA/DASA. The final mating of the Probe to the Orbiter and the loading/pressurization of the Propulsion System were performed at Kennedy Space Center (KSC). Galileo was mated to the IUS upper stage in the Vertical Processing Facility. The Orbiter electrical power sources, the Radioisotope Thermal Electric Generators (RTGs), were installed after the Galileo/IUS stack was in the Shuttle Atlantis cargo bay. On October 18, 1989, the Atlantis launched the Galileo/IUS cargo into a 160 n.m. parking-orbit. On the fifth revolution, exactly as planned, the Galileo cargo was deployed. The launch and deployment were perfect. One hour after deployment, the IUS-19 accelerated Galileo into its prescribed interplanetary trajectory, spun-up Galileo to 3 rpm, and released it. IUS performance was flawless.

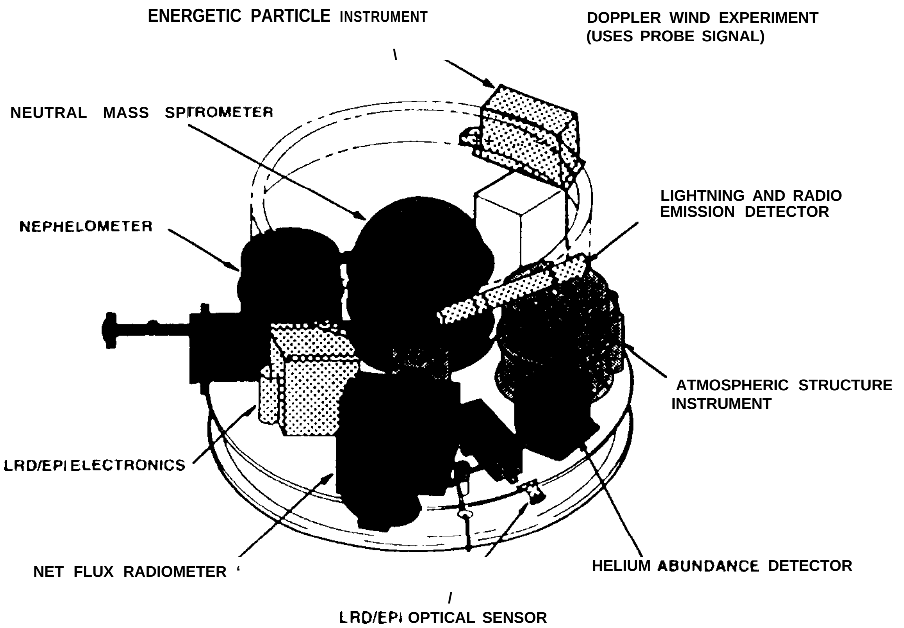

Figure 3. Probe Instruments

When Project Galileo was started in October 1977 as a FY78 new start, launch was to be in January 1982 using a three-year direct trajectory to Jupiter. The planned launch system was the Space Shuttle with a three-stage planetary IUS, which was then being designed. Ultimately, Project Galileo required five major reprogramming due to launch vehicle development problems. The last was a result of the Challenger accident. At the time of Challenger in late-January 1986, Galileo and its newly built, high-energy, wide-body Centaur upper stage were at KSC being prepared for a planned May 1986 launch on a 2.5 year direct trajectory to Jupiter for arrival in December 1988. In the wake of the Challenger accident, NASA determined that the risk of flying the cyrogenic Centaur inside the Shuttle was too great and cancel led the Centaur-In-Shuttle Program. Prior to the cancellation Project Galileo was asked to determine an alternate launch method, The Project devised and offered the following alternative and NASA accepted. The Project would build a small kick-stage using the Star-48 solid rocket motor and integrate it with the Spacecraft. The already flight-proven 2-stage IUS and Shuttle would impart sufficient launch energy that the kick-stage could then get Galileo into a two-year orbit around the sun, returning to Earth for a gravity assist to achieve the Earth-to-Jupiter direct transfer. This well-known technique (called delta-VEGA) would require a large delta-V near aphelion. This would be provided by the Spacecraft Propulsion System and would require enlargement of its tanks by 50%. Two weeks after accepting this alternative and canceling the Centaur, NASA declared that the cargo weight of this alternative was too high even though it was much LESS than the previously committed Galileo/Centaur weight of 62,500 pounds, let alone the original commitment of 65,000 pounds.

So in July 1986, Project Galileo had no way to get to Jupiter. The only viable alternatives required two separate launches and a new separate Probe carrier spacecraft. The costs appeared prohibitive and the threat of cancellation was very real to Project Galileo. The Galileo trajectory designers at JPL saved the mission. Recognizing that the existing, flight-proven two-stage IUS could only accelerate Galileo to a Mars or Venus interplanetary transfer trajectory, they searched for a way to use Mars or Venus gravity-assist to get Galileo to Jupiter. Mars was not in a useful position in its orbit any time in the next several years (i.e., not at the right place at the right time), but Venus was. Consequently, Galileo flew an entirely counter-intuitive, six-year trajectory to Jupiter dubbed VEEGA (Venus, Earth, Earth Gravity-Assist) (Figure 4). Virtually all of the launch energy was used as a "retro-maneuver" to cause Galileo to "fall" in toward the Sun to arrive at Venus on February 10, 1990 receiving a Venus gravity-assist which placed Galileo on a trajectory back to Earth. Ironically, this restored the heliocentric orbital energy so that Galileo was in a one-year orbit around the Sun. When Galileo approached Earth in December 1990 it had the same speed with respect to the Sun as when it was being built in California (30 km/see). But, it was now in a slightly elliptical heliocentric orbit so it was crossing the Earth's orbit at a substantial angle and the approach speed to Earth was now 8.9 km/sec. See the vector diagrams in Figure 5. The minimum energy transfer from Earth's orbit to Jupiter's requires achieving a heliocentric speed of 39 km/sec. The Earth approach velocity was nearly perpendicular to the heliocentric velocity. The function of the Earth gravity-assist was to rotate the Earth-relative velocity so that the departure velocity would directly add (algebraically) to the heliocentric Earth velocity of 30 km/sec to achieve the required 39 km/sec near tangent to Earth's orbit. To achieve this with one Earth-Gravity-Assist (EGA) would have required a closest approach well below the surface of the Earth. Capable as Galileo is, a subterranean trajectory was beyond even its capability! Two EGA's were required. The first was targeted to result in an exactly two-year orbit around the Sun- causing Galileo to return to Earth on December 8, 1992 for a second EGA. The second EGA put Galileo in a six-year orbit around the Sun, which has an aphelion at Jupiter's orbit. Thus. half way around this highly elliptical transfer orbit—three years after the second EGA—Jupiter overtook Galileo. Near aphelion Galileo was moving at only about half of Jupiter's orbital speed.

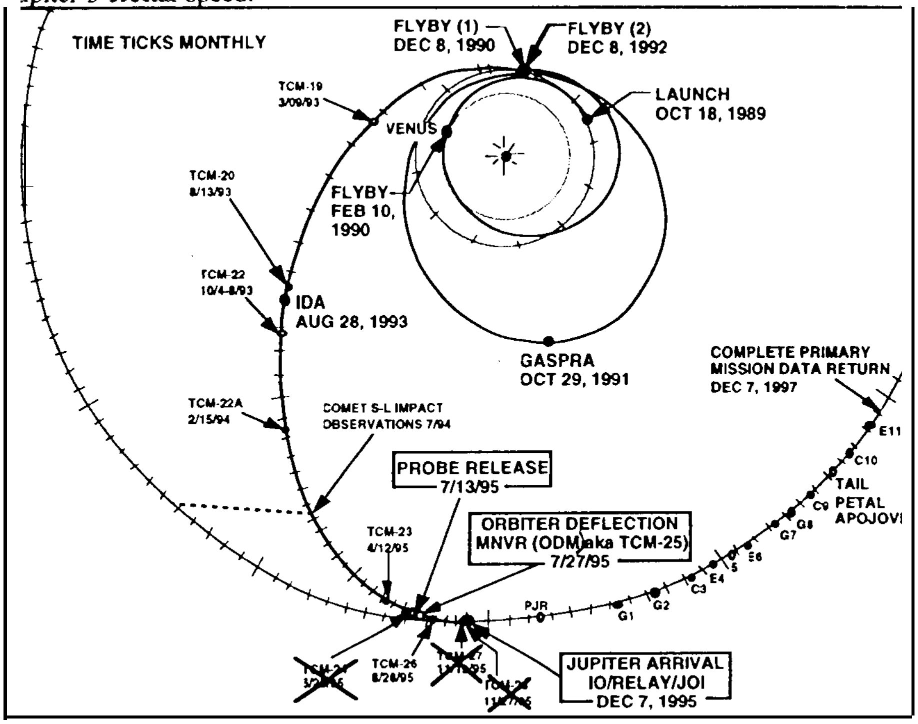

Figure 4. Galileo VEEGA Trajectory .

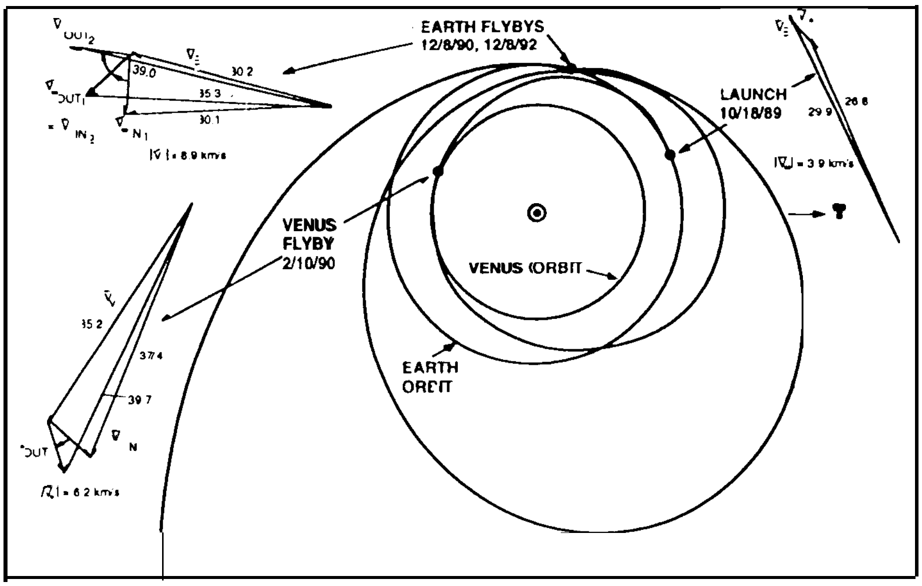

Figure 5. VEEGA Velocity Diagrams

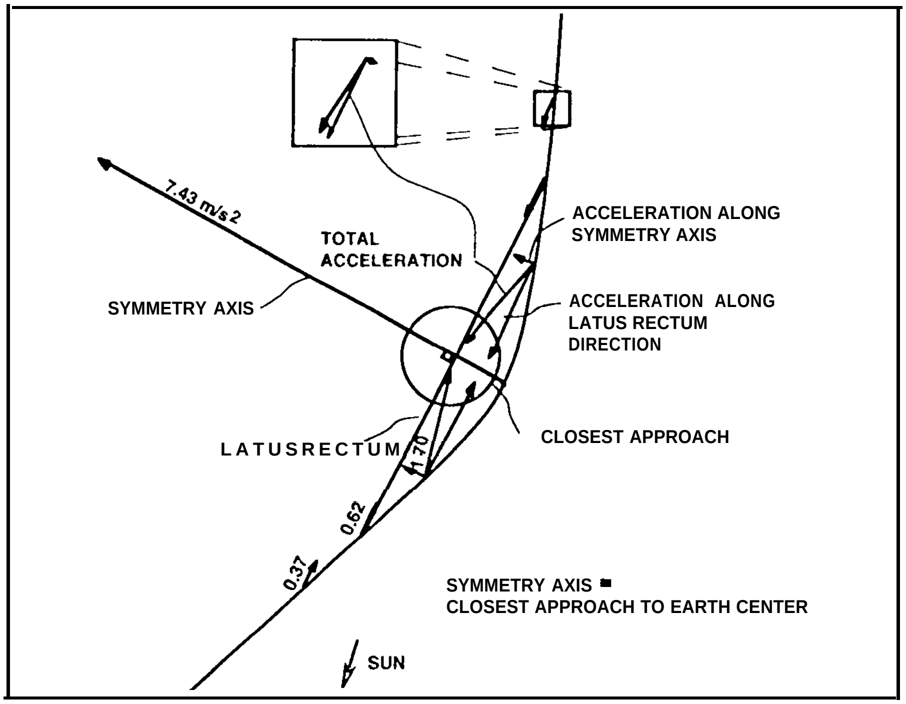

Figure 6-. Earth Gravitational Acceleration During 1st Earth Flyby

Many technical people are puzzled as to why gravity-assist works. They know that the spacecraft must leave the assisting body with the same speed as it arrived due to conservation of energy in the two-body problem. So where does the assist come from? The author developed the illustration in Figure 6, which has been quite successful in explaining the mechanics. The spacecraft flyby trajectory is a hyperbola symmetric about the point of closest approach. Resolve the gravity acceleration vector into its components along and perpendicular to the symmetry axis. At every point inbound the perpendicular component will be exactly cancelled by its mirror image outbound so there can be no net effect perpendicular. The component along the axis grows rapidly to the point of closest approach and is identically doubled outbound. The net gravity assist is always along the symmetry axis in the direction from the point of closest approach through the center of the assisting body. It is indeed the integral of the acceleration along the axis that is the velocity change that results in a departure direction different from the approach direction, with no net change in speed relative to the assisting body—what is referred to as the "bending angle" or turning of the planet-relative velocity vector in the earlier discussion. Beyond the points where the perpendicular to the symmetry axis through the planet center (the latus-rectum) intersects the flyby trajectory, the gravity component along the axis is opposite the assist direction, but is very small and the integral effect over the "infinite" approach is quickly offset by the rapidly growing "positive" component after crossing the intersection point. The identical positive integral mirror image outbound provides the "overshoot" to exactly compensate the outbound integral past the intersection point. Figure 7 displays the velocity gain vs. time from the closest approach for Galileo's first Earth flyby. The slope reaches zero at 37 minutes before closest approach, corresponding to crossing the intersection point (la[us-rectum) with a "deficit" of400 m/see. The deficit is cancelled 22 minutes later (the zero crossing). The net gravity assist of 7,239 m/sec was produced in the 30 minutes from 15 minutes before to l S minutes after closest approach. Notice how the overshoot outbound offsets the outbound negative integral—the vertical mirror image of inbound on the display. Remarkably, these Earth gravity assists each produced twice the delta-V the IUS did. It is emphasized that the net delta-V produced by gravity-assist is a physical delta-V in inertial space whose effect is entirely independent of whether it came from a rocket or planet gravity.

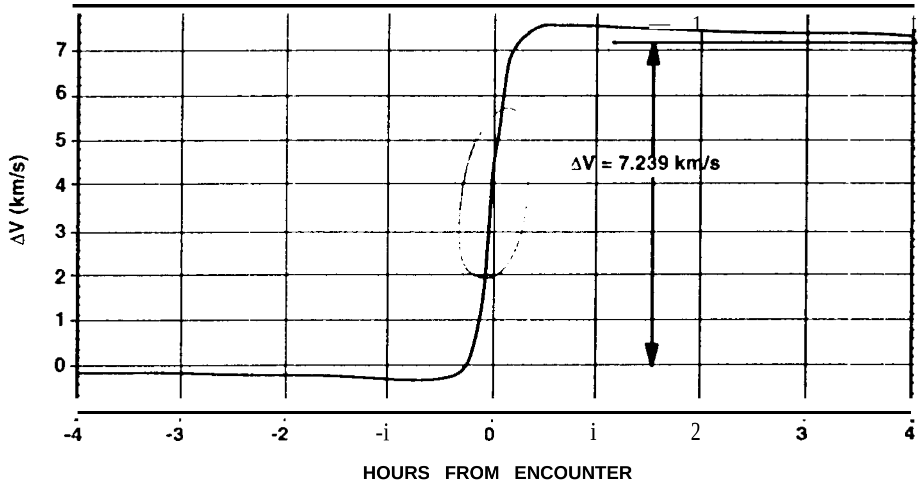

Figure 7. Velocity Gained by 1st Earth Flyby

As shown in Figure 4, Galileo was the first spacecraft'to encounter an asteroid—-Gaspra—in October 1991 about halfway around its two-year heliocentric Earth-to-Earth trajectory. The propellant-optimal VEEGA trajectory was modified at a modest increase in use of spacecraft propellant to perform a second asteroid encounter—with Ida–-in August 1993. The Gaspra encounter provided the world's first resolved images of an asteroid. The Ida encounter yielded the discovery of a moonlet orbiting Ida now named Dactyl-the first known moon of an asteroid. In July 1994, Galileo's position enabled direct observation of the Shoemaker: Levy-9 cornet fragments as they impacted Jupiter, whereas the impacts were beyond Jupiter's limb as seen from Earth.

Also, note in Figure 4 that the Orbiter released the Probe five months before Jupiter arrival. The Probe had no control system and once the umbilical was cut, there was no further communication with the Probe until the one-way relay link with the Orbiter was established after the Probe's parachute was deployed. The Orbiter precisely adjusted the pre-release trajectory so that the release impulse and all subsequent forces acting on the Probe during its five-month ballistic trajectory to Jupiter would result in entry within the prescribed 2.8° entry corridor. The Orbiter then turned to align its spin axis parallel with what would be the entry velocity vector and then increased the spin rate from 3 rpm to 10.5 rpm to provide adequate stability to the Probe so its entry angle of attack would not exceed 7.0°.

Reconstruction of (he entry indicates excellent performance—only 15% of the path angle margin was used.

Two weeks after release of the Probe, the Orbiter was "deflected" to its required Jupiter arrival trajectory. The Orbiter was targeted to pass 1,000 km above the surface of Io (the innermost Galilean satellite) for a gravity -'assist to reduce its speed and thus reduce the amount of propellant required to insert the Orbiter into orbit around Jupiter. The 10 flyby was introduced in the first year of development (1978) to help solve performance problems since it was fully compatible with the Probe overflight at 200,000 km for the Relay Link, The arrival geometry is illustrated in Figure 8. Ironically, the Io flyby dictated all of the arrival timing, including the Probe entry time.

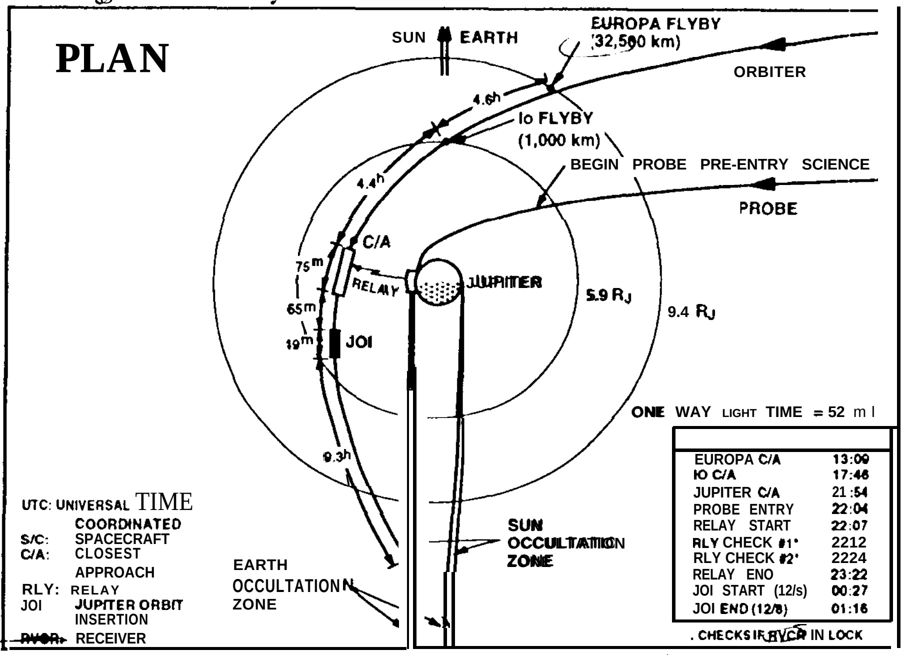

Figure 8. Jupiter, rival(December 7, 1995)

The Orbiter Deflection Maneuver (ODM) was by design the first use of the 400 N main engine. At 62 m/sec it was Galileo's largest interplanetary maneuver. (The release five months before arrival was a trade between ODM propellant and delivery accuracy and Probe battery use.) Since it is believed that a propulsion failure caused the loss of the Mars Observer spacecraft; tire Project–including its propulsion colleagues in Germany y—performed an exhaustive review of the Galileo Propulsion System and developed elaborate strategies for minimizing risk prior to this first inflight burn of the 400 N engine. While telemetry data indicated some checkvalve anomalies, vigorous management of the system minimized risk and propulsive performance has been excellent throughout the mission.

Since Project inception, the foundation of the Orbiter Mission has been the use of Galilean satellite gravity-assists to perform an Orbital Tour of the Jupiter System. The primary mission Tour is illustrated in Figure 9. It consists of eleven orbits of Jupiter in two years with a very close flyby of a Galilean satellite on every orbit but one. Each flyby provides the gravity-assist to change the orbit so that

Galileo will encounter the next desired satellite one revolution later and thereby bootstrap its way around the Jupiter system and sweep through a good portion of Jupiter's magnetosphere including a deep penetration into the magnetotail. Figure 4 shows the position of Jupiter at each of the satellite encounters.

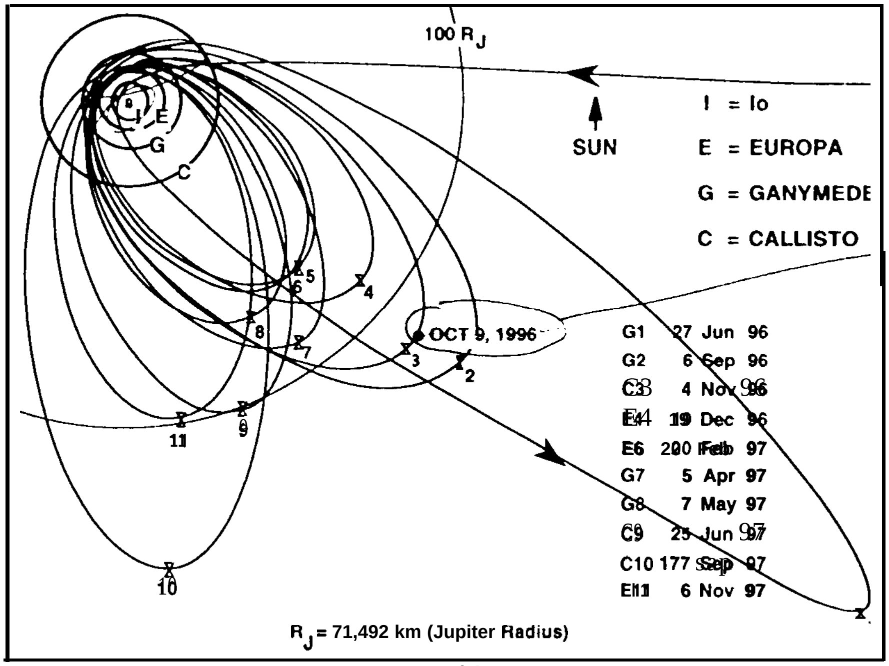

Figure 9. Orbital Tour of the Jupiter System

The second use of the 400 N engine was a 49-minute bum to become nominally captured into a seven-month Jupiter orbit. This was the largest nominal orbit that reasonably guaranteed capture in-the presence of dispersions and, therefore, minimized the propellant requirement. At the high point in this orbit (apojove), the 400 N engine was used for the third and final time to raise the orbit low point (perijove) from 4 R_J (Jupiter radii) to 11 R_J. The Orbiter radiation protection was designed to allow only one passage at 4 R_J with the remaining perijoves between 9 and 11 R_J.

The first in-orbit satellite encounter was with Ganymede to most efficiently reduce the orbit size and period from seven months to two months. Since Galileo's orbit was inclined to the plane of the Galilean satellites, the second encounter also had to be with Ganymede and at the same place in Ganymede's orbit—the current nodal position of the satellite plane and Galileo's orbit. The second Ganymede Gravity-Assist produced the plane change that essentially put Galileo's orbit in the same plane as the satellites. From then on, orbital period changes basically produce the tour.

On approach to Jupiter, navigation estimates indicated the 10 flyby altitude was 100 km low. Rather than correct this as originally planned with one or two approach maneuvers, the 900 km 10 altitude was accepted because it would result in a one-week shorter orbital period and, since Ganymede's period is about one week, it would be easy to accommodate the actual 10 delivery and orbit insertion burn dispersions by targeting the orbit trim maneuvers to a Ganymede encounter one

TABLE 1 Summary of Galileo's Tour of Jupiter's Satellites

Encounter	Daft	Satellite	Inbound Outbound	Altitude (km)	Latitude (deg)
G1	27 Jun 96	Ganymede	In	844	302
G2	6 Sep 96	Ganymede	In	250	79 5
C3	4 Nov 96	Callisto	In	1096	14
E3A	6 Nov 96	Europa	Out	31818	0
E4	19 Dec 96	Europa	Out	695	0
(E5A)	20 Jan 97	Europa	Out	27555	-1
E6	20 Feb 97	Europa	In	589	-17
E7A	4 Apr 97	Europa	In	24993	2
G7	5 APr 97	Ganymede	out	3105	55
C8A	6 May 97	Callisto	In	33176	-42
G8	7 May 97	Ganymede	In	1602	28
C9	25 Jun 97	Callisto	In	420	2
G9A	26 Jun 97	Ganymede	In	80246	0
Tail Petal Apojove	8 Aug 97				
C10	17 Sep 97	Callisto	In	528	5
E11	6 Nov 97	Europa	In	1127	.66

Deterministic ΔV: Jupiter Orbit Insertion = 645 m/s, Perijove Raise = 375 m/s, Tour= 23 mLs
Total Radiation = 123 krad

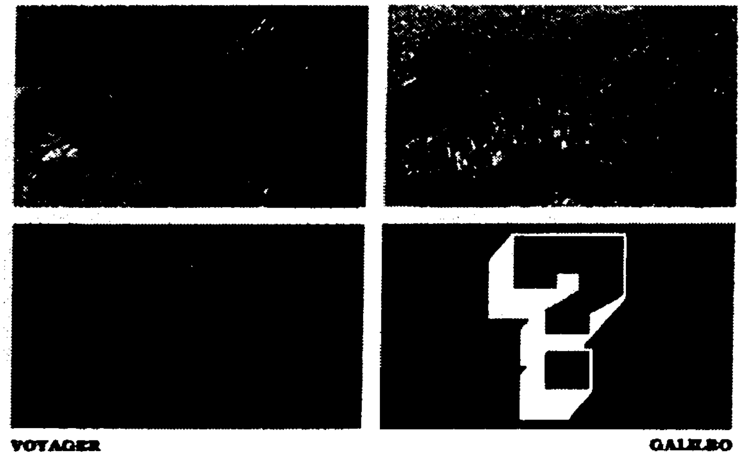

Figure 10 Comparison of Resolution of Voyager and Galileo

week earlier. The navigation and insertion burn were so good that the two orbit trim maneuvers were cancelled as were the approach maneuvers. This scenario is fully described in (D'Amario 1997).

TABLE II gives the flyby altitudes of the Orbiter's satellite encounters. These are typically 100s of times closer than the Voyager spacecraft flybys in 1979. This improvement in resolution by orders of magnitude is yielding absolutely stunning images of the Galilean satellite surfaces that are causing profound changes in the scientific view of the formation and evolution of these bodies (Refs __ and __)). Figure 10 presents the display used throughout the Project this to indicate the power of this improvement. The lower-left panel shows Voyager's typical best resolution on Europa. The upper panels show the New York New Jersey area at Voyager resolution and at Galileo resolution. Project Galileo is now filling in the "question mark" with awesome images, but is not surprised in finding nothing resembling New York City.

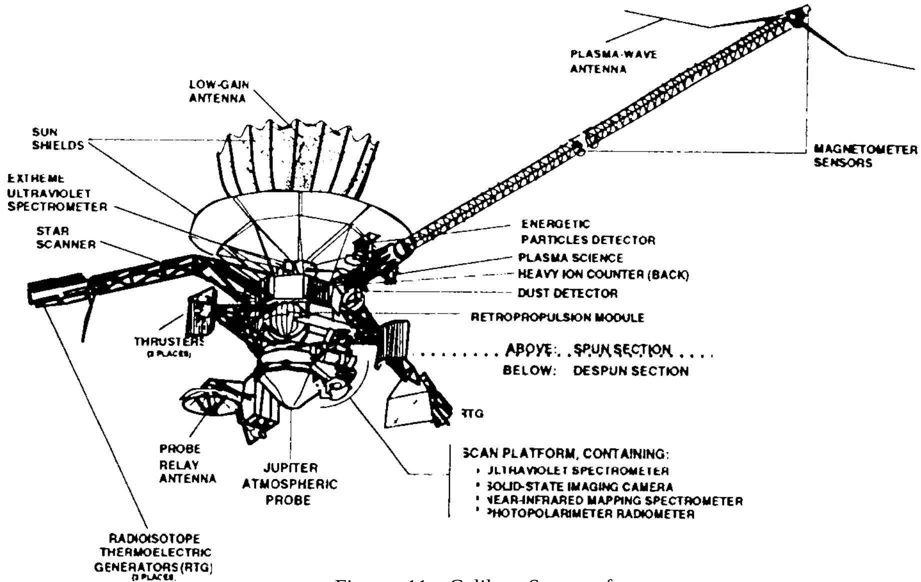

Figure 11, Galileo Spacecraft

The Galileo spacecraft is illustrated in Figure 11. Comprehensive descriptions of the spacecraft and its operation are given in (Landano 1997 and O'Neil 1997). The-most salient features will be mentioned here. Galileo is the only *dual* spin planetary spacecraft and arguably the most capable ever flown. Everything from the propulsion system on up is spun, normally at 3 rpm. Everything below constitutes the de-spun section, which carries four telescopic instruments, the Probe, the relay receiving antenna for the Probe data, and associated electronics for these elements. The combination of the spin bearing assembly and the elevation axis supporting the scan platform provides very precise azimuth and elevation control to steadily point the remote sensing instruments at the observation target while the spinning section sweeps the fields and particles instruments through the local region. There are eleven science instruments on the Orbiter and all are perform ing very well except the Photopolarimeter. The remote sensing is performed by a Solid-State visible imaging camera, a Near-Infrared Mapping Spectrometer, an Ultraviolet Spectrometer, and a Photopolarimeter/ Radiometer on the scan platform and an Extreme Ultraviolet spin-scan instrument on the spun section. The in-situ fields and particles instruments are a Magnetometer, a Plasma Detector, a Plasma Wave Spectrometer, an Energetic Particles Detector, a Dust Detector, and a Heavy Ion Counter. The Radio signal is also used scientifically to measure gravity fields and atmospheres, The major scientific results to date are presented in a variety of papers in this proceedings volume.

Following the perfect launch, the flight to Venus and back past Earth was excellent. Then, several months after the first Earth flyby at the prescribed time in April 1991 the high-gain antenna (HGA) failed to deploy. For the next two years, everything possible was done to get the HGA deployed while in parallel the extraordinary mission workaround of using the low-gain antenna with a 10,000 times weaker power density received at Earth was conceptually developed. Galileo made its planned first-ever spacecraft encounters of asteroids-Gaspra and Ida—without the HGA or any of the envisioned workarounds. In the last three years before arrival at Jupiter, the Project did a massive redesign of the flight software to provide onboard data compression. editing, and new downlink coding while the Deep Space Network (DSN) developed the corresponding receiving capabilities on Earth, including new, state-of-the-art full - spectrum recorders and the arraying of several antennas in Australia with the 70m antenna in California.

The new orbital phase flight software was radioed to Galileo in May 1996, completely replacing the software in the main computer and in most of the instrument computers just in time to perform the first encounter with Ganymede in June. The last of the new DSN capabilities went on-line as planned in November 1996 to support the third encounter—Callisto. Galileo encountered Europa on December 19th—all the moons Galileo Galilei saw in 1610 have now been observed and/or sensed by his namesake a million times closer than he was. The remaining six encounters of the primary mission will be performed in 1997.

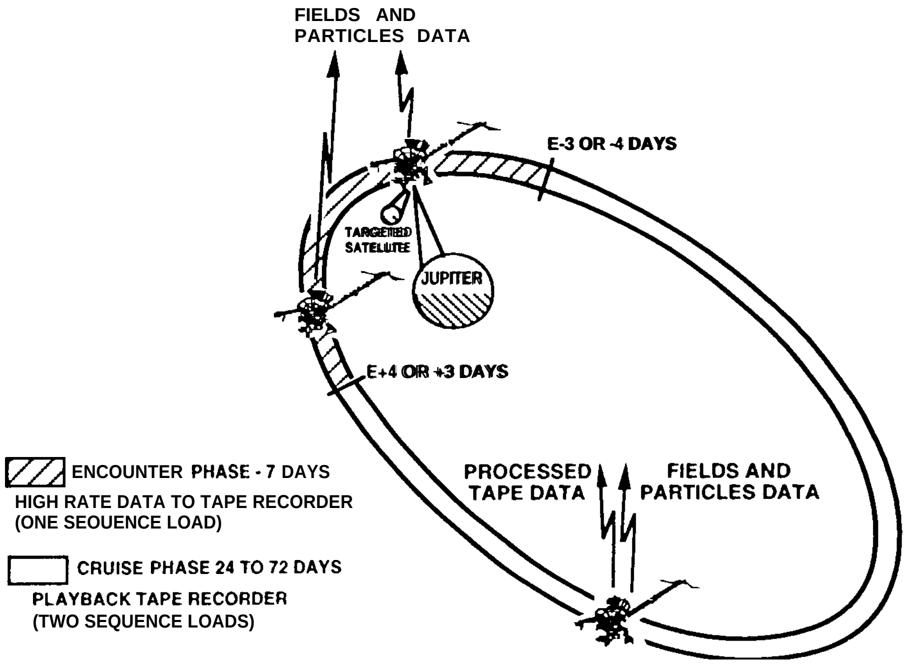

Figure 12. Operations Scenario

Without the HGA, Galileo is entirely dependent on its single tape recorder for imaging and other high-rate data, The operating scenario is illustrated in Figure 12. For one week around closest approach to Jupiter and the targeted satellite, the images and other data are stored on the recorder. Then for the one to two months during the orbital cruise between encounters, the data is read from the recorder in very small batches ("gulps") with editing and compression "on the fly" until the central computer storage buffer is full. In parallel, the buffer data is being encoded and telemetered to Earth at rates from 20 to 160 bps depending on tracking station(s) and range (i.e.. as Earth revolves in orbit. the distance to Jupiter varies between -1 and 6 AU). When the buffer is near empty, another gulp is read from the tape, The recorder can store the data equivalent of about 150 full-frame, full-resolution images. Generally, not all the recorded data can be returned between the encounters at the desired compression and priorities are assigned via uplinked "playback tables" to determine what is returned. Engineering and low-rate fields and particles science data are typically fed to the buffer in parallel with the data read from the tape. This operational scenario was very ambitious in its design; - performance to date has been outstanding. Galileo is meeting a large majority of its original science objectives in this manner and may well far exceed some of them.

Project Galileo is indeed performing superbly at Jupiter—a most fitting tribute to its namesake Galileo Galilei of Padova!

ACKNOWLEDGMENTS

Project Galileo represents the work of thousands of people. They all deserve acknowledgment for the many accomplishments of Galileo to date and for the tremendous promise it is now' fulfilling at Jupiter.

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