Deep Space Network Support for the Galileo Mission to Jupiter: Jupiter Orbital Operations From Post-Jupiter Orbit Insertion Through the End of the Prime Mission

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Deep Space Network (DSN) support for the Galileo mission to Jupiter began at launch in October 1989 and continued through the end of the prime mission in December 1997. The tracking and data acquisition support that was provided by the DSN up to the time that the spacecraft arrived at Jupiter (December 1995) is described in earlier issues of this publication [1–3]. This article, the final one of the series, covers the period from January 1996 through December 1997 and describes DSN support for the Galileo orbital operations at Jupiter, which included 10 satellite encounters over a period of 17 months.

For a substantial portion of this period, the DSN was operated in the fully arrayed configuration for Galileo passes. This involved real-time combining of spacecraft signals from the DSN 70-m and 34-m antennas at Canberra with those from the 70-m antenna at Goldstone. The combined signals were enhanced further by the addition of the signal from the Australian 64-m radio astronomy antenna at Parkes, located 260-km northwest of Canberra. This article describes the implementation and remarkable performance of this very complex arrangement under real-time operational conditions.

I. Introduction

Deep Space Network (DSN) support for the Galileo mission to Jupiter began at launch in October 1989 and continued through the end of the prime mission in December 1997. The major events that took place during this period are shown in sequence on the mission trajectory depicted in Fig. 1. The tracking and data acquisition services that were provided by the DSN up to the time of spacecraft arrival at Jupiter (December 1995) are described in [1–3].

This article, the final one of a series, covers the period from January 1996 through December 1997 and describes DSN support for the Galileo orbital operations at Jupiter, which included 10 satellite encounters over a period of 17 months. The overview of mission events for 1996 through 1997 shown in Fig. 2 amply illustrates the intensity of the mission operations activity that took place during this period.

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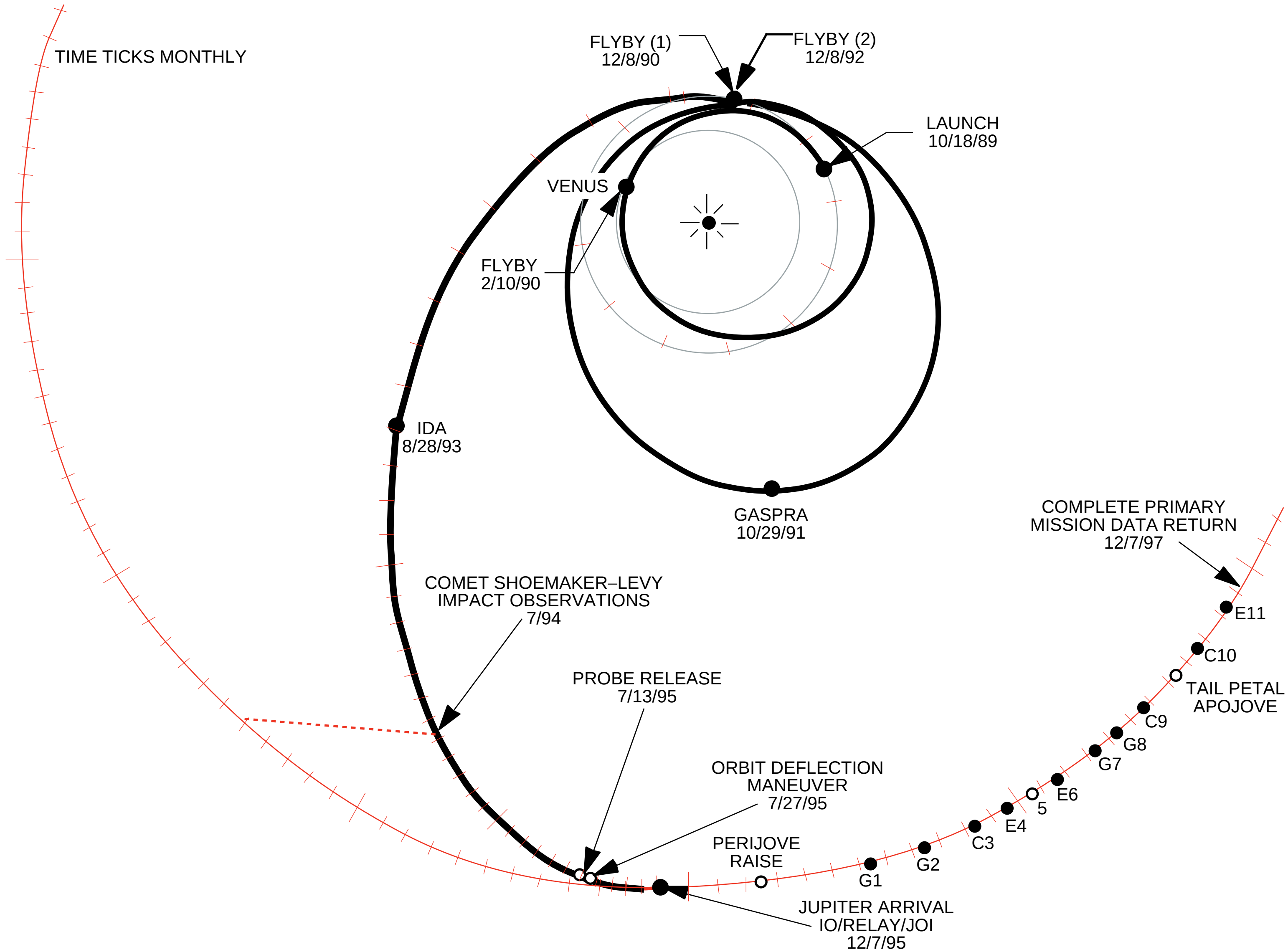

Fig. 1. Galileo prime mission trajectory.

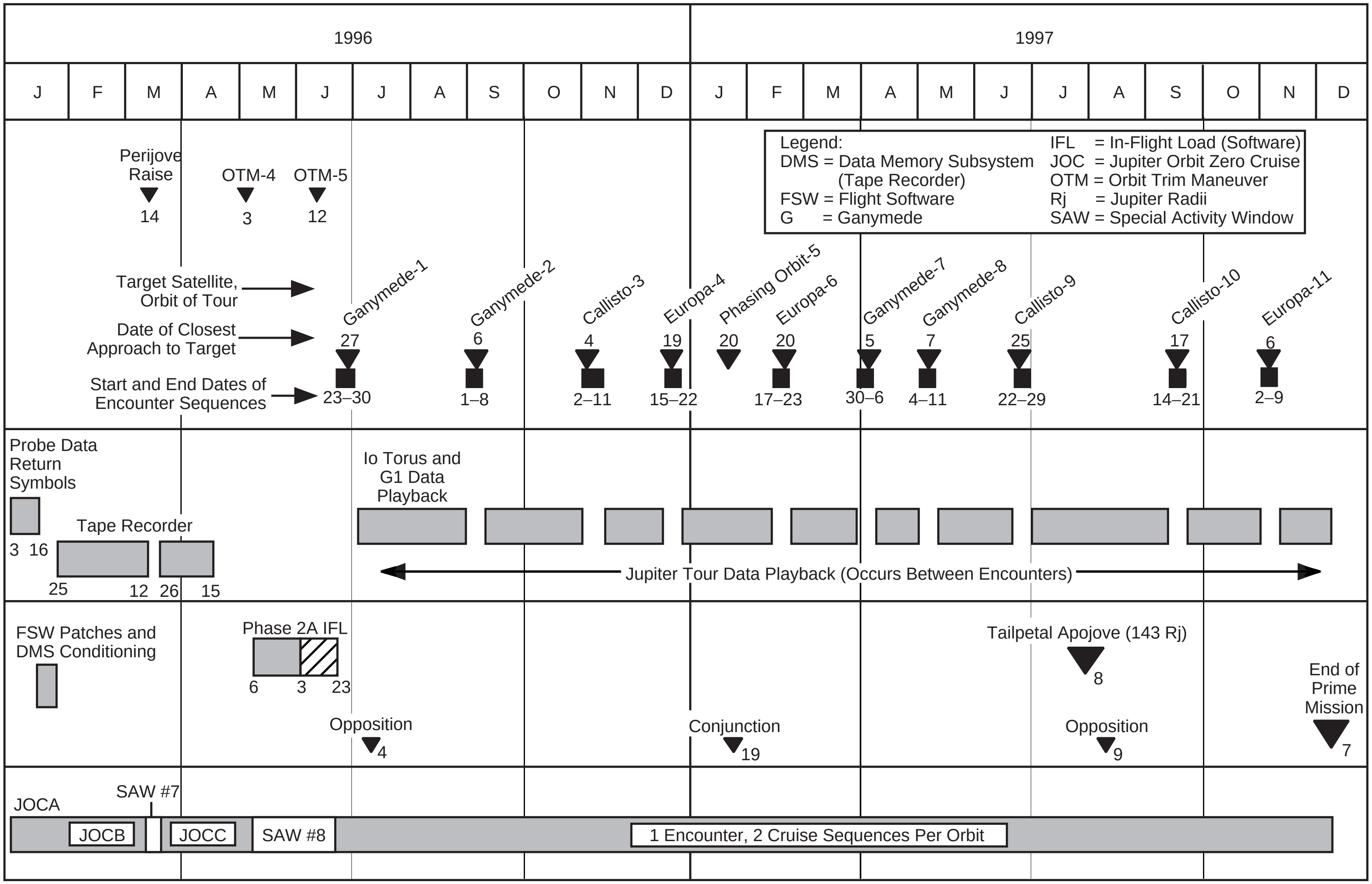

Fig. 2. Galileo mission overview, 1996–1997.

II. The Galileo S-Band Mission

A. DSN Telecommunications Strategy

During the period reviewed here, DSN support for the Galileo mission to Jupiter was based mainly on the telecommunications strategy described in [4]. The decision to adopt the 2.3-GHz (S-Band) configuration in place of the original 8.4-GHz (X-Band) configuration for Galileo support was made by the Galileo Project in January 1993 as a consequence of the failure of the spacecraft's X-band high-gain antenna to deploy fully, despite repeated attempts to free the stuck ribs.

To maximize mission data return under these new conditions, a complex telecommunications link-improvement strategy was developed jointly by the Project and the DSN. The concept, described in [4], involved substantial changes to both the spacecraft and the DSN. The spacecraft changes included software design to introduce new data handling and compression techniques and improved error-correcting codes.

The DSN changes involved various enhancements to the three Deep Space Communications Complexes that could provide a factor of 10 increase in data return from the Galileo spacecraft as compared with the data return that would have resulted from use of the existing DSN configuration under the new mission conditions. The design is shown in conceptual form in Fig. 3. It included the addition of a new telemetry subsystem that could serve as a specialized signal processor specifically designed to handle the Galileo low-signal conditions. It was to be called the DSCC Galileo telemetry (DGT) subsystem and was installed in parallel with the existing Block V receiver (BVR) and telemetry channel assembly (TCA), which formed a part of the existing DSN telemetry subsystem. The BVR and TCA continued to provide for Doppler extraction and spacecraft emergency support.

The BVR was a new digital receiver that had been introduced into the DSN in 1995 and had provided the operational support for Galileo described in [3]. When fully implemented, the BVR was capable of acquiring and tracking the spacecraft carrier and subcarrier in a residual or suppressed-carrier mode and of demodulating carrier, subcarrier, and symbols for delivery to a feedback concatenated decoder (FCD) in the DGT or the TCA processor. The BVR interface to the FCD was developed only for the nonarrayed mode. The interface to the FCD in the array mode was not completed.

In addition to the DGT, an ultra-low-noise receive-only feed system was to be added to the Canberra 70-m antenna to reduce the S-band system noise temperature to 12.5 K. Prior to installation of this so-called "ultracone," Galileo operations had been conducted with a feed cone having a system noise temperature of 19.9 K in the diplexed transmit–receive mode and 15.6 K in the receive-only mode.

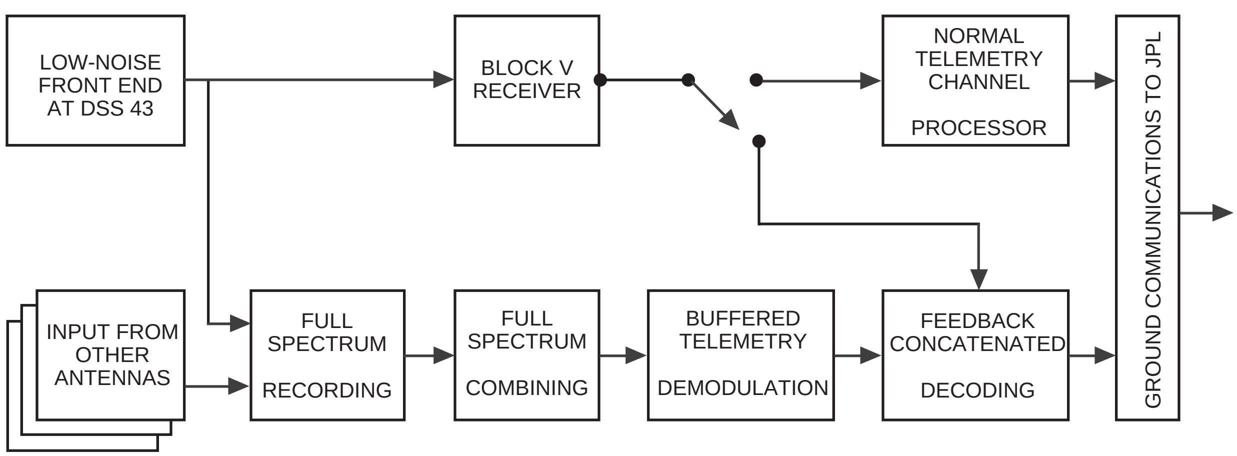

Fig. 3. Conceptual form of the DGT for Galileo.

Further enhancement of the Galileo downlink signal was to be obtained by the use of the following antenna arraying techniques at the Canberra Deep Space Communications Complex (CDSCC):

(1) Intercontinental arraying of the DSS-14, 70-m-diameter antenna at the Goldstone Deep Space Communications Complex (GDSCC), California, with the DSS-43, 70-m antenna at CDSCC, Australia, during mutual view periods.

(2) The addition of two of the three 34-m antennas at CDSCC into the array with the 70-m antennas at CDSCC and GDSCC.

(3) The addition of the Australian 64-m radio telescope at Parkes, called DSS 49 for DSN identification, into the array to allow it to support the Galileo mission as an additional element of the CDSCC array.

Thus, the timeline for arraying was generally: (1) begin the array with two 70-m antennas and two 34-m antennas, (2) add Parkes about 2 hours later, (3) then delete the Goldstone 70-m antenna at its set, and (4) finally, delete Parkes at its set about 2 hours before the CDSCC array set.

It should be noted that NASA provided several enhancements to the Parkes radio telescope to increase its contributions to the array. The sum of the DSN and Parkes ground enhancements increased data return tenfold.

B. DSN Configuration for Jupiter Orbital Operations

The overall network configuration used to support this phase of the Galileo mission is shown in Fig. 4. At each antenna, the S-band signal from the spacecraft was converted to 300 MHz by an open-loop downconverter, the outputs of which were fed simultaneously to the BVR channel and the full spectrum recorder (FSR) channels of the DGT.

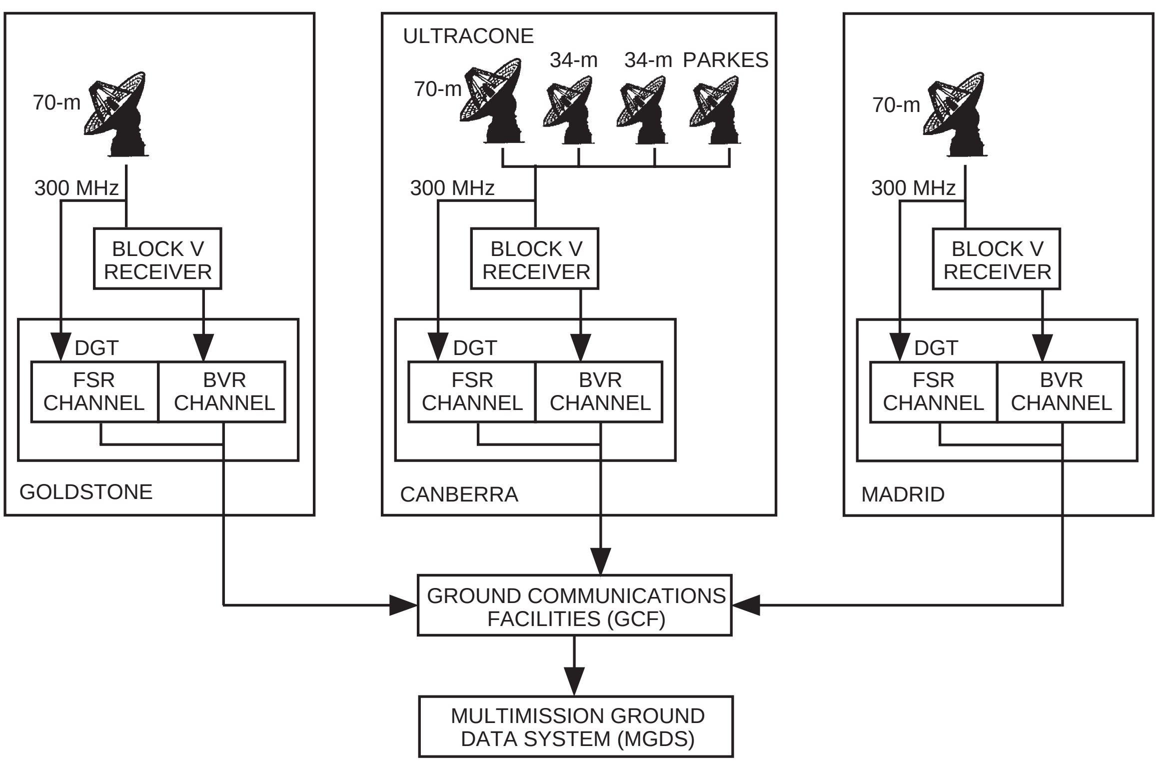

Fig. 4. DSN configuration for Jupiter orbital operations.

Prior to the first Ganymede encounter (G1) in June 1996, the BVR channel provided Galileo signal-processing and estimation functions and performed carrier, subcarrier, and symbol demodulation. The soft-symbol-stream output was delivered to the TCA for routine data decoding and processing. Later, after the spacecraft had been reprogrammed with the in-flight Phase 2 software, the BVR receiver delivered a symbol stream from the 70-m antennas to the FCD for decoding the special Galileo telemetry downlink, as shown in Fig. 3.

During and after the G1 encounter, the FSR channel was used to support orbital operations in the single-antenna mode, as shown in Fig. 5. The FSR channel contained an FSR, a buffered telemetry demodulator (BTD), and an FCD. In all modes of operation, the full spectrum IF signals were recorded first by the FSR for each individual antenna. In the single-antenna mode, the sampled spectrum stream from the FSR passed directly to the BTD for demodulation to a symbol stream that then was decoded into data bits by the FCD. When the FSR channel was used in the full arraying mode, the sampled spectrum streams from each of the FSRs first were combined in the full-spectrum combiner (FSC) using the full spectrum combining techniques described in [5] to produce a single stream with improved signal power-to-noise density characteristics. The enhanced signal spectrum then was passed to the BTD for demodulation to a symbol stream and to the FCD for decoding into data bits. This capability was introduced during the third encounter, Callisto 3 (C3). Since the array capability was implemented only at CDSCC, the FSC was not included in the FSR channel at the other sites.

Various local area networks provided for transportation of digital signals between elements of the DGT and between the DGT and the rest of the Signal Processing Center (SPC).

During overlap periods, the full-spectrum digital output of the Goldstone FSR was sent to CDSCC via a router and the Ground Communications Facility (GCF). At CDSCC, the full-spectrum signal from DSS 14 became an input to the CDSCC array during Goldstone–Canberra overlapping view periods. A second FSR channel with a record-only capability was used to provide backup, as shown in Fig. 6. The Galileo configuration at the Madrid Deep Space Communications Complex (MDSCC) was essentially the same as that at Goldstone, only without the router–GCF link to CDSCC. The Parkes arrangement also was similar to GDSCC except for simplified Galileo telemetry control functions. Also, a fiber-optic transmission link was used to carry the Parkes signals to CDSCC for arraying.

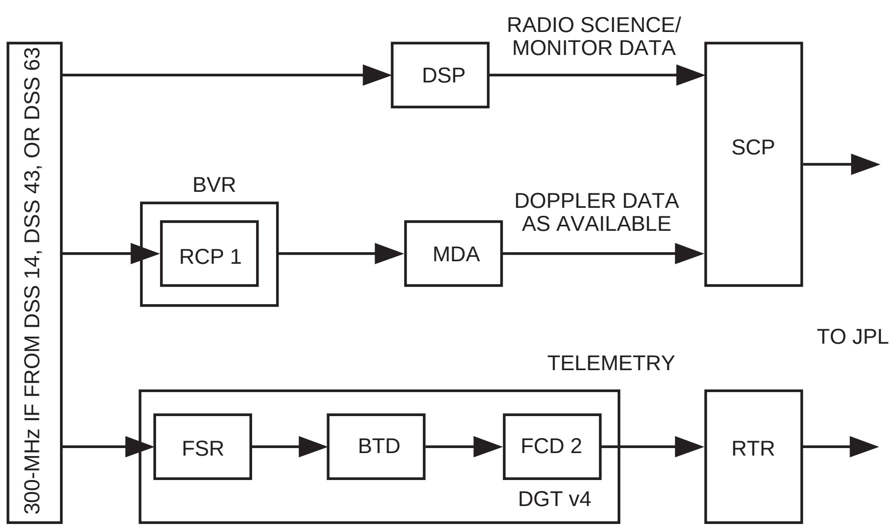

Fig. 5. DSN Galileo telemetry at SPC 10, SPC 40, and SPC 60, single-antenna mode.

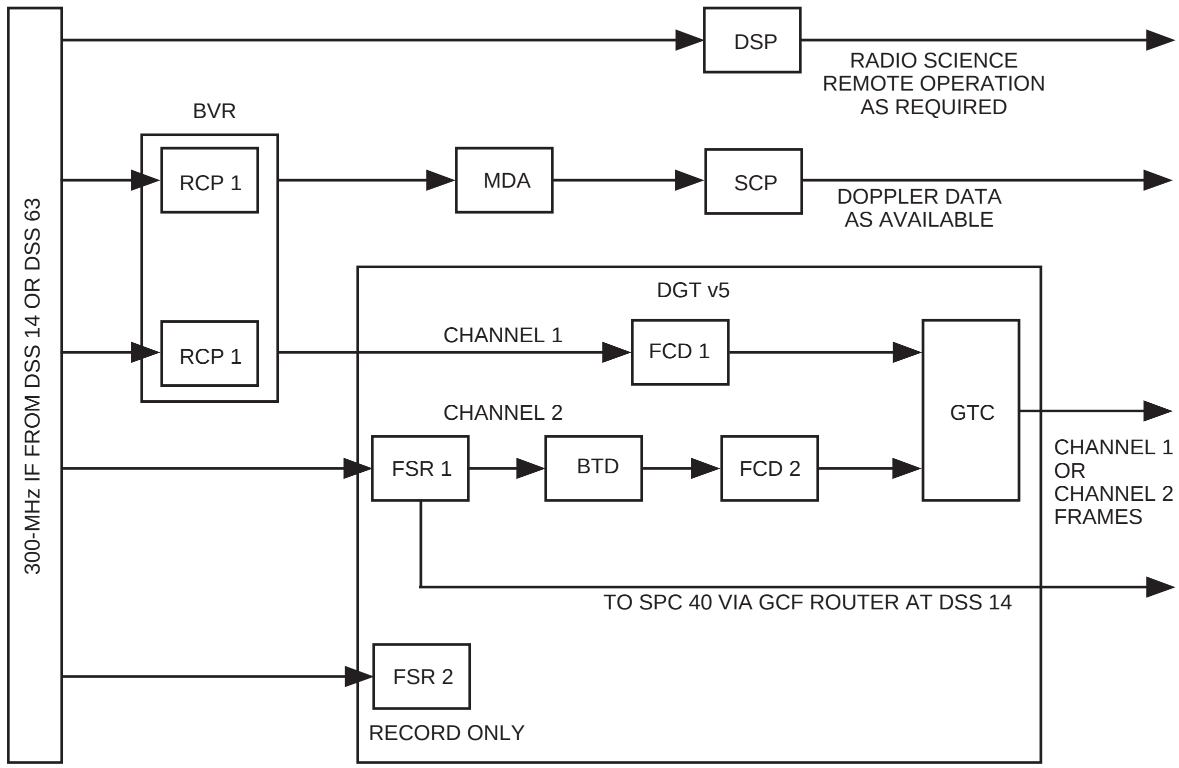

Fig. 6. DSN Galileo telemetry at SPC 10 and SPC 60, nonarray mode.

At all sites, the FSR channel was used for normal production processing of received data where possible data gaps were induced due to loss of BVR lock during the signal acquisition process. Since data gaps were highly undesirable, use of the FSR channel enabled many gaps that did occur during signal acquisition to be filled by one of three methods: near-real-time processing, post-pass processing, or reprocessing of the recorded data streams at JPL.

Because the southerly declination of Jupiter during this period gave the Australian antennas a longer view period than those at the Northern Hemisphere stations, the Canberra site was implemented with the full arraying capability described above. This allowed all the antennas at CDSCC to be used in an arrayed configuration, together with independent signals from the Commonwealth Scientific Industrial Research Organization (CSIRO) radio telescope at Parkes. In addition, during mutual view periods, the full-spectrum signal from the 70-m antenna at Goldstone could be added to the array. This view period overlap lasted almost 4 hours during the Galileo tour.

An estimate of the achievable and actual data rates to be expected from the use of arraying techniques is shown in Fig. 7 for a Callisto encounter in 1997. The actual configuration of the DGT at the three complexes for the Callisto encounter in November 1996, when arraying was used for the first time in critical real-time operations, is shown in Fig. 6 for GDSCC and MDSCC and Fig. 8 for CDSCC. The Callisto (C3) and Europa (E4) encounters both were conducted in the full-spectrum combining mode.

III. DSN Support for Galileo in 1996

A. General

During the first 5 months of the Jupiter orbit (called the J0 orbit), from December 1995 through April 1996, the mission was supported by the three 70-m antennas (with the ultracone at CDSCC) as a

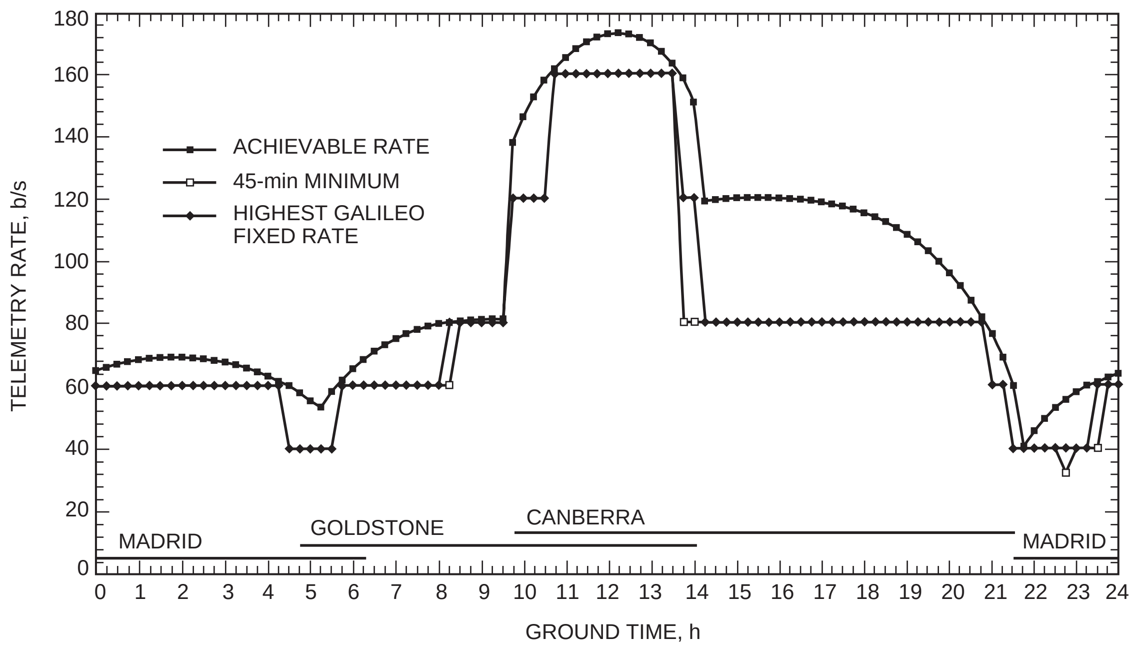

Fig. 7. Achievable and actual data rates at the Callisto 9 encounter.

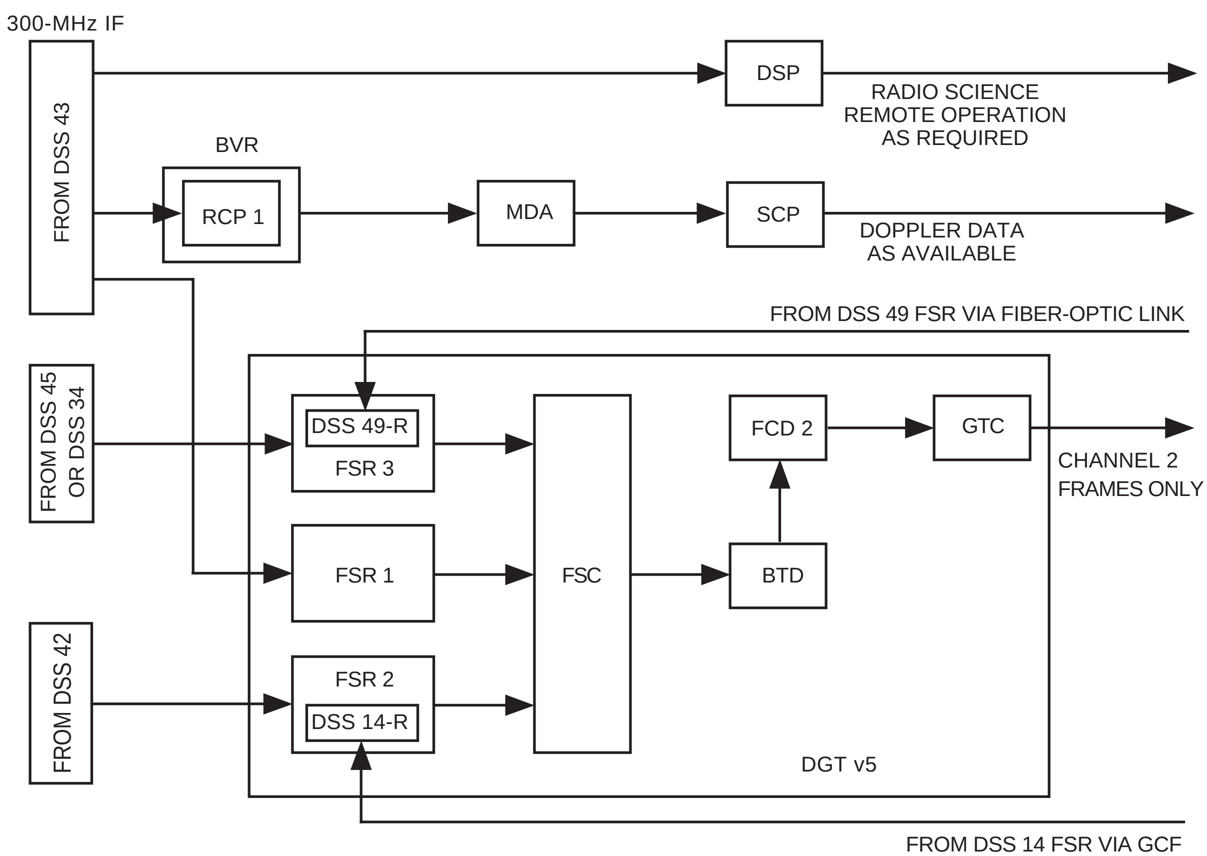

Fig. 8. DSN Galileo telemetry at SPC 40, array mode.

continuation of the pre-Jupiter orbit insertion (JOI) configuration. By May 1996, DSN support for the mission had been enhanced by the addition of the DGT at all sites. By November, however, DSN support also was augmented at CDSCC by the full-array configuration consisting of the 70-m antenna plus two 34-m antennas in array with the Parkes antenna and the 70-m antenna at GDSCC. The full-array capability of the DSN then would permit the Galileo spacecraft data rate to be raised from 40 to 120 b/s during Goldstone–Canberra overlap periods. It was estimated that a maximum data rate of 160 b/s would be achievable on occasion, as shown in Fig. 7.

In 1996, the DSN provided the Galileo Project with 9536 hours of 70-m antenna tracking time, somewhat exceeding the requested time of 9439 hours. The 34-m antenna tracking time amounted to 1488 hours out of a requested 1639 hours. The Parkes antenna contributed 880 hours for the year out of 890 requested. Minor ground outages and resource allocation changes (i.e., antenna schedule changes) accounted for the small differences.

The average telemetry data capture rate for the period from January through October was 98.5 percent, typical of the rate in previous years. Beginning in November 1996, the DSN antenna array mode was used to support regular Galileo orbital operations, and the number of telemetry data transfer frames actually transferred to the Project became the measure of the DSN telemetry capture rate. Each telemetry data transfer frame comprised 16,384 bits. Under this system, the transfer frame rates for November and December 1996 were 93.0 and 97.2 percent, respectively.

By the beginning of 1996, all the components of the single-antenna version of the DGT were on site, in place, and being tested, with the exception of some elements of the Parkes installation. Initially, the DGT raised some concerns by showing an intolerance of changes to or deviations from its expected sequence of operations. In particular, it appeared sensitive to changes in predicts or sequences that affected the link margins. Now aware of the constraints of predict-/sequence-driven operations, both the Project and DSN tightened procedures to minimize any changes to 7-day schedules, track times, and antenna scheduling, or changes that would require a DGT configuration change in real time.

After a successful ground data system operations demonstration in early May using simulated Phase II flight software, the single-antenna version of the DGT Version 4 (v4) was put on line for Galileo mission support. A short time later, in-flight loading of the Phase IIA flight software to the spacecraft began. The configuration of the DGT v4 in the single-antenna mode is shown in Fig. 5. The first critical support event would be the first Ganymede (G1) encounter on June 27. The spacecraft utilized its new flight software, and the DSN supported with the DGT.

By mid-year, the BVR, which had been providing operational support since 1995, was being used in DGT data flow tests with DSS 14, DSS 43, DSS 49, and DSS 63. That is, for the first time, BVR output was flowing to the DGT.

Earlier problems with the system noise temperature of the Parkes antenna had been resolved, and modifications to the feed to improve the measured antenna-gain-to-system-noise-temperature (G/T) performance were complete. The resulting value of 17.5 K for the Parkes antenna system noise temperature met the specification for its performance as an element of the Australian array, and engineering tests in May with DSS 43, DSS 42, and DSS 49 gave results within 0.2 dB of the expected array gain.

By the end of the year (1996), 285,846 commands had been transmitted to Galileo since launch. Of these, 10,260 were transmitted in 1996.

B. 1996 Mission Operations

While implementation and testing proceeded toward completion of the full-array capability in November 1996, the DSN continued to provide full support for all mission operations. In the early part of 1996, DSN support was devoted mainly to recovery of the remainder of the data from the Probe entry events of 1995. This was completed in April 1996. One hundred percent of the probe data bits were received and verified on the ground. The crucial perijove raise maneuver on March 14 that enabled the prime mission satellite tour was covered by DSS 43 under difficult, weak signal conditions, thus complicating the data acquisition, but it afforded an opportunity to demonstrate the capabilities of the new BVR and FSR channels.

The Galileo spacecraft S-band downlink to DSS 43 provided one-way Doppler data throughout the maneuver. With the spacecraft low-gain antenna (LGA) oriented 46.5 deg off-Earth and the Earth–spacecraft distance only slightly less than maximum range, these were the most difficult weak-signal conditions of the mission. Telecommunications-link modeling, simulation of the maneuver Doppler profile in the BVR, and a 30-minute in-flight end-to-end check of the configuration 1 day before the actual maneuver were used to verify the telecommunications-support plan.

Before and after the burn, the downlink was configured to the minimum bit rate of 8 b/s in the suppressed-carrier mode. Throughout the burn, however, the link was set at a 53-deg modulation index, residual carrier, in an effort to balance the carrier tracking in the face of the burn dynamics with the possibility of receiving telemetry data during the burn. Although telemetry data were lost at, or just before the start of the 25-minute burn, the BVR retained carrier lock throughout the burn. This allowed the Project to confirm in real time that the spacecraft was behaving as expected, even without telemetry.

The BVR dropped lock (as expected) at the end of the burn, but DSS 43 was able to reacquire the suppressed-carrier downlink by using the spectral display on the FSR/DGT receiver to determine the exact frequency reference to relock the BVR and deliver engineering telemetry to the Project shortly thereafter. These efforts kept the Project informed of the spacecraft performance during the crucial "perijove raise" maneuver, under extraordinarily difficult telecommunications conditions.

On May 13, the DSN began transmitting commands to support the in-flight reprogramming of the Galileo spacecraft for Phase II flight software operations. This critical activity continued through May 22 without incident and with complete success. The total command radiation time for the in-flight load was 65 hours and 9 minutes. There were no aborts. After verifying that both command and data subsystem (CDS) strings on the spacecraft had been loaded correctly and the data properly processed by the ground data system, the Project gave approval for the spacecraft to begin full operations on the new Phase II software. The spacecraft immediately began transmitting data in the new packetized telemetry format at 32 b/s. The new software provided data compression and other capabilities to maximize the data return from the orbital tour using the tape recorder and the low-gain antenna.

Science instrument memory readouts (MROs) continued throughout the year, interspersed with regular verification of the spacecraft radio frequency subsystem (RFS) parameters.

Lost time due to antenna problems was minimal in 1996.

In June, optical navigation (OPNAV) in conjunction with two-way Doppler data became the prime navigation data type in the orbit determination process for the satellite encounters. The DSN delivered all 33 OPNAV images scheduled for the G1 encounter.

Playback of the plasma wave data that were taken during passage through the Io torus was begun in early June and completed a week before the G1 encounter.

Three orbital trim maneuvers (OTMs), OTMs 4, 5, and 6, required to position the spacecraft for the close (835-km) G1 encounter on June 27 were executed successfully by the spacecraft, and the 10-b/s engineering data were delivered by the DSN without incident.

After the Ganymede G1 image return sequences had been completed, the DSN returned to supporting routine spacecraft operations for the Galileo mission. During this period, the downlink on the LGA could sustain a telemetry bit rate of 40 b/s. The DSN supported OTMs 7, 8, and 9, tape recorder conditioning events, and an increasing number of OPNAV image returns in preparation for the second Ganymede encounter on September 6.

During the DSS-43 pass on August 24, the spacecraft entered the "safing mode" in response to a "CDS A-string down" fault condition, with consequent loss of telemetry. Commands immediately were sent to switch to the B-string, and the station again locked up to the time-division multiplexed (TDM) telemetry, which indicated that the switch had been executed correctly on the spacecraft. OTM 9 was executed correctly in this mode. By August 29, the problem had been diagnosed and commands sent to recover the A-string and return the spacecraft to normal operation with packetized telemetry and fully suppressed carrier. DSS 63 then was the first station able to acquire packetized telemetry again with no problems.

Ground data system (GDS) testing using the new DGT array capabilities at DSS 14, DSS 43, DSS 42, and DSS 49 (Parkes) began in early September. For the first time, the Galileo spacecraft signal was processed through the DGT, with full frequency spectra from DSS 14, DSS 43, DSS 42, and DSS 49 combined in real time at SPC 40 using DSS 43 as the reference (anchor) station. The tests satisfactorily demonstrated the real-time combining capability. Real-time data were transmitted via the GCF to the Galileo telemetry subsystem at JPL, and post-pass transfer files were generated and transferred to the Project for nonreal-time processing. With several problems identified for correction, the tests continued through October to meet the needed date of November 1 for the Callisto C3 encounter.

On September 10, two uplink acquisitions by DSS 63 failed to achieve lock on the spacecraft prime receiver. A third uplink sweep with the sweep range expanded from the normal value of 100 Hz to 300 Hz was successful. After verifying that the uplink tuning sequences were valid and analyzing the spacecraft engineering data, the Project determined that the spacecraft's prime receiver's best-lock frequency had drifted from its nominal value. With the assistance of the DSN, the Galileo Telecommunications Team continued to analyze the problem. Over the next several weeks, tests were carried out on the spacecraft downlink spectrum and the radio subsystem tracking and automatic gain control (AGC) loops. By the end of September, these tests had shown that the time constant for the spacecraft receiver tracking loop to return to its best-lock frequency had settled out at a value slightly higher than the preanomaly value of 3905 seconds. It was concluded that the spacecraft's radio subsystem again was operating normally and that no further tests were necessary. As a precaution, however, the DSN generated contingency uplink-operations tuning procedures that could be used to minimize future data losses.

In preparation for the Callisto C3 encounter in November, GDS testing of DGT Version 5 (v5) continued through September and October, using stations DSS 14, DSS 43, DSS 42, DSS 45, and DSS 49 (Parkes) in the arrayed configuration. A total of 24 tests were carried out, of which 13 were fully successful, 9 were partially successful, and 2 were unsuccessful. The spacecraft was sequenced to run for limited periods at telemetry rates of 120 and 160 b/s to validate the predicted array-gain performance for the DGT. Configuration and operational problems that appeared during the tests were identified and corrected as the tests progressed.

Following completion of the test series on October 27, a readiness review conducted by the DSN and the Project determined that the new capabilities were ready for operational support. Operations demonstrations began on October 27 and continued through November 1. During the demonstration tracks, the full-array support capabilities were used for flight support, but the spacecraft data rate was not increased to take advantage of the increased performance available from the array. The four operations demonstration tests identified and resolved several configuration and procedural problems that would have affected flight support had they not been corrected. Callisto C3 flight support using the DGT in arrayed mode began on November 2.

With the addition of the DGT to mission operations, the Galileo telemetry data-rate profiles took on an added complexity for DSN operations. A typical daily pass in this period began with DSS 43, DSS 42, DSS 45, and DSS 49 in array mode and supporting telemetry at 80 b/s. As Canberra set, the supportable rate dropped to 20 b/s. During the following single-station pass at Madrid (DSS 63), the rate rose to 32 b/s at maximum elevation before dropping again to 20 b/s as DSS 63 set. The first part of the Goldstone (DSS-14) pass could support 32 b/s until the overlap with Canberra began. Adding DSS 14 to the DSS 43–DSS 42–DSS 49 array at that point allowed the data rate to be increased to 120 b/s for about an hour before Goldstone dropped out of the array shortly before set. Without DSS 14, the DSS 43–DSS 42–DSS 49 array could support only 80 b/s, stepping down through 40 b/s to 20 b/s again as Canberra set. Although this sequence introduced considerable complexity into DSN operations, it maximized the Galileo data return by fully exploiting the new DSN capability for conducting intercontinental array operations using the DGT on a daily routine basis.

Based on the operational performance of the DGT in supporting the Callisto C3 encounter and confidence in the DSN ability to deal with the increased operations complexity, the Project scheduled every pass from then on through the end of the mission in the array mode. This, together with regular spacecraft engineering management activities, optical navigation passes, and preparation for the Europa E4 encounter, characterized DSN support through November and December 1996.

The Europa E4 encounter in December was conducted in very much the same way as the Callisto C3 encounter. The full array capability with the same configurations as shown in Figs. 6 and 8 was employed during overlap periods to maximize the data return. As the DSN accumulated operational experience with arrayed operations and the performance of the spacecraft, BVR, and DGT, the quantity of data returned improved. Lessons learned from the C3 encounter were put into effect, and anomalies that had appeared during the C3 support periods were corrected. Improved operational procedures for radio science occultations were developed and put into effect for the E4 encounter. Playback of the Europa science data (arrayed mode) began on December 21, and OTM 17 executed correctly on December 23. Typical data rates for these events were from 80 to 120 b/s in the DSN arrayed mode.

As a result of 1996 being a leap year, all sites experienced temporary problems with the radio day change from DOY 365 to DOY 366. In general, the problems were related to predicts for the BVR, metric data processor (MDA), and DGT.

C. Jupiter Satellite Encounters

1. Ganymede G1. In preparation for the first Ganymede G1 encounter, a DSN readiness review was held on June 6. The G1 encounter requirements called for S-band, convolutionally coded ($K = 14$ and $R = 1/4$, where K is the constraint length and R the rate) packetized telemetry in the suppressed-carrier mode at bit rates from 8 to 80 b/s. In the spacecraft safing mode, this would revert to 10 b/s coded ($K = 7$ and $R = 1/2$) TDM. The DSN telemetry system was required to maintain lock through all data rate changes and to provide post-pass transfer files with all gaps filled. Spacecraft commanding was to be provided on S-band at 32 b/s with 100-kW (nominal) uplink power, and radio metric data would consist of two-way Doppler in suppressed-carrier mode. Monitor data requirements were expanded to include additional parameters from the BVR and the subcarrier and symbol monitor data for analysis purposes.

DSN support for G1 was to be provided by the 70-m antennas at Goldstone (GDSCC), Madrid (MDSCC), and Canberra (CDSCC) using the configuration shown in Fig. 5. Arraying was not a requirement for G1 support and would not be available until early November. The status of operational testing, training, and support data products in the network was presented to the DSN Readiness Review Board by the Network Operations Project Engineer (NOPE) and was deemed acceptable by the review board, and the DSN was declared ready.

The closest approach to Ganymede 1 occurred on June 27, 1996, at 12:04 a.m. Pacific Daylight Time (PDT) over DSS 14. Spacecraft engineering telemetry indicated the onboard sequence was executing normally. The pass over DSS 63 prior to the closest approach was nominal, except for a minor monitor data outage.

Although the Doppler data from DSS 14 confirmed the expected change in velocity due to Ganymede gravitational effects, an incorrectly labeled set of predicts resulted in the loss of most of the real-time data during the short (4-hour, 15-minute) pass on the operational real-time string. Post-pass processing of a recorded data stream from a backup engineering string was used to retrieve most of the lost data for post-pass delivery to the Project.

At this phase of the mission, the DGT in single string–single antenna configuration could support a Galileo suppressed-carrier telemetry bit rate of 40 b/s over DSS 14 and DSS 63 and up to 80 b/s over DSS 43. The Ganymede imaging and other scientific data were played back from the spacecraft and received by the DSN over the following days. After processing and analysis by the science teams, the first data from the Ganymede G1 encounter were presented by the Project at a press conference on July 10.

2. Ganymede G2. DSN support for the Ganymede G2 encounter began with the encounter sequence upload from DSS 63 on August 31. The Ganymede closest approach occurred over DSS 63 at 12:39 p.m. PDT on September 6. Although the DGT FSR lost signal detection briefly on three occasions around the closest approach, the downstream assemblies were able to successfully decode the data, and no data were lost.

The BVR dropped lock twice during the pass but was able to provide key Doppler data during the closest approach period. The BVR problems were attributed to using outdated predicts and retaining information from the previous support, which caused the BVR to initiate a communications mode change when in fact the spacecraft was not changing modes.

On September 7, command sequences associated with the playback of G2 science data were uplinked to the spacecraft, and the return of the science data began shortly thereafter.

The events of this encounter provided invaluable experience for the DSN in the operational performance of the DGT, which had just started into the GDS testing phase of its implementation at this time. The lessons learned were incorporated into the ongoing test program as it continued toward the C3 encounter readiness on November 1.

3. Callisto C3. The Callisto C3 encounter occurred on Monday, November 4, 1996, with the closest approach over DSS 63 at 6:20 a.m. PST Earth received time (ERT). The DSN array support configuration for the C3 encounter is shown in Fig. 6 for Goldstone and Madrid and in Fig. 8 for Canberra.

Although the BVR maintained lock and provided Doppler throughout the high dynamic period around closest approach, the FSR was not able to hold lock due to the integration time in use and the high Doppler signal dynamics. Throughout the closest approach period, the spacecraft was sequenced to the telemetry fill data mode at 8 b/s to reduce the possibility of the BVR dropping lock on the downlink and thereby losing the critical high-rate Doppler signature at the time of closest approach. The encounter support strategy is shown in Fig. 9.

Immediately after the period of high Doppler rate, the telemetry rate was returned to its pre-encounter value of 20 b/s for the remainder of the DSS-63 pass. Playback of the C3 science data began shortly afterwards and was completed on December 13 as planned.

The C3 encounter marked the beginning of routine Galileo operations using the array mode. From this point on through the end of the prime mission, all Galileo passes were scheduled and supported in the array mode.

4. Europa E4. The closest approach for the Europa encounter occurred on Wednesday, December 18, at 11:43 p.m. PST (ERT) over CDSCC. The Galileo spacecraft passed within 692 km of the surface of Europa, closer (by a factor of 300) than the only previous encounter with Europa, made by Voyager 2 in July 1979.

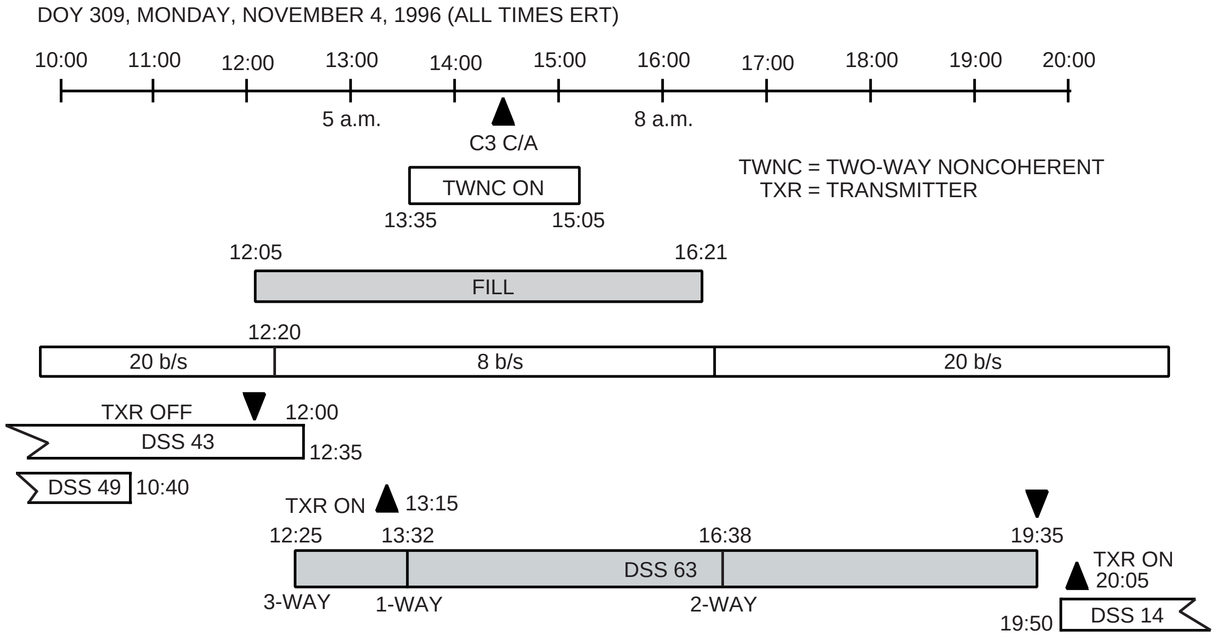

Fig. 9. Callisto C3 encounter support strategy.

DSS 42, DSS 43, and DSS 49 covered the event in the array mode. Neither DSS 14 nor DSS 63 was in view at that time. There was a Europa occultation for a few minutes on either side of the closest approach point. Bit rates followed a profile similar to that used for C3. Because of the occultation, the spacecraft downlink was switched to the noncoherent mode with the DSS-43 transmitter off. At rise over DSS 63, the spacecraft was reacquired in two-way mode and operations continued. The E4 command sequences associated with the playback of E4 science data were uplinked the following day.

D. Radio Science

In the first successful demonstration of radio science remote operations on August 18, 1996, the radio science subsystems in the SPCs at Canberra (SPC 40) and Goldstone (SPC 10) were configured and controlled from JPL without station operator intervention. Following this successful demonstration, the new radio science software entered the acceptance and operational soak testing cycles prior to its transfer to formal operational use.

The operational use of the new remote operations capability was to provide radio science support at DSS 43 (ingress) and DSS 63 (egress) for the Earth occultation by Jupiter on November 8, following the Callisto 3 encounter. Ingress was successfully supported with no data loss. Egress support was unsuccessful, due to a configuration error that invalidated the recorded data.

Following an intense series of radio science remote operations to thoroughly qualify the system, the radio science support at DSS 14 and DSS 43 for the Europa occultation on December 18 and Jupiter occultation on December 20 also was conducted in the remote mode. On both occasions, the remote operation capability worked well, and the desired radio science data products (open-loop and Doppler data) were delivered as specified to the Radio Science Team.

IV. DSN Support for Galileo in 1997

A. General

The DSN provided the Galileo Project with 99.3 percent of the 20,026 hours of antenna tracking time that was scheduled for Galileo support in 1997. Minor outages, weather, and schedule conflicts accounted for the lost time. The DSN antenna array mode was used to support regular Galileo orbital operations throughout the year. Most of the Canberra array passes included DSS 49, the Parkes radio telescope, and the Goldstone antennas during the mutual view period. The Parkes radio telescope contributed 2382 hours of array time for the period from November 1, 1996, through November 6, 1997, with only 0.2 percent of time lost.

In the antenna array mode of operation, the percentage of transmitted spacecraft telemetry data frames actually transferred to the Project becomes the measure of DSN telemetry capture rate. The performance of the Galileo telemetry array (using this system of accountability) for the period from November 1996 (the first use of arraying) through December 1997 (the end of the prime mission) is given in Table 1.

Table 1. Galileo telemetry array performance.

Month	Percent
1996	
November	93.0
December	97.2
1997	
January	92.9
February	94.9
March	97.0
April	98.5
May	98.2
June	98.2
July	99.1
August	98.2
September	97.1
October	97.2
November	93.1
December	99.1

By the end of the prime mission, 286,630 commands had been transmitted to Galileo since launch, 764 of which were transmitted in 1997.

The new 34-m beam-waveguide (BWG) antenna at SPC 40 (DSS 34) was utilized for the first time as an additional element in the Galileo array on January 28, 29, and 31. After a minor problem with the radio metric predicts was corrected, the new antenna appeared to be meeting the expected gain enhancement of 0.34 dB. It was planned that DSS 34 would be used in routine Galileo operations in the middle of February.

Ground communications capability from SPC 60 to JPL was increased substantially by the completion of the Madrid “big pipe” in January when the available communications bandwidth increased from 640 to 1024 kb/s. Thereafter, all Galileo DGT operations used this capability, keeping the “little pipe” as a backup.

An improved version of the DGT software (v6.0) was installed at SPC 40 in February and first used for operational support in March. This version of the DGT software corrected several anomalies that were detected in earlier versions and provided additional capability to run at the higher data rates of 120 b/s (480 symbols/s) and 160 b/s (640 symbols/s), which would be required later in the mission.

In October 1997, the new multimission Emergency Control Center (ECC) at Goldstone was used for an "all up" demonstration test of its capability to support emergency Galileo mission operations. Under the control of Galileo mission operations personnel, the ECC successfully completed a Galileo spacecraft track including spacecraft commanding, telemetry processing, and monitor and control.

B. 1997 Mission Operations

DSN mission operations for Galileo in 1997 covered six major satellite encounters, retrieval of from 4 to 6 OPNAV image frames per orbit through G7, three orbit trim maneuvers per orbit, and occultation radio science support of the events in addition to regular telemetry, command, and radio metric activity.

By early 1997, Galileo mission operations were routinely conducted in the DSN array mode, comprising Goldstone DSS 14 and Canberra stations DSS 43, DSS 42, and DSS 34 or DSS 45, plus the Parkes radio telescope, DSS 49. The station configurations were similar to those shown in Figs. 4, 5, 6, and 8, except for the substitution of DSS 34 for DSS 45 beginning with the latter part of the E4 playback in February.

In the early part of the year while the Earth-to-spacecraft range was greatest, the maximum telemetry bit rate during array periods typically was from 60 to 80 b/s. Later in the year, however, as the Earth spacecraft range decreased, higher bit rates became possible during array periods reaching from 120 to 160 b/s in August. The data rate profile for a typical array pass during this period is shown in Fig. 10.

The positions of the Galileo spacecraft at the beginning and end of 1997 are given in Table 2.

Array operations were interrupted on several occasions during the year due to high winds at Parkes and Goldstone, which required the large antennas to be stowed temporarily for safety. These data generally were replayed from the spacecraft tape recorder, so data were not always lost.

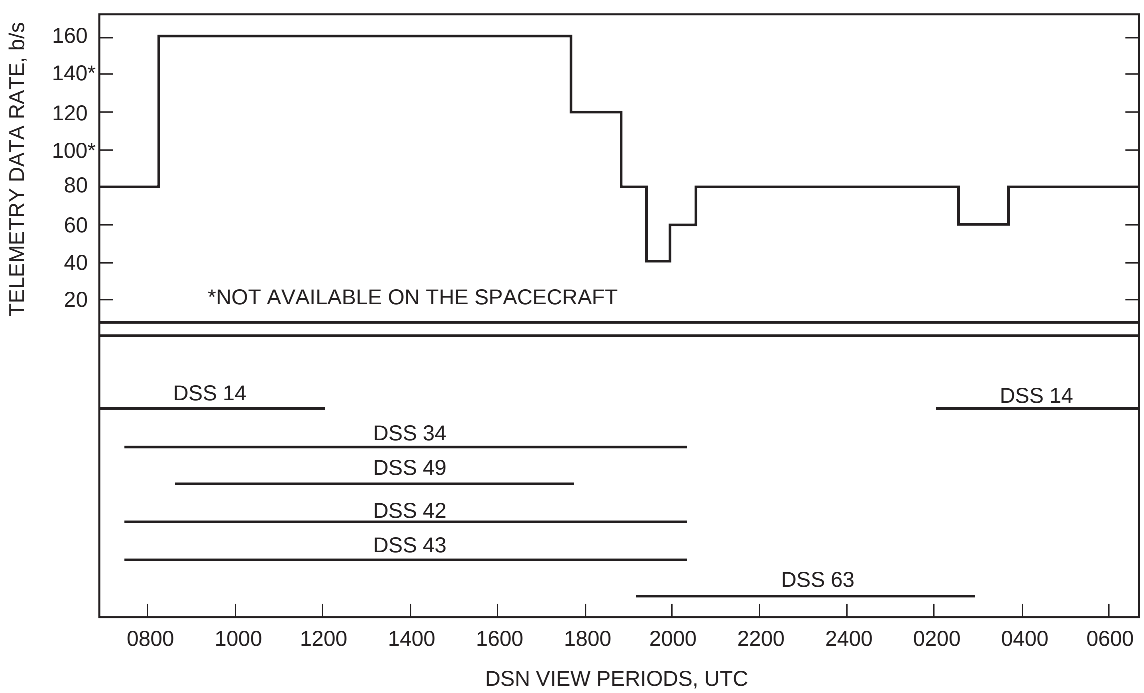

Fig. 10. A typical Galileo telemetry data rate profile during DSN full-array operations: August 1997.

Table 2. Galileo spacecraft positions at the beginning and end of 1997.

Spacecraft position	January 1997	December 1997
Distance from Earth	915,000,000 km (6.1 AU)	820,000,000 km (5.5 AU)
Distance from Sun	772,000,000 km (5.2 AU)	754,000,000 km (5.0 AU)
Distance from Jupiter	5,000,000 km (71.7 Jupiter radii)	2,800,000 km (39.2 Jupiter radii)
Round-trip light-time	102 min	92 min

Periodic uplink telecommunications tests were performed during the year to verify the spacecraft receiver threshold. During the tests, the uplink carrier power was reduced in steps until the receiver dropped solidly out of lock. These and similar tests conducted in 1996 confirmed that the spacecraft receiver threshold had not changed from its value of 150.5 dBm, which was measured at launch in 1989.

Reflecting improved reliability resulting from increased operational experience, the quantity of valid data returned from delta differential one-way ranging (ΔDOR) passes reached its highest level during 1997. Of the 30 ΔDOR measurements that were scheduled during the mapping phase of the Galileo mission, 24 were successful, 2 failed, and 4 were canceled by the Project. These data have contributed significantly to improvement of the Jupiter ephemeris.

C. Jupiter Satellite Encounters

1. Europa E4. The images captured by Galileo during the first Europa encounter on December 19, 1996, were released at a news briefing at NASA Headquarters in Washington, DC, on January 17, 1997. At the briefing, it was reported that, although the images did not show currently active volcanoes or geysers, they did reveal flows of material on the surface that probably originated from them. It was the first time that actual ice flows had been observed on any of the moons of Jupiter. The ice flows, as well as dark scarring on some of Europa's cracks and ridges, appeared to be remnants of ice volcanoes or geysers. The new images heightened interest in Europa and its ability to support living organisms.

Playback of Europa 4 science data continued through January with increasing interference from solar noise as the conjunction period approached. The spacecraft entered the solar conjunction period on January 10, and playback was paused on January 11 as the spacecraft then was at a Sun–Earth–craft (SEC) angle of less than 7 deg. No telemetry was expected from the spacecraft at this time. Telemetry resumed on January 28, by which time the SEC had increased to greater than 7 deg. Spacecraft data rates generally were maintained at 8 to 32 b/s during this period.

Playback of the E4 science data resumed after the conjunction period at data rates ranging from 32 to 80 b/s as the downlink margins permitted and was completed on February 16, 1997. In preparation for the approaching second targeted encounter with Europa (E6), optical navigation imaging passes and three OTMs were scheduled by the Project and supported successfully by the DSN in January and February.

The interruption to uplink and downlink resulting from the solar conjunction that occurred on January 19, 1997, during orbit 5 effectively precluded an E5 encounter with Europa, as can be seen in Fig. 2. The mission plan for the E5 non-targeted encounter did not provide for any science data recording. This allowed completion of the E4 science playback prior to the next Europa encounter (E6) scheduled for February 20.

2. Europa E6. The second encounter with Europa (E6 in the Galileo mission sequence) took place on February 20, 1997, with the closest approach occurring at 9:56 a.m. PST over DSS 14. At the point of closest approach, the spacecraft altitude above the Europa surface was 587 km, almost 100 km closer than the closest approach altitude for the E4 encounter. Science data were taken by all the remote sensing instruments, and fields and particles observations also were made.

During the E6 encounter period, from February 20 through February 25, the DSN supported all planned radio science experiments and downlink mode changes between carrier and suppressed-carrier tracking. This encounter sequence included four Europa occultations, an Io occultation, and a Jupiter occultation. Goldstone station DSS 14 provided prime support for the Io occultation at the start of the Jupiter occultation, while Madrid station DSS 63 supported the exit from Jupiter occultation.

The second Europa encounter (E6) was covered by DSS 14, DSS 43, and DSS 63. The stations delivered all expected telemetry and tracking data products, despite the large number of real-time reconfigurations necessitated by the downlink mode changes called for in the encounter sequence. Playback of the E6 science data began 2 days later on February 22 and was completed on March 28, 1997.

3. Ganymede G7. The third Ganymede encounter (G7 in the mission sequence) was executed on the seventh orbit on April 5, 1997. The closest approach occurred at 11:56 p.m. PDT on April 4 over DSS 63. Because the flyby altitude was relatively high (greater than 3000 km), the Doppler dynamics were such that the DSS-63 receiver and telemetry systems were able to maintain telemetry and Doppler lock throughout the closest approach period. Unlike most of the other encounters, there were no occultations during this encounter to disrupt the telecommunications links. All expected telemetry data and tracking data were provided to the Project in real time. The spacecraft tape recorder playbacks began on April 6 during the Goldstone–Canberra array period and were completed on May 3, 1997.

4. Ganymede G8. The Galileo spacecraft flew by Ganymede for the fourth and final time during the prime mission on Wednesday, May 7. The closest approach occurred at 9:38 a.m. PDT as the spacecraft passed 1585 km above the satellite surface. During the encounter, Galileo gathered science data on the surface shape and atmosphere and made high-resolution studies of specific topographic features of the Ganymede surface.

The fourth Ganymede encounter (G8) was covered by DSS 14 and four Australian stations, all of which provided excellent support during the entire period. The overview of the strategy employed to support this encounter, given in Fig. 11, illustrates the complexity of encounter operations in the array mode. The maximum telemetry data rate achieved was 80 b/s during the array period.

Nearly all of the expected telemetry data were received and processed in real time. All expected downlink mode changes were supported successfully by the Deep Space Communications Complex spectrum processing (DSP) subsystem and BVR in support of the radio science occultation activity. The DSPs at both SPCs were operated remotely by the Radio Science Team, which successfully completed all of the complex occultation sequences in real time and retrieved all data recorded by the DSP.

Playback of the G8 science began on May 11 and was completed by late June, just prior to the start of the Callisto C9 encounter period.

5. Callisto C9. DSN support for the Callisto C9 encounter began 3 days before the closest approach, which was planned to occur on Wednesday, June 25. All stations supporting the pre-encounter passes performed well using the nonarrayed mode at SPC 10 and SPC 60 and the fully arrayed mode including DSS 49 at SPC 40. The basic configurations are shown in Figs. 6 and 8, respectively. These configurations were then in current use for all Galileo support.

The encounter included a short (11-minute) Earth occultation by Callisto that occurred almost exactly at the closest approach time in the Goldstone–Canberra overlap period. Both DSS 14 and DSS 43 recorded

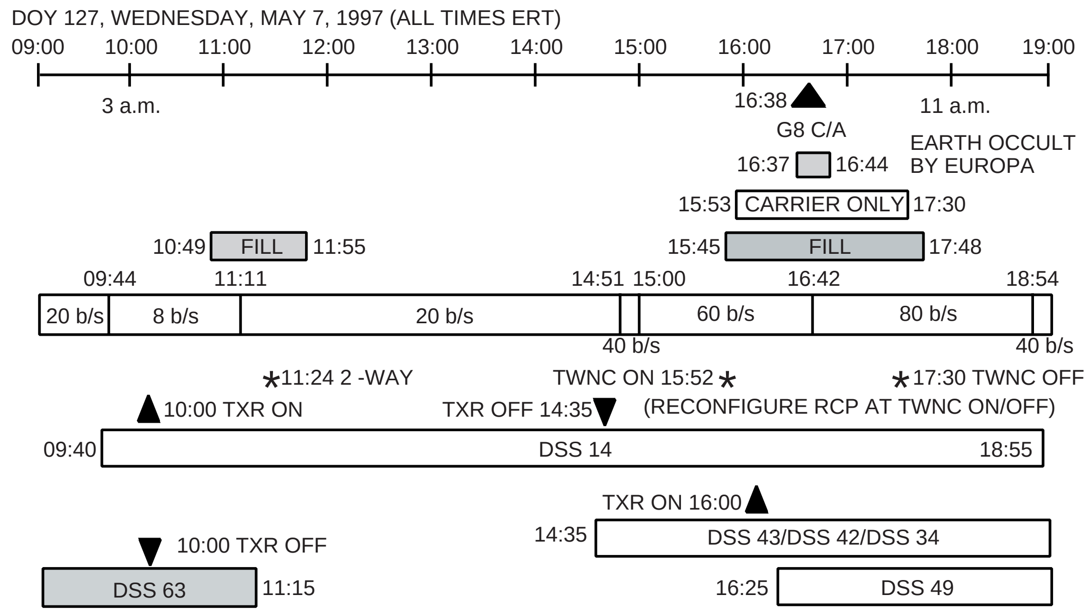

Fig. 11. Ganymede G8 encounter support strategy.

radio science data with the DSP for about 1 hour on either side of the closest approach, with the spacecraft in the carrier-only mode.

Immediately after the occultation period, the FSC at SPC 40 experienced difficulty accepting the DSS-49 input for array processing. With the real-time help of the DGT engineering advisors at JPL, the problem quickly was traced to a bias of 0.5 Hz in the carrier frequency at the FSR at DSS 49. This situation was created by a predicts transmission problem to DSS 49. With the two frequencies aligned, the SPC-40 combiner was able to process the arrayed data in the normal way. About 75 minutes of data were lost, most of which were later recovered through reprocessing of the FSR tapes at JPL.

Telemetry data rates during the encounter period varied between 20 and 80 b/s depending on the antenna elevation and overlapping of the various arrayed elements in the downlink. Spacecraft tape recorder playback of the Callisto C9 science data began during the Canberra array on June 29 and was completed on September 13, 3 days before the Callisto C10 encounter.

This orbit (9) was an unusually long one and included a total of 10 occultations between Ganymede, Io, and Jupiter in the last week of July and first week of August. Radio science activity was correspondingly heavy in the period.

By August, the spacecraft had reached its closest distance to Earth, and the increased telecommunications link margin resulting from minimum Earth-to-spacecraft range was reflected in the availability of higher telemetry data rates for routine array operations. The data-rate profile for a typical array pass in this period is shown in Fig. 10. As of August 14, 1997, the position of the Galileo spacecraft was as given in Table 3.

6. Callisto C10. The third (and final) encounter of Callisto in the prime mission took place during orbit 10 on September 16, 1997. The closest approach occurred at 5:54 p.m. PDT during the DSS 63–DSS 14 overlap. Although there were no occultations during this encounter, the Radio Science Team used the two-way Doppler data to conduct a gravity field measurement of the satellite. The spacecraft performed nominally, and DSS 43 and DSS 63 provided radio metric and telemetry support throughout the entire encounter period with no significant anomalies being reported. During the high Doppler dynamics

Table 3. Galileo spacecraft position on August 14, 1997.

Spacecraft position	Value
Distance from Earth	4.1 AU
Distance from Sun	5.1 AU
Distance from Jupiter	140.8 Jupiter radii
Round-trip light-time	68 min 30 s

period, both DSS 43 and DSS 14 experienced a loss of lock in their DGT telemetry channels. Fortunately, the loss of lock occurred at different times at each site so that at least one telemetry channel was in lock throughout the encounter. Playback of the C10 science data began on September 21 and was completed on November 2. All Galileo passes were supported with the CDSCC antennas configured in the full array mode, including Parkes.

7. Europa E11. The Europa E11 encounter on Thursday, November 6, 1997, was the final targeted encounter for the Galileo primary mission. All science instruments except for the extreme ultraviolet (EUV) instrument were powered on and made observations throughout the period. The closest approach occurred at 1:13 p.m. PST near the end of the DSS-63 view period and shortly before the view period began at DSS 14. Playback of the E11 science data began on November 9 and ended on December 14, thus completing the final event in DSN support for the Galileo prime mission.

At the time of the E11 encounter, the Galileo spacecraft trajectory status was as given in Table 4.

Table 4. Galileo spacecraft trajectory status at the E11 encounter.

Spacecraft position	Value
Distance from Earth	5.0 AU
Distance from Sun	5.0 AU
Distance from Jupiter	10.5 Jupiter radii
Round-trip light-time	82 min 22 s

The E11 sequence started on November 2. In the early stages of the sequence, telemetry data were lost several times due to DGT problems at SPC 40 and to heavy rain on contiguous passes at Canberra and Madrid. The closest approach was to be covered by DSS 63 near the end of its view period and 7 minutes before the scheduled time for spacecraft rise at DSS 14. However, about 6 minutes before the closest approach, the DSS 63 antenna went to brake due to a film height alarm, and the uplink and downlink were lost. An attempt to make an early acquisition of the spacecraft signal at DSS 14 was not successful, due to uncertainties in the spacecraft receiver frequency caused by the premature loss of uplink at DSS 63. By the time communication with the spacecraft had been reestablished, over 14 minutes of radio science (two-way Doppler) data and real-time telemetry had been irretrievably lost. Normal tracking in the full-array mode was resumed at the start of the Canberra view period.

The Europa E11 encounter also marked the end of scheduled Parkes support for the Galileo mission. After this pass, the Canberra–Goldstone array would comprise DSS 43, DSS 42, DSS 34, and DSS 14 only.

The addition of the Parkes radio telescope to the integrated Parkes–CDSCC–GDSCC array configuration was of the greatest help in recovering the encounter science data. It was estimated that approximately 17 percent of the total telemetry data that were recovered by the DSN on orbits C3 through G8 could be attributed to the addition of the Parkes radio telescope, with excellent Parkes staff support, to the Canberra–Goldstone array.

D. Additional Radio Science Details

Radio Science activity for Galileo in 1997 continued to remain high at all complexes. The recently completed capability for remote operation of the DSP was used by the Radio Science Team at JPL to configure the hardware and software at the complexes and to record and return the desired radio science data. This proved very beneficial to the Radio Science Team in conducting the experiments and to the DSN in reducing the operator work load at the stations. Under the terms of a special interface agreement with the Radio Science Team, the DSN provided FSR tapes for all radio science experiments. On several occasions in 1997, the Radio Science Team recovered radio science data, which otherwise would have been lost, by post-pass processing of the FSR tapes.

Most of the six satellite encounters that occurred in 1997 were accompanied by one or more occultations, which afforded prime opportunities for radio science observations. The six occultation experiments performed by the Radio Science Team at Goldstone and Canberra during the E4 and E6 encounters in December 1996 and February 1997 were particularly significant since they led to the discovery that Europa has an ionosphere. In announcing this discovery, the lead investigator said that the presence of an ionosphere is an indication of the existence of an atmosphere on the icy moon.

Another very important radio science observation was made a week after the E6 encounter, on February 26. The orbital tour was designed so that Earth would be occulted by Io on that date. The Radio Science Propagation Team was able to measure the ionosphere and estimate the characteristics of Io's extremely thin atmosphere. This was the first of the six Io occultations that collectively would provide the first complete picture of the complex Io ionosphere on a global scale.

Although the low altitudes of the 1997 encounters generally caused high Doppler dynamics during closest approach, the DSN radio science system was able to capture (except in one instance) the Doppler data for delivery to the Radio Science Team. These data were used by the celestial mechanics investigators to determine the gravitational field and internal structure of the various satellites and led to the discovery that Io, Europa, and Ganymede all have dense cores, while Callisto is uniform throughout.

Although the spacecraft high-gain antenna (HGA) problem in 1991 resulted in loss of the enhanced Gravitational Wave Search, Faraday Rotation, and Solar Corona Experiments, the Galileo Radio Science Team was able to use the radio science capabilities of the DSN throughout the prime mission to make significant contributions to the fields of celestial mechanics, radio propagation, and gravity field determination. These included ionosphere soundings and analyses of the internal structure of Ganymede, Io, Callisto, and Europa; long-term observations of the solar wind; and improvement of the Jupiter ephemeris.

V. The Galileo Europa Mission

Although the Galileo prime mission formally ended on December 7, 1997, orbital mission operations continued under a new mission name, the Galileo Europa Mission (GEM). The GEM will extend through December 1999, assuming the spacecraft remains operable, and will feature eight encounters with Europa, four with Callisto, and one or two close flybys of Io. The first major event of the GEM was a very close (200-km) flyby of Europa on December 16, 1997. The DSN will provide tracking and data acquisition support for the GEM through 1999 at a greatly reduced level.

VI. Conclusion

The end of the Galileo prime mission in December 1997 signaled the conclusion of a particular DSN association with the Galileo Project that had spanned almost 20 years. Obviously, the extension of the Galileo mission over the next several years will involve the DSN, but the nature and circumstances of that involvement will differ from that which prevailed during the years of the Galileo prime mission.

The engineering and operations functions of the DSN are in the process of transition to a more centralized, industry- and contractor-based style of management and operation that will be more suited to the new missions of the period. Among the first of the missions to feel the effects of these changes will be the Galileo Europa Mission.

The entire course of the DSN support for the Galileo prime mission is documented in [1–3] and this article. Highlights of DSN support for Galileo from 1986 through 1997 are listed below:

(1) The change from the 1986 launch to the 1989 launch resulting from the Challenger disaster.

(2) The complexity of a Space Transport System launch.

(3) The problems of resource allocation and resolution of conflicts for antenna time.

(4) The addition of an X-band uplink to the RFS as a demonstration command link.

(5) The potential for success in the search for gravitational waves afforded by the X-band uplink and downlink.

(6) The DSN 64-m to 70-m antenna extension program.

(7) The need for arraying DSN antennas with Parkes and the Very Large Array (VLA) and the search for other large-aperture antennas to accomplish the original mission at maximum Earth–Jupiter range.

(8) Great expectations and complex planning for receiving the Io imaging data.

(9) New high-efficiency (HEF) and BWG antennas.

(10) Innovative DSN response to the spacecraft HGA problem, resulting in a new S-band mission redesign.

(11) In-flight reprogramming of the spacecraft computers to introduce new coding and data compression techniques.

(12) The design and implementation of the unique DSCC Galileo telemetry (DGT) subsystem.

(13) Successful employment of intercontinental arraying between the United States and Australia on a routine operational basis.

(14) The valuable and excellent support provided to the DSN in support of Galileo by the Parkes radio astronomy facility.

Acknowledgments

The combined efforts of the men and women of the Deep Space Network, its supporting technical service organizations, and international partners made all the accomplishments listed above possible. At this time, it is appropriate to formally recognize their invaluable contribution to the success of the Galileo prime mission.

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