The Galileo Mission to Jupiter: Interplanetary Cruise Post-Earth-2 Encounter Through Jupiter Orbit Insertion

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This article documents DSN support for the Galileo interplanetary cruise after the December 1992 Earth-2 flyby through the Jupiter Orbit Insertion in 1995. It includes the asteroid Ida encounter and playbacks and Shoemaker–Levy 9 comet support.

I. Introduction

The Galileo spacecraft made its second and final encounter with Earth as it passed its point of closest approach (C/A) 303 km over the South Atlantic Ocean on December 8, 1992. This, the last of three planetary gravity assists (Venus–Earth–Earth), changed the spacecraft velocity slightly so that its elliptical orbit would intersect the orbit of Jupiter on December 7, 1995, about 780 million km from the Sun. The navigational accuracy, based on DSN radiometric data enhanced with Galileo optical navigation data, was nearly perfect. Galileo was within 1 km of its intended path and 0.1 s early at its arrival point.

Following the Earth encounter, further attempts were made to unfurl the partially deployed high-gain antenna (HGA) by intensive hammering of the antenna drive motors. Some small movement of the unfurling mechanism was detected, but there was no indication of rib release. By the end of January 1993, a total of 13,320 motor “hammer” pulses had been accumulated, and the Project concluded that there was no longer any significant prospect of deploying the HGA. The Project, therefore, decided to proceed to implement the Galileo S-band Mission using only the LGA, confident of achieving at least 70 percent of its primary objectives, all of the atmospheric Probe Mission, and several thousand high-resolution Jupiter satellite images. The Telecommunications and Data Acquisition (TDA) support provided to the Galileo Project by the DSN and other agencies prior to January 1993 is documented in [1,2].

This article describes the TDA support provided by the DSN and other agencies to the Galileo Mission redefined as described above by the Project in January 1993. It covers the interplanetary cruise segment of the mission—February 1993 through Jupiter Orbit Insertion (JOI) in December 1995.

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II. The Galileo S-Band Mission

A. Background

From the time of its launch in October 1989 until the planned HGA deployment in April 1991, the Galileo spacecraft relied on S-band (2.3-GHz) uplinks and downlinks for its telecommunications (telecom) support by the DSN. These links were used for telemetry, command, navigation, and radio science. After the HGA deployment, the mission was to have used the X-band (8.4-GHz) capabilities of both the spacecraft and the DSN to provide the additional telecommunication performance margin required to meet all of the mission objectives at maximum Earth-to-Jupiter range. The DSN configuration that was used to support the original design of the mission is discussed in [2]. However, the HGA deployment in April 1991 was not successful and, despite intensive efforts to recover the HGA over the following 2 years, the HGA remained unusable.

Meanwhile, both the Project and the DSN had studied the feasibility of continuing the mission using only the existing S-band capability and the low-gain antennas (LGAs) on the spacecraft. These studies showed that, with the addition of data compression and new coding to the spacecraft flight software, together with a substantial enhancement in DSN receiving capability at S-band and improved data processing at JPL, a viable Galileo Mission to Jupiter could be achieved. Because of the long lead time required to implement the new DSN capabilities required for Galileo operations at Jupiter, the DSN began design and development almost immediately, and by February 1993 when the decision to commit the Galileo Mission to S-band was made, the DSN had made substantial progress toward meeting the new requirements. Concurrent with the new implementation effort, the DSN continued to support the ongoing mission at low data rates consistent with the existing S-band capability, gradually upgrading and testing capabilities and facilities as the new hardware and software became available.

Significant mission events along the Galileo spacecraft trajectory during the period being discussed here are shown in Fig. 1. An overview of the Mission from 1993 through the end of the mission in 1997 is provided in Fig. 2.

B. Interplanetary Cruise

The basis for the DSN configuration for the Galileo S-Band Mission (hereafter referred to as the Mission) is given in the *Galileo Detailed Mission Requirements* document.[2] However, to support the low data rates transmitted by the spacecraft during the interplanetary cruise portion of the Mission through JOI, only the 70-m antennas at Goldstone (GLD), Madrid (MRD), and Canberra(CBR) were used; the the arrangement is shown in Fig. 3.

C. Orbital Operations

To support orbital operations in 1996 and 1997, when the science data return from Jupiter required much greater telecommunications performance, several 34-m antennas and the Parkes radio-telescope antenna were added in an arraying mode to the baseline network configuration. TDA support for this part of the Galileo mission will be discussed in a later article.

III. DSN Support for Galileo in 1993

A. General

Through most of 1993, the Galileo S-band downlink was able to sustain a telemetry data rate of 40 bps on the 70-m network. The round-trip light time, which was 8 min in March, had increased to over 74 min

[2] *Galileo Detailed Mission Requirements*, JPL D-10785 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 15, 1994.

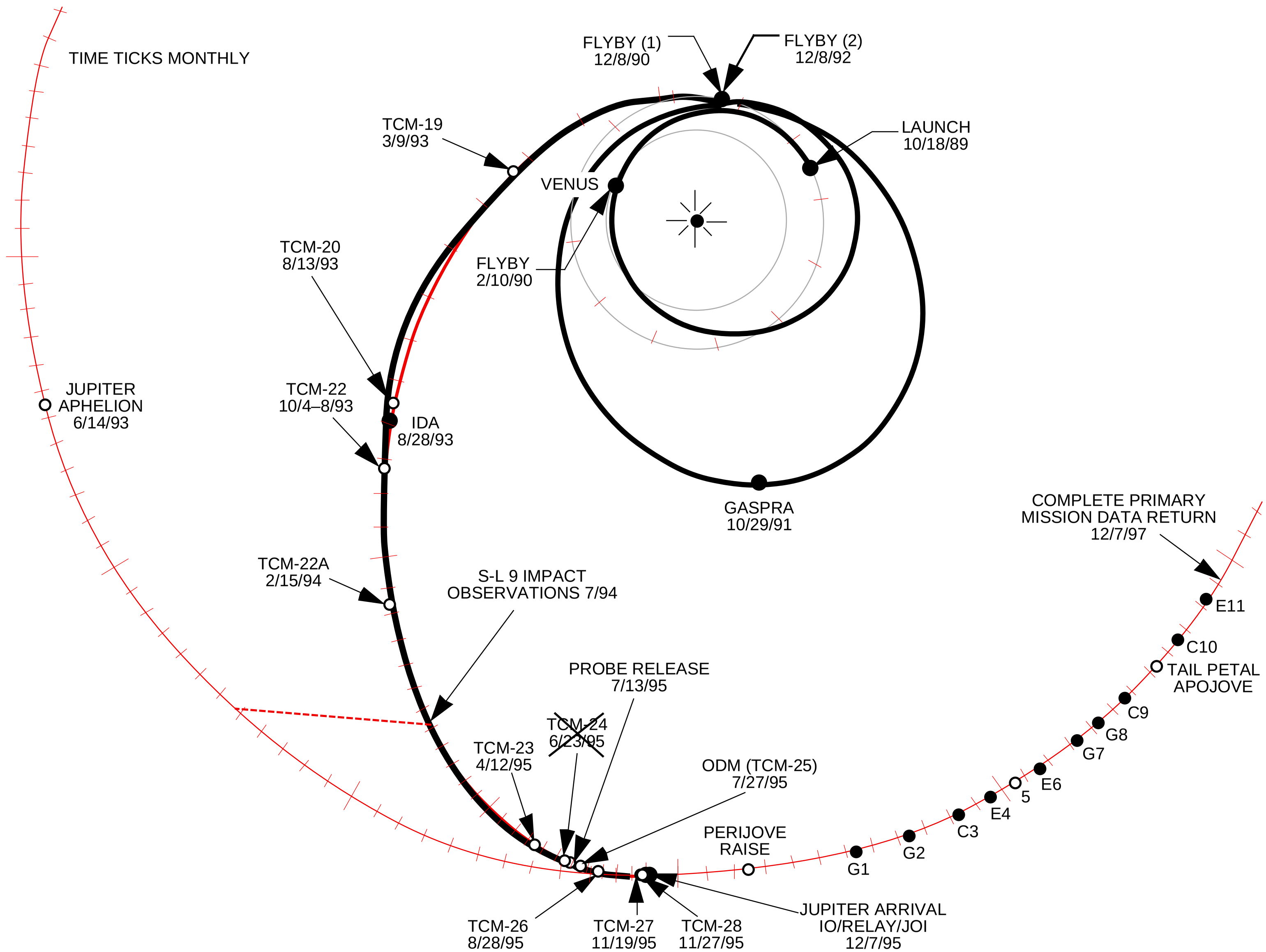
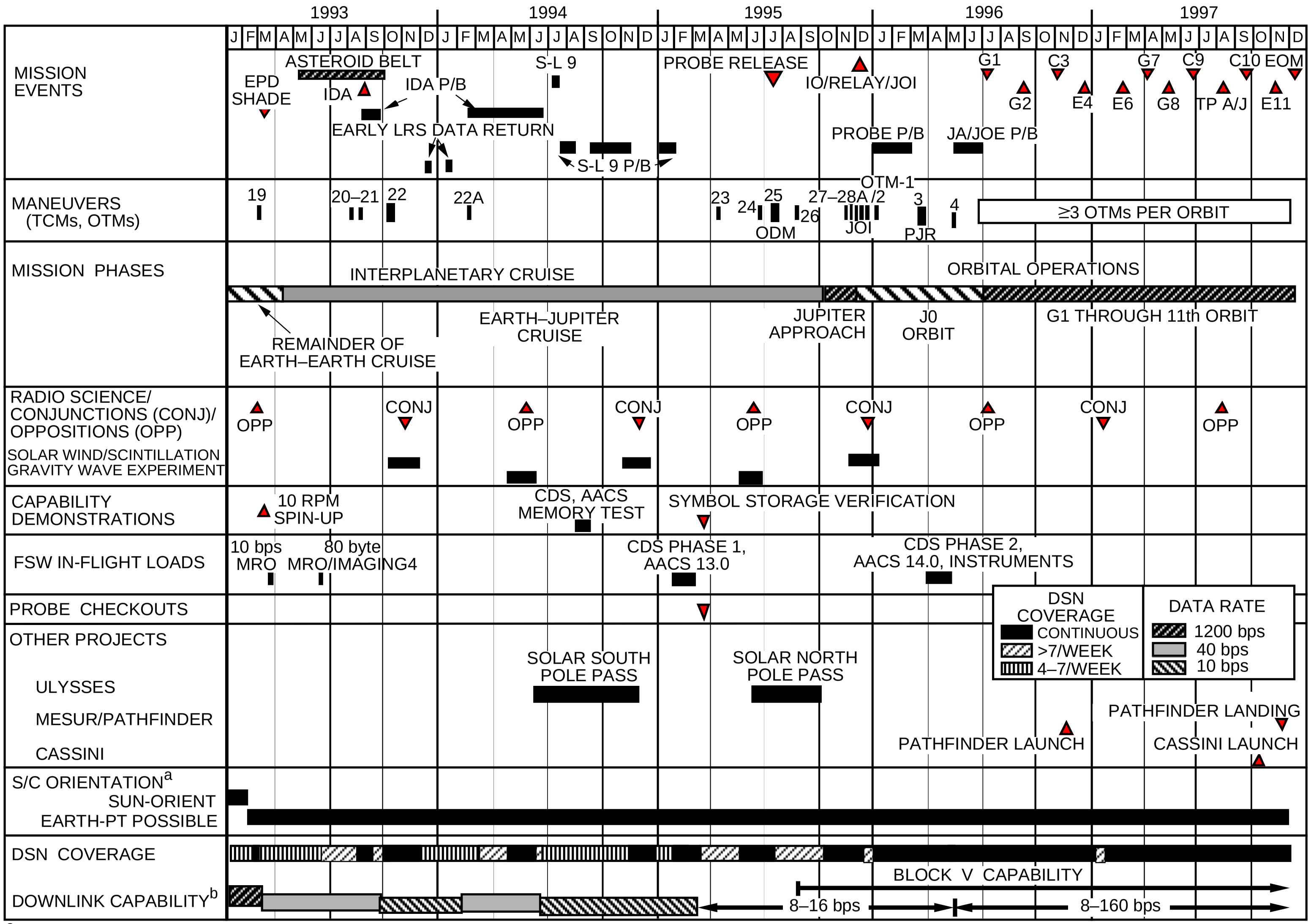


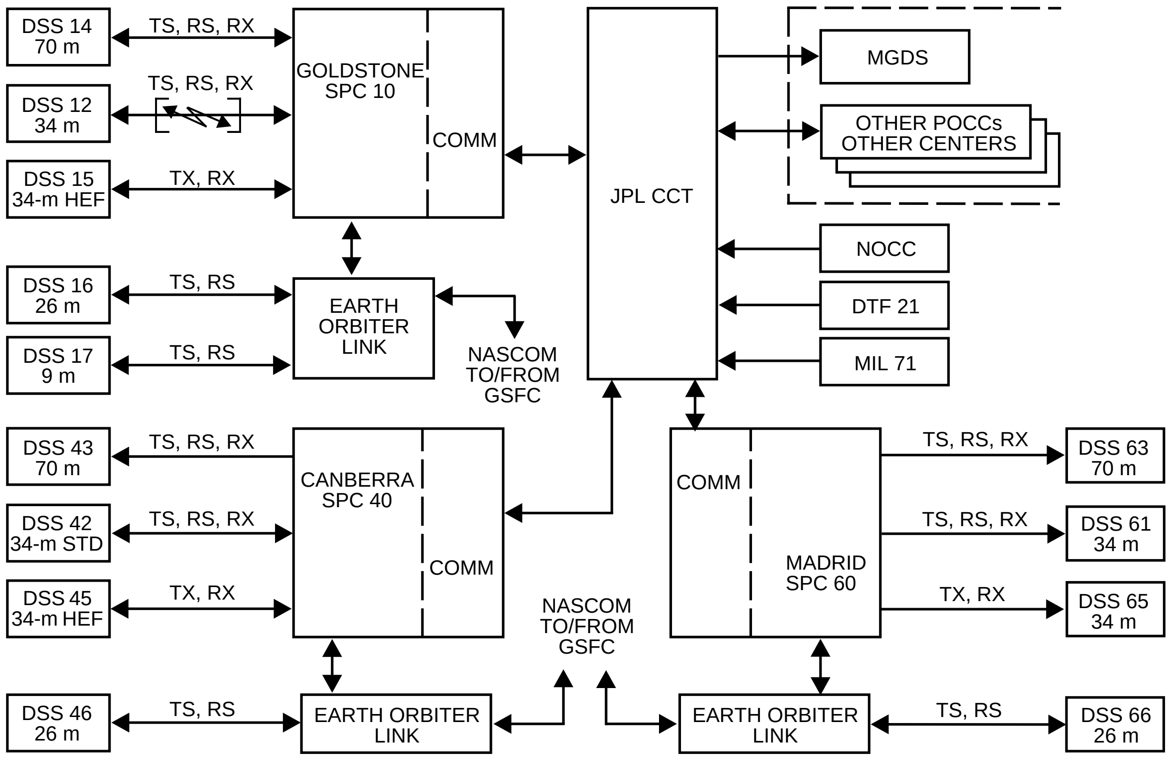
Fig. 1. Galileo spacecraft trajectory.



[a] THERMAL CONTROL CONSIDERATION ONLY. STAR SET AVAILABILITY TBD.

[b] DOWNLINK CAPABILITY SHOWN IS BEST CAPABILITY VIA LGA-1, S-BAND TRAVELING WAVE TUBE AMPLIFIER HIGH POWER TO SINGLE 70-m THROUGH 10/96, THEN GOLDSTONE 70-m/CANBERRA 70-/34-/34-/34-m/PARKES ARRAY.

Fig. 2. Galileo Mission overview for 1993 through 1997.



COMM = GROUND COMMUNICATIONS
MIL 71 = MERRIT ISLAND LAUNCH AREA
(FLORIDA) POCC = PROJECT OPERATIONS CONTROL CENTER
NOCC = NETWORK OPERATIONS CONTROL CENTER
GSFC = GODDARD SPACE FLIGHT CENTER
DTF = DEVELOPMENT AND TEST FACILITY

TS = TRANSMIT S-BAND
RS = RECEIVE S-BAND
RX = RECEIVE X-BAND
TX = TRANSMIT X-BAND
NASCOM = NASA COMMUNICATIONS

Fig. 3. The S-band network for the interplanetary cruise.

by November, when the diminishing link margin due to increased range forced a bit-rate reduction to 10 bps.

During the March through December 1993 period, the DSN provided the Galileo Project with 3821 actual hours out of 3884 hours of scheduled tracking time on the 70-m network. Minor outages due to weather, low film-height alarms, and some short-term failures accounted for the lost time. There was no time scheduled for tracking on the 34-m network. The average telemetry data capture rate for the period was 98.0 percent, and over 18,000 commands were correctly transmitted to the spacecraft. There were three command aborts due to DSN-related problems.

In October and November, several tests to observe the effects of solar conjunction on the “in-lock” stability of the command uplink (U/L) were carried out over Deep Space Station (DSS) 43 at Sun–Earth–Probe (SEP) angles ranging from 8.5 to 1.2 deg. The tests confirmed that the command detector unit (CDU) lock-up was intermittent and unstable when the SEP angle was less than 3.9 deg.

As part of the Signal Processing Center (SPC) upgrade, the new DSN command subsystem, the metric data assembly, and the DSN telemetry subsystem were integrated throughout the network and authorized for operational support after an extensive period of testing that included ground data system (GDS) tests with Galileo and demonstration tracks on Galileo and other spacecraft.

The development model of the advanced receiver was used at Goldstone to demonstrate fully suppressed carrier tracking with the Galileo spacecraft with an effective symbol signal-to-noise ratio (SSNR) of only -3 to -1 dB. The subcarrier and symbol tracking loops operated with an extremely narrow bandwidth of 30 mHz.

Both DSS 43 (from February through April) and DSS 14 (from October through December) were out of service for about 2 months for replacement of elevation bearings and overhaul of elevation and azimuth gear boxes as part of a program to minimize any chance of failure during Galileo support in the next 3 years. Both antennas returned to service on schedule.

Problems that affected Galileo during 1993 were the low-film height on the hydrostatic bearing, and the failure of the 400-Hz generator for the high-power transmitter (TXR) at DSS 14, and a power transformer failure at DSS 43 during the Ida encounter.

B. Routine Mission Operations

Navigation cycles that provide near-continuous acquisition of two-way Doppler and ranging data during consecutive passes of the spacecraft over DSS 63, DSS 14, and DSS 43 and back to DSS 63 were carried out several times throughout the year to improve the quality of the navigation data for Galileo. Delta differenced one-way range (DOR) passes were carried out between the station pairs of DSS 14/DSS 43 and DSS 14/DSS 63 as opportunity permitted. Four of the five scheduled delta DOR passes were successful, and one was lost due to the Mars Observer emergency.

Seven tests of the spacecraft ultrastable oscillator (USO) were made to verify the state of the USO for long-term trend analysis and to collect Gravitational Red Shift Experiment data. Memory read-outs (MROs) for low-rate cruise science instruments, the extreme ultraviolet (EUV) instrument, the dust detector subsystem (DDS), and the magnetometer (MAG), continued throughout the year.

The DSN supported three trajectory correction maneuvers (TCMs): on March 19 (TCM-19), on August 13 (TCM-20), and from October 4 through October 7 (TCM-22), although the final portion of TCM-22 was delayed due to a problem at DSS 43. TCM-21, which was planned to execute just prior to the Ida encounter, was determined to be unnecessary and was cancelled by the Project. TCM-22 was the largest of the 10-N maneuvers and imparted a 38.6 m/s change to the spacecraft velocity to target the Galileo Probe to its entry corridor for release in July 1995.

Beginning in May, the advanced multimission operations system (AMMOS)/multimission ground data system (MGDS) command system began testing with various DSN stations. These tests also validated the flow of DSN monitor data through the MGDS. Problems that occurred in the early tests were corrected, and the later tests were successful. On the basis of these tests and a period of parallel operation with the old Mission Control and Computing Center (MCCC) command system, the Project transitioned to the new MGDS command system on October 26.

C. Ida Encounter

The asteroid Ida encounter event on August 28 is shown on the mission events timeline in Fig. 2. The closest approach to Ida occurred at 10:22 a.m. Pacific Daylight Savings Time (PDT) over DSS 63. The Project had planned to acquire five optical navigation (OPNAV) images prior to encounter to enhance the radio metric navigation accuracy. All three 70-m antennas were needed to retrieve the telemetry images, and the playback (P/B) time for each optical frame was approximately 32 h at 40 bps. However, the spacecraft experienced several bus resets that precluded OPNAV #1 and OPNAV #3, and DSN recovery efforts for Mars Observer resulted in partial loss of OPNAV #5. Nevertheless, the final navigation estimate indicated Galileo was well within science targeting requirements, making a planned correction maneuver (TCM-21), unnecessary. It was, therefore, cancelled.

At Ida minus 4 h 16 min, the spacecraft unexpectedly turned off its gyros and switched to cruise mode. Recovery of the scan platform pointing position required transmission of a precisely timed command at Ida encounter minus 3 h 18 min. This was followed by additional real-time commanding after the closest approach to restore the configuration for subsequent sequence events. The DSN was able to support all this unplanned activity by making a rapid reconfiguration of DSS 63 from its low-noise, listen-only mode to provide the necessary command uplink support.

Data playback at 40 bps began on September 3 and continued nominally until September 5, when DSS 43 suffered a failure of the 1000-kVA power transformer. Since DSS 43 was a key station in the Ida image return sequence, a 24-h work schedule was put into effect to meet a return-to-service date of September 12. Additional coverage was rescheduled from DSS 14, and DSS 63 coverage was extended whenever possible to maintain the image data return plan. Real-time commands were required on September 6, 7, and 8 to replay image data that had not been received on the ground and to reposition the tape recorder for subsequent sequence-controlled MRO events. The final playback of the Ida imaging was completed on September 22, by which time all five frames of the Ida image had been acquired by the DSN. On September 23, as planned, real-time commands were sent to switch the downlink rate from 40 bps to 10 bps at the end of the Earth–Jupiter sequence #3 (EJ-3) and to turn the two-way noncoherent (TWNC) mode off for the start of EJ-4.

D. Radio Science

The DSN generated closed-loop and open-loop radio science (RS) data to support a joint Gravitational Wave Experiment with Mars Observer and Ulysses in March and April 1993.

During superior conjunction (November 5 to December 2), the Galileo Solar Wind Scintillation Experiment was supported by using DSS 12 connected to the DSN spectrum processor at SPC 10 via an RF-to-IF downconverter and a fiber-optic circuit. The radio metric and open-loop radio science data generated for the experiment were to be correlated with similar data derived from Ulysses, which was operating out of the ecliptic.

IV. DSN Support for Galileo in 1994

A. General

In 1994, the Galileo S-band downlink was able to support 40 bps between March and late June. For the rest of the year, it remained at 10 bps. During the year, Galileo received 5318 actual hours out of 5396 hours of scheduled tracking time on the 70-m network. There was no time scheduled on the 34-m antennas. Minor outages due to weather, low film-height alarms, and short-term failures accounted for the lost time. The DSN transmitted 98,660 commands to the spacecraft with zero aborts, and the average telemetry data capture rate for the year was 98.6 percent. No time was lost in 1994 due to DSN-scheduled antenna downtime.

Solar conjunction occurred on December 1 at a Sun–Earth–spacecraft angle of approximately 0.2 deg. Reliable telemetry could not be processed until December 6 when the Sun–Earth–spacecraft angle exceeded 4.0 deg. During December, several command tests were performed at DSS 63 to determine if the spacecraft CDU would acquire and maintain lock at Sun–Earth–spacecraft angles ranging from 10.0 to 6.0 deg. Spacecraft telemetry confirmed that the CDU locked up and remained in lock throughout the test.

Galileo participated in two DSN multimission verification tests on December 29, 1993, and January 6, 1994, with SPC 10. The test objective was to verify the new Type B telemetry processor assemblies (TPAs). The tests verified telemetry (40 and 10 bps) and monitor (MON 5-9/5-11/5-15) data through the new Type B TPA string. The new Type B TPAs entered the DSN soak at DSS 63 on January 17, and the new Galileo data rates of 8 bps and 16 bps were demonstrated at that time.

In the initial tests in February, the block V receiver (BVR) locked up on the Galileo residual carrier but was unable to lock up on the Galileo subcarrier in the low power mode at a modulation index (MI) of 90 deg (suppressed carrier). Some design modifications were made and, in a further series of tests in October, November, and December, the BVR acquired (with predicts) and tracked the Galileo signal at all modulation index settings, including the suppressed-carrier mode, and flowed telemetry to JPL. Doppler data were recorded with the metric data assembly (MDA). The tests successfully demonstrated BVR suppressed-carrier acquisition and tracking. A final report was issued in late January 1995.

The performance of the full-spectrum recorder (FSR) channel was verified with Galileo data from the BVR passes of February 21 and March 3. The test results showed excellent agreement with theory and predictions in terms of SNR, harmonic contribution, and tracking-loop performance.

The latest software was installed in the last of five telemetry subsystem groups at each of the complexes at Goldstone, Canberra, and Madrid in May and June as part of the SPC data system upgrade. The software was immediately put into soak testing on live spacecraft data.

Galileo telemetry data that were acquired simultaneously at DSS 14 and DSS 15 earlier in the year were successfully combined using a prototype of the full-spectrum combiner (FSC) in June 1994. The FSC is one component of the DSN Galileo telemetry (DGT) subsystem that was being built to enhance DSN downlink performance for the orbital operations phase of the Galileo mission. The mean combining gain achieved with the experimental data was within 0.02 dB of the gain expected from perfect combining. The FSC combining gain was required to be within 0.1 dB of perfect combining. Later experiments would test the performance for intercontinental combining using DSS 43 and DSS 14. The tests were successful, and results were consistent with theory.

The introduction of industry standard protocol and the use of commercial software to provide the wide area network connections between a Deep Space Communications Complex (DSCC) and the central communications terminal (CCT) at JPL were demonstrated in data flow tests conducted with the new Ground Communications Facility (GCF) routers at Goldstone (GDSCC) and the CCT in July.

All 70-m DSN antennas were operational in 1994 and, except for minor short-term problems, no time was lost due to antenna downtime. There were no significant problems in the DSN that affected Galileo support in 1994.

B. Routine Mission Operations

The Project conducted two GDS tests with DSS 63 in February to verify successful integration of the MGDS software into the Galileo GDS. Running in parallel with the mission telemetry system (MTS), the MGDS successfully handled telemetry (40, 10, 16, and 8 bps) and monitor and command data from the DSN. In addition, the test verified the new Galileo phase 1 flight software telemetry rates (8 and 16 bps) through the new DSN Type B TPA. After reviewing the status of parallel operations, the Project decommitted the former MTS on August 19. The MTS had processed the Galileo telemetry data from the DSN since launch. All future Galileo telemetry operations would use the more powerful advanced multimission operations system (AMMOS)/multimission ground data system (MGDS). Established DSN interfaces via the GCF were not affected.

Several tests to verify the condition of the spacecraft's ultrastable oscillator (USO) and to collect data for the Gravitational Red Shift Experiment were carried out throughout the year.

Only one trajectory correction maneuver (TCM-22A) was required in 1994, and this was successfully accomplished at 10 bps on February 15. This TCM imparted a 0.1-m/s change to the spacecraft velocity and aimed the spacecraft at a point inside the Probe's required Jupiter atmosphere entry corridor.

The downlink data rate was switched from 10 to 40 bps in March, as was planned for this portion of the mission, to start playback of the remainder of the Ida science data. The playbacks included the low-resolution near-infrared mapping spectrometer (NIMS) data as well as the high-resolution imaging data. Ida science data return continued to completion through the end of June, by which time 98.7 percent of the science data transmitted by the spacecraft had been successfully received by the DSN and processed through the GDS.

The DSN experienced only minor outages due to weather and short-term equipment problems during its support of the Ida science data return.

On August 29, the dual-drive motors on the spacecraft HGA were pulsed 1080 times in a final, but unsuccessful, attempt to free the stuck ribs before the start of the pre-Jupiter activity.

C. Comet Shoemaker–Levy 9 (S-L 9)

Five of the eleven science instruments on board the spacecraft were able to observe the S-L 9 comet impacts on Jupiter, with most of the opportunities being assigned to the NIMS and solid-state imaging (SSI) instruments because of their greater likelihood of success. Most of the observations were stored on the tape recorder, which holds the equivalent of 130 SSI full-resolution images. Due to the telemetry limitation of 10 bps, only about 5 percent of the tape contents could be played back. The time available for playback was constrained by the activities of 1995, beginning with the phase 1 in-flight load. After that, spacecraft operations were consumed with preparations for the Probe release, the Orbiter deflection maneuver, and then the JOI. The S-L 9 observations began on July 16 and continued through July 22. Playback of the science data return commenced in early August and continued through January 1995, with an interruption between November 27 and December 5, 1994, due to solar superior conjunction.

D. Radio Science

The DSN generated closed-loop Doppler data and open-loop radio science data for the Gravitational Wave Experiment in April, May, and June. The DSN also provided support for the Galileo Solar Wind Scintillation Experiment as the spacecraft approached superior conjunction. However, between November 28 and December 5, downlink carrier acquisition became impossible as the SEP approached 0.7 deg. After conjunction, the experiment resumed and continued through December 28. The DGT also gathered data during the conjunction to try to understand the effects of the solar noise on the telemetry processing. Combining losses indicated that the solar noise was somewhat quiet for this conjunction.

V. DSN Support for Galileo in 1995

A. General

The Galileo S-band downlink was able to sustain a data rate of 10 bps through January and February 1995 and from 8 to 16 bps for the rest of the year. During the year, Galileo received 6234 actual hours out of 6390 hours of scheduled tracking time on the 70-m network. Minor outages due to weather, two earthquakes (at Goldstone), and short-term failures accounted for the lost time. There was no time scheduled for 34-m support this year. The DSN transmitted 103,779 commands to the spacecraft with one abort, and the average telemetry data capture rate for the year was 97.8 percent. In 1995, repair and rehabilitation of the 70-m antennas occupied a total of 105 days.

In January, the results of the suppressed-carrier tests that were performed with the spacecraft in October, November, and December 1994 were reviewed. It was confirmed that the block V receiver (BVR) and full-spectrum recorder (FSR) could successfully track the Galileo spacecraft in the suppressed-carrier mode, even during periods of low SEP near conjunction. In addition, it was concluded that the FSR and full-spectrum combiner (FSC) had successfully demonstrated the capability of combining the Galileo signals received from the DSS-14 and DSS-43 70-m antennas in an intercontinental array. On the basis of these results, it was decided that the BVR would be used at Goldstone and Canberra for Galileo support during the Probe release and orbit deflection maneuver (ODM) in July. It would also be used for continuous support starting in September and would cover the Probe relay, the Jupiter Orbit Insertion (JOI) in December, and the subsequent return of the Probe science data.

Because telecommunication performance measured during the 1994 tests was approximately 1-dB below the predicted values, it was recommended that the prediction program used for mission planning and selection of data rates should reflect the actual measured performance of the BVR rather than the theoretical values. The 1-dB reduction in expected performance would not affect relay/JOI support, since there were ample margins for the required 10-bps data rate. However, data return following JOI would be affected and had to be replanned.

A test on November 26 over DSS 43 showed no difference in Doppler quality resulting from a telemetry modulation index change from 90 deg (suppressed carrier) to 58 deg (residual carrier).

Based on the Telecommunications Science and Engineering Division's analysis of solar noise degradation of the BVR tracking-loop performance in the suppressed-carrier mode, a special configuration table was developed for use during Galileo Jupiter arrival day activities, when solar effects would be most severe. The special configuration table was installed, tested, and approved for use at all 70-m sites in time to support DSN operations on December 5, when the spacecraft transitioned from the suppressed-carrier to the residual-carrier mode.

By mid-May, BVRs had been installed at all DSCCs, and testing with the new MDA and antenna pointing assembly (APA) had been completed. In May, June, and July, the BVR was demonstrated in GDS tests at DSS 14 and DSS 43. During these tests, the BVR locked up on the spacecraft suppressed-carrier downlink, and telemetry data at 8, 10, and 16 bps from DSS 14 and DSS 43 were processed and displayed in the Galileo Mission Support Area (MSA). Good two-way Doppler data were also generated and verified by Galileo navigation. Compared to the block IV receiver, the BVR data showed greatly reduced receiver high-frequency noise characteristics and were virtually free of cycle slips, even for SEP angles as low as 5.7 deg. For 1-s Doppler samples, the data noise was reduced by at least a factor of three. As was planned earlier in the year, the BVR successfully supported the Galileo ODM activities in late July as prime support at DSS 14 and DSS 43 with the spacecraft in the suppressed-carrier mode.

To collect data to refine telecommunication performance prediction parameters, a 16-bps telemetry performance test was performed over DSS 14 in September. The BVR was used while the spacecraft was in the suppressed-carrier mode. Ground monitor data were collected over a range of uplink transmitter power levels.

On September 11 in a test over DSS 63, the BVR locked up on the Galileo suppressed-carrier and telemetry at 8, 10, and 16 bps was successfully received and processed at JPL. Upgraded metric data assembly (MDA) software provided acceptable Doppler data during the test. With this test, the BVR had been fully implemented and demonstrated throughout the 70-m network. Finally, on September 18, the Galileo spacecraft was switched to the suppressed-carrier downlink configuration that, together with the BVR at the 70-m stations, would be the standard mode of operation.

The Goldstone 70-m antenna was taken out of service for 6 weeks in April to complete the regrout of the hydrostatic bearing and rehabilitation of the subreflector. The 70-m antenna at Canberra was taken out of service for 7 days in May for installation of the ultracone to provide enhanced S-band downlink capability for the Galileo mission. Replacement of the subreflector rotation mechanism required that DSS 63 be taken out of service for about 4 weeks in August. Similar work was carried out at DSS 43 in September, as well as the azimuth runner regrout, structural strengthening, the high-power motor generator set overhaul, and radial bearing maintenance. Two earthquakes (in August and September) in the general area of Goldstone caused short interruptions to DSS 14 service to Galileo. The antennas were inspected prior to resumption of service, but no damage was found.

On November 14, during the uplink of a critical relay/JOI command sequence, the DSS-14 antenna went to brake because of a film-height alarm, thereby interrupting the uplink process. The DSS-43 antenna was brought up early, and the sequence was completed satisfactorily. This event was to influence the Project decision to request a "battle short" (i.e., to override certain alarms and continue to track) condition for DSS 14 and DSS 43 on December 7 to cover the Probe relay/JOI events. After considerable discussion, the DSN agreed to maintain a battle short configuration at DSS 14 and DSS 43 on JOI day and the day after to cover the orbit trim maneuver (OTM). Since the OTM was cancelled, the "battle short" requirement for that day was withdrawn.

For various technical reasons, the overhaul of the high-power motor generator of DSS 43 could not be completed during the September downtime. It eventually had to be transported to the U.S. for repair. As a result, the Galileo Project had to redesign its uplinks for DSS 14 and DSS 63 only until the motor generator was restored on November 4.

B. Routine Mission Operations

The Galileo Project continued to carry out routine spacecraft operations management, which included DMS (DMS tape recorder) conditioning, USO tests, retropropulsion (RPM) 10-N flushing activity, and a checkout of the SSI. A variety of routine telemetry tests involving the spacecraft command and radio systems were carried out periodically to provide detailed information relative to telecommunication hardware functionality and performance.

Playback of the Shoemaker–Levy 9 science data was finally completed on January 29. Preliminary analysis indicated all the data were received properly in real time or during post-pass processing during periods of scheduled DSS-14 maintenance.

Phase 1 of a two-phase package of new flight software was successfully uplinked to the spacecraft in February. The purpose of the new software was to compensate for the fact that without the HGA the Probe data could not be transmitted to Earth in real time. The DMS tape recorder was to have been used as backup to the real-time link but became the primary method of data acquisition. The new software enabled the command and data subsystem (CDS) memory to be used for backup data storage through the primary Probe mission. The phase 2 flight software will be sent to the spacecraft in May 1996 to be used in conjunction with the DSCC Galileo telemetry (DGT) subsystem for mission support starting immediately thereafter.

TCM-24, planned for June, was not needed since it was determined that TCM-23 had already achieved the desired Probe aim point accuracy. TCM-25 was the actual RPM burn for the ODM, and TCM-26 was used to fine tune the spacecraft trajectory to the Io–Jupiter encounter aim point by removing the small trajectory errors due to the ODM underburn of 1.2 percent. These events are shown in the mission timeline in Fig. 2.

Navigation cycles carried out in June and August provided acquisition of Doppler data during four consecutive passes of the spacecraft over DSS 14, DSS 43, and DSS 63 and then back to DSS 14.

Regular MROs provided cruise science data acquisition from the low-rate science (LRS) instruments throughout the year. Additional MROs on the dust detector instrument were performed in August to collect data on the greatest Jovian dust storm so far observed in the Galileo Mission. Jupiter approach (JA) science MROs were performed frequently throughout November and December.

With the transmission of the Jupiter approach-sequence memory load to the spacecraft in October, the Project transitioned from the interplanetary cruise phase of the mission to the orbital operations phase, as shown in Fig. 2.

On October 10, the SSI camera was turned on in preparation for taking the Jupiter approach global image (JAGI) the following day. After the image was recorded, the tape recorder failed to respond correctly to the playback commands, and subsequent MROs of the JAGI image were cancelled. Several diagnostic tests were carried out, and it was concluded that, although the tape recorder was not damaged and could run and read its tape in a normal manner, a section of the tape may have been damaged and should not be used. The recorder was commanded to rewind the potentially damaged part of the tape and cover it with approximately 25 wraps of tape as a precaution against further trouble. Subsequent engineering telemetry data indicated that the recorder was responding normally to record and replay commands. As a consequence of the recorder anomaly, subsequent mission sequences were modified to eliminate or minimize the use of the recorder in order to preserve its availability for the Probe entry science data capture and playback activity. Additional confidence in the tape recorder functionality was provided by three checks carried out in mid-November in which real-time commands were sent to select, move, and read tape records for short specified periods. Engineering telemetry indicated that the recorder responded correctly.

To prepare DSS 14, DSS 43, and DSS 63 for supporting the relay/JOI activity, ground data system (GDS) tests were conducted by the Project in October and November.

As a contingency measure, the Project had developed the capability to conduct all Galileo mission operations from Goldstone in the event that a natural disaster precluded operations at JPL. A key element of the Galileo Emergency Project Operation Center (EPOC) was the capability to command the spacecraft through any DSN 70-m antenna. This capability was demonstrated successfully on November 2 by transmitting a command to the spacecraft through DSS 63.

C. Probe Release and Orbit Deflection Maneuver

The Probe release sequence began on July 5 with the Probe power-up sequence, status check, and the setting of the coast timer. The Probe transferred to internal power on July 7, and telemetry verified that the Probe cable "cut" command executed correctly on July 10 at 10:26 p.m. On July 11, under stored sequence control, the spacecraft turned to the Probe release attitude in preparation for the spin-up that initiated at 01:37 a.m. on July 12 and completed 27 min later. "GO" commands were sent at 08:31 a.m. to initiate Probe release at 11:07 p.m. The Probe release executed nominally, with the first indication of release being a change in the spacecraft Doppler data of -0.6 Hz. Subsequent telemetry readings of the Probe separation switches indicated that the Probe had separated from the Orbiter as planned. The timeline for the Probe separation activity is shown in Fig. 4.

The ODM sequence began at 01:32 a.m. on July 17 with verification of the proper operation of the propulsion system latch valves. On July 21, under stored sequence control, the spacecraft turned from the Probe release attitude to the ODM burn attitude. The ODM burn, which started at 12:38 a.m. on July 27, had a duration of 308 s, performed nominally, and was well within specification. (Note that all times are Earth-received time (ERT) and are given in PDT.)

D. Probe Data Relay and Jupiter Orbit Insertion

To permit the Probe radio oscillators to temperature stabilize, on November 27 they were turned on, and the following day the spacecraft transitioned to the dual-spin mode in preparation for relay/JOI activities.

On November 30, the first phase of the Jupiter zero orbit encounter (JOE-A) prime sequence memory load, which covered spacecraft activities from December 3 to December 7, was uplinked to the spacecraft. The J0E-B prime sequence memory load, which included the critical relay/JOI time period, was uplinked to the spacecraft on December 1. On December 4, the JOE-C sequence memory load, which covered spacecraft activities from December 8 to January 3, 1996, and included the return of Probe symbol data along with windows for orbit trim maneuvers (OTMs) 1 and 2, was uplinked to the spacecraft over DSS 14 without incident.

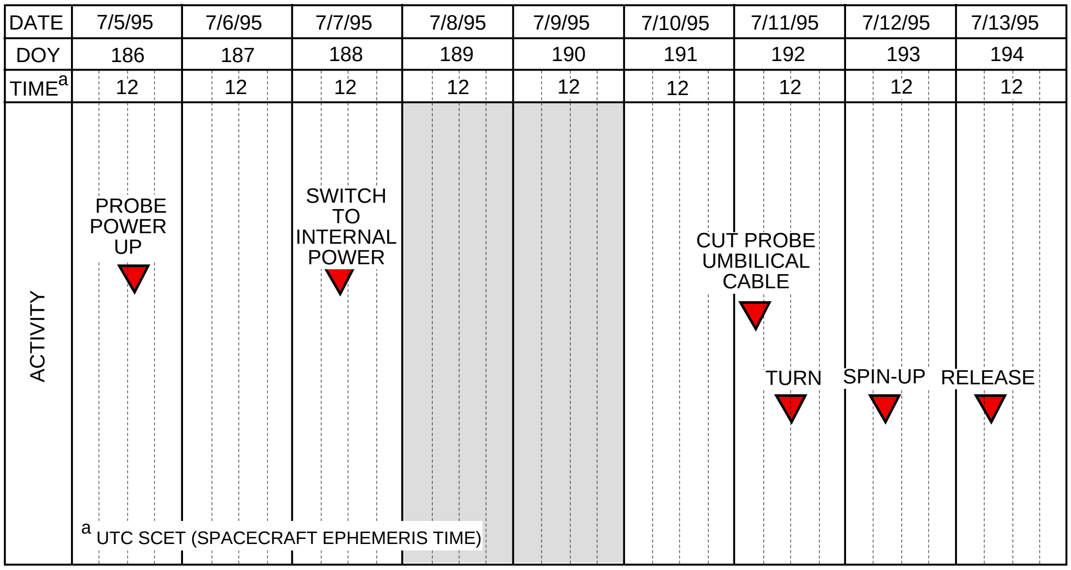


Fig. 4. The Probe release timeline.

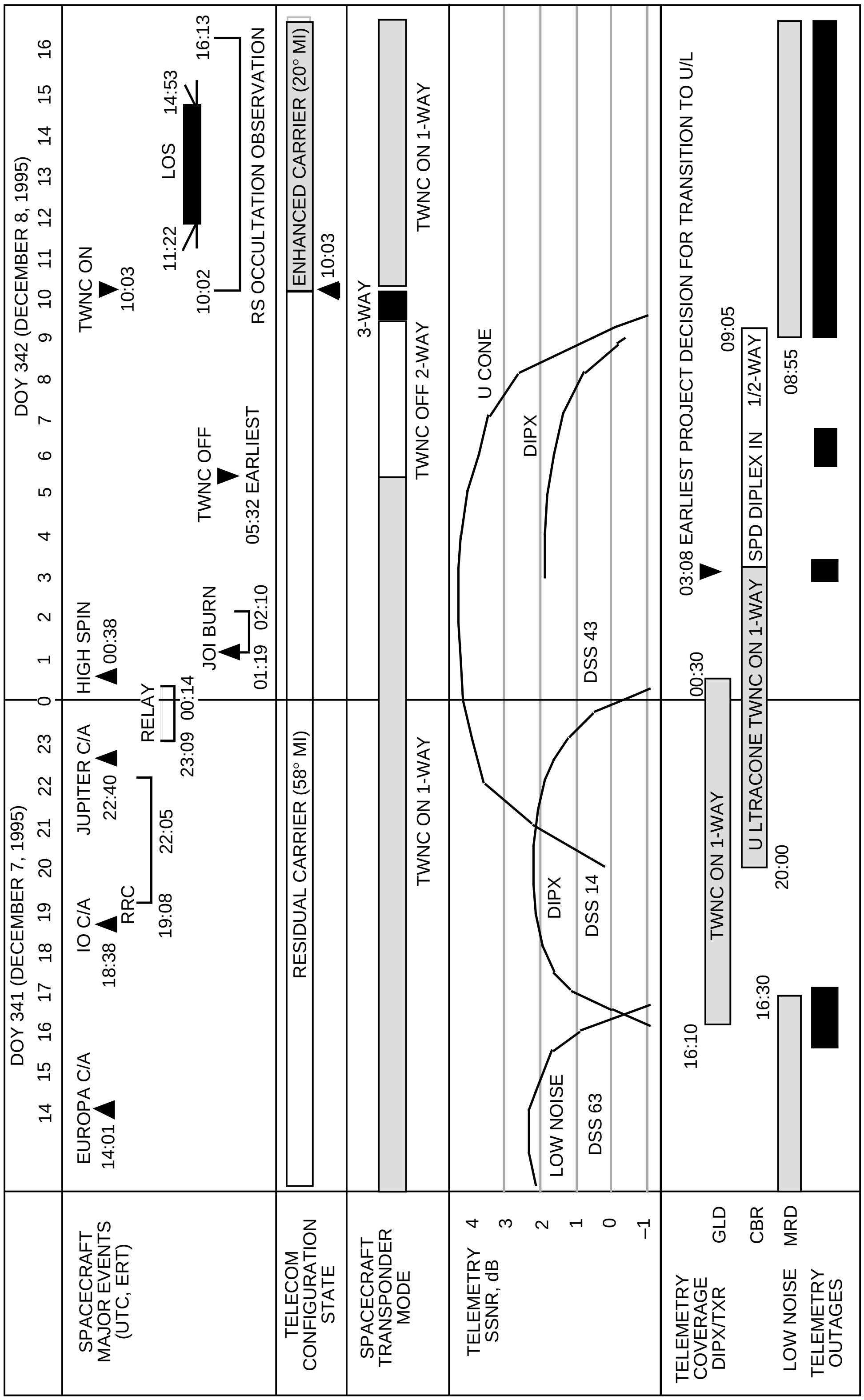
The spacecraft downlink transitioned from the suppressed-carrier mode (modulation index 90 deg) to the residual-carrier mode (modulation index 58 deg) on December 5 to minimize solar degradation in the BVR receivers at all 70-m stations. On December 6, the relay radio hardware (RRH) receivers on the spacecraft were turned on in preparation for the Probe relay.

The Galileo spacecraft arrived at Jupiter on December 7, 1995, during the overlapping view periods of DSS 43 and DSS 14, as shown in Fig. 5. With the exception of a brief problem with the high-power transmitter at DSS 14 caused by a coolant leak, both stations supported these critical Galileo passes without incident. Jupiter closest approach was at 2:46 p.m., and Probe relay started at 2:59 p.m. [Note that all times are Earth-received times and are given in Pacific Standard Time (PST).]

The relay radio antenna (RRA) was repositioned four times between 3:28 p.m. and 3:58 p.m. to maintain pointing at the Probe's location in Jupiter's atmosphere. Downlink telemetry at 3:10 p.m. and 3:22 p.m. verified that the RRH receivers were in lock. By 4:14 p.m., recording of Probe data was complete and the RRH receivers and oscillators were turned off. The RRA was then stowed, and spin-up to 10.5 rpm began in preparation for the JOI 400-N engine burn. The spin-up completed nominally at 5:05 p.m., and the 400-N engine burn began at 5:19 p.m. for a duration of 48 min 59 s, at which time the burn was terminated by the accelerometers. Preliminary results indicated a slight underburn of 0.1 percent.

From the DSN perspective, support for the Probe and JOI events was very nominal. Both receivers at DSS 43 maintained lock and provided good Doppler residuals throughout the burn to verify JOI burn performance. Based on the highly precise targeting performance of the spacecraft, the Project decided that no OTMs would be required prior to the perijove raise maneuver scheduled for March 1996. A DSN briefing message notified DSS 63 of the cancellation of OTM 1. The first satellite encounter (with Ganymede) would now occur on June 27, 1996, one week earlier than previously planned.

With a solar separation angle of less than 7 deg on December 9, the spacecraft entered the solar conjunction period and minimum scheduled spacecraft activity. By 4:15 a.m. on December 10, MROs of the Probe data stored in the CDS memory began over DSS 43 at a data rate of 8 bps. Preliminary indications were that 57 min of data were transmitted from the Probe and recorded by the spacecraft



RRC = RELAY READINESS CONFIGURATION
DIPX = DIPLEXER
SPD = S-BAND POLARIZATION DIVERSITY

Fig. 5. Telemetry coverage for JOI.

prior to loss of the Probe signal. Actual tape playback would commence at the end of January 1996 and was expected to take about 2 months to complete at 10 and 16 bps. These data were to be forwarded to the Probe Science Team at Ames Research Center for analysis over the next several months.

As of noon Thursday, December 14, 1995, the Galileo spacecraft status was as shown in Table 1.

Table 1. Galileo spacecraft status on December 14, 1995.

Parameter	Status
Distance from Earth	940,117,300 km (6.3 AU)
Distance from Sun	793,205,000 km (5.3 AU)
Speed relative to Jupiter	21,700 km/h
Distance from Jupiter	5,180,900 km (0.03 AU)
Round-trip light time	104 min 32 s
Spacecraft attitude	5 deg off-Sun (leading) 5 deg off-Earth (leading)
Downlink telemetry rate	8 bps (coded) on LGA-1

E. Radio Science

Data taking for the second and final long round-trip light-time Gravitational Wave Experiment began on May 20 and ended on June 28, 1995. With the approach of superior conjunction, the Solar Wind Scintillation Experiment using the spacecraft radio frequency equipment resumed on November 24 and was completed on December 4. Open- and closed-loop radio science observations were made at DSS 43 and DSS 63 during the Jupiter occultation period on December 8.

VI. Conclusions

Support provided by the DSN from February 1993 through Jupiter Orbit Insertion in December 1995 included the following:

(1) In each of the 3 years reviewed here, the DSN supported a major Galileo event: asteroid Ida (1993), comet Shoemaker–Levy 9 (1994), and Jupiter arrival (1995), which included the first Jupiter occultation.

(2) The Project decision in January 1993 to change the mission from X-band to S-band because of the HGA problem had profound implications for the DSN. DSN operations had to be replanned and new hardware and software designed, implemented, and tested. Although most of the new development would not be required for operations until Jupiter orbit operations in 1996, a significant amount of operations and engineering effort was expended in these years in the installation, testing, and transfer to operations.

(3) Starting from an engineering model in 1993, the block V receiver reached maturity and provided invaluable support for the Jupiter arrival events in December 1995.

(4) Although the hydrostatic bearings on the 70-m antennas were extensively reworked in these years, film-height alarms remained a cause for concern but caused no problems at JOI.

(5) A solar conjunction and a solar opposition in each of the 3 years provided good data for radio science observations. Gravitational wave observations, some in conjunction with Ulysses, were also supported.

(6) An emergency control center for Galileo was established at Goldstone and could have supported all operations had that been necessary.

(7) Many resource scheduling problems that appeared intractable early in 1993 were eventually resolved by DSN scheduling to fully meet Galileo requirements for 70-m tracking time in each of the 3 years. The 34-m network was used only for test purposes during this time.

(8) Over the period from January 1993 to December 1995, the DSN maintained an average telemetry data capture rate of 98.1 percent. In the same period, the DSN correctly transmitted over 220,000 Galileo commands. There were four command aborts.

Acknowledgments

DSN support for Galileo Mission Operations was provided by elements of the Pasadena Operations, Madrid Operations, Canberra Operations, and Goldstone Operations organizations. Displaying a careful and conscientious attitude to routine responsibilities and a rapid and innovative response to unforeseen situations, these teams were essential contributors to the high quality of DSN support for Galileo in the years 1993 through 1995.

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