Galileo Post-Gaspra Cruise and Earth-2 Encounter

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TDA Mission Support and DSN Operations

This article documents DSN support for the Galileo cruise after the October 1991 encounter with the asteroid Gaspra. This article also details the Earth-2 encounter and the special non-DSN support provided during the Earth-2 closest approach.

I. Introduction

The launch, initial acquisition, Venus encounter, Earth-1 encounter, asteroid Gaspra encounter, and associated cruise periods have been documented [1]. This article documents the cruise period following the Gaspra encounter and leading up to the Earth-2 encounter, as well as the Earth-2 activities.

Also documented are the first solar conjunction experienced by the JPL Galileo Project in January 1992 and the many High-Gain Antenna (HGA) anomaly recovery windows that were identified. These windows were used to perform minisequences designed to attempt to free the stuck ribs [1]. These activities included cooling turns, warming turns, and Dual-Drive Actuator (DDA) motor calibrations. DSN support requirements are noted.

Finally, due to an unexplained increase in velocity noticed during closest approach to Earth in the first flyby, Galileo requested special non-DSN coverage during the Earth-2 DSN tracking coverage gap at the closest approach. The DSN negotiated support with the National Space Development Agency of Japan (NASDA), the European Space Agency (ESA), the NASA/Tracking and Data Relay Satellite System (TDRSS), and the University of Chile. This special support is also documented.

II. Solar Conjunction 1992

On January 22, 1992, the spacecraft passed behind the Sun, with a minimum Sun–Earth–craft (SEC) angle of approximately 2 deg. As part of the HGA anomaly recovery effort, a minisequence for the Cooling Turn No. 4 needed to be uplinked prior to the conjunction. The sequence was scheduled to go active on January 28, 1992, and last through February 8, 1992.

The upload was originally planned for January 13, 1992, from Deep Space Station (DSS) 14, as the Project did not plan to command inside of a 5-deg SEC angle. The SEC angle was greater than 5 deg on that day. Unfortunately, problems were encountered, which caused several commands to not be accepted by the spacecraft. The DSN verified configurations to ensure that this anomaly was not due to the ground equipment. DSS 43 was scheduled in real time to resend the commands, and again not all commands were correctly received and processed by the spacecraft. Solar effects had begun disrupting the data downlink from approximately an 8-deg SEC angle. The incidence of errors detected in the telemetry by the Project increased coincident with the smaller SEC angles.

Also, radio science data collected during this time confirmed highly variable solar activity. Several plasma ejection events were detected by the radio scintillation experiment. That experiment is a conjunction support requirement for the DSN for all conjunctions. Due to the HGA anomaly, the first conjunction was supported on the LGA. The effect was that the Project had to reschedule some DSN support, to relinquish other support, and also on occasion to reconfigure the spacecraft for 34-m standard antenna passes. The experiment was successfully supported by the DSN.

After the uplink problems on January 13, 1992, more commanding was attempted on January 14, 1992, from DSS 14 again. Both the Project and the DSN were surprised by the inability to command at greater than a 5-deg SEC angle, since other projects had not experienced such problems. Investigation of the ground equipment revealed no ground problems that could have been contributors. The low SEC angle and associated solar interference appeared to be the root cause of the problem. Due to the spacecraft range and the HGA anomaly, the uplink power of 100 kW was the norm for commanding to the LGA. All attempts through the DSS 14 pass on January 14, 1992, utilized 100 kW. Though all commands were sent twice, no commands were processed by the spacecraft.

At this time the transmitter uplink power of 400 kW was requested and authorized. Commands were again radiated, with two attempts planned for each. However, the high-power transmitter began to periodically trip off with crowbar fire alarms. Finally, the transmitter was declared red, and the pass was completed downlink only. Thus, all planned commands could not be sent.

One last attempt to transmit the cooling turn sequence before conjunction was planned over DSS 63 on January 15, 1992. If it proved to be unsuccessful, the sequence would not be executed, and this attempt in the series of activities to free the stuck ribs on the HGA would be lost.

Again, the 400-kW transmitter uplink power was requested and utilized. Early in the pass, the transmitter tripped off once for a short duration. Then it was solidly operational for several hours, allowing multiple sets of commands to be transmitted. Surprisingly, the commands sent later in the pass were the ones processed by the spacecraft. Then the automatic gain controls (AGC's), both on the ground and on the spacecraft, appeared to stabilize. Incidentally, solar activity had begun to subside. At last the commanding was successful and the cooling turn was executed as planned.

III. DSN Support for High-Gain Antenna Activities

The HGA was not successfully deployed as planned in April 1991 [1]. An anomaly recovery team was quickly formed to assess the problem and potential solutions. Since the Probe mission was still intact, and the spacecraft was otherwise perfectly healthy, only minimum-risk ideas were considered. The most plausible failure scenario was that the mid-rib guide pins were stuck in their receptacles. The best engineering judgment led to a walking pin theory as a possible solution to this HGA anomaly.

This theory was based on a model which showed that by alternately warming and then cooling the HGA tower, the tower would expand and contract and would allow small movement of the guide pins until they were eventually walked out. Cooling turns (CTs) and warming turns (WTs) were carried out throughout 1991 and 1992 (Fig. 1). These turn events involved turning the spacecraft either about 45 deg off-Sun to expose and thus heat the HGA tower, or about 165 deg to shield the tower and thus contract it.

The DSN support for the various cooling and warming turns was unique in many respects. For instance, during Cooling Turn No. 2, the Low-Gain Antenna 2 (LGA-2) was switched on because of the large aspect angle of the LGA-1. Even with the LGA-2, the lowest Galileo data rate of 10 bps was not always supportable on the telecommunications link.

Furthermore, nonstandard temperature control was first attempted to maximize cooling. This involved turning some heaters off, etc.; but of more importance was that the Ultra Stable Oscillator (USO) was turned off. This meant that the DSN had to generate separate predictions for the Auxiliary Oscillator. The DSN predictions unit also had an unknown in the USO predictions after the USO was powered back on. This unknown consisted of the effects of temperature changes on USO frequency, which had been minimally characterized in flight.

Temperature changes during the turns resulted in significant drift of the Voltage Controlled Oscillator (VCO). For example, the VCO drifted about 4.5 kHz in the week of precooling before the actual Cooling Turn No. 2. Two-way operation with the VCO is the prime support configuration for the DSN.

The DSN tracking predictions unit was able to adapt well to these frequency changes. They maintained close interaction with the Galileo spacecraft team to ensure good temperature monitoring. The USO was again turned off during Cooling Turns Nos. 3–6.

One other way that the DSN support was affected during cooling turns was that the Travelling Wave Tube (TWT) was powered to its low power state, again to minimize temperature. This decreased the telecommunications link by 4.8 dB and further complicated the data acquisition process. As the spacecraft moved toward aphelion, the telemetry link margin was negative for the cooling turns. The DSN contributed to the Project's strategy for monitoring the spacecraft state. The strategy developed was that the Project would schedule DSN tracking support for about 2 hr every 8–10 hr to monitor for presence of carrier. If the spacecraft were to safe itself, it would orient itself towards the Sun, default to 10-bps telemetry, and change subcarriers. The received AGCs would indicate the respective changes.

The DSN supported these alternate cooling and warming turns through July 1992. As time went on, the walking pin theory was examined repeatedly, and the Project determined that the expectation of the stuck pins walking out was unlikely. The model showed that there was little to be gained after about six turns, as the curves became quite steep; i.e., if the model was correct, the pins should have been freed by completion of a half-dozen maneuvers.

One other HGA activity was supported by the DSN in July 1992. In conjunction with the DDA motors' on activity of July 21, 1992, the LGA-2 was retracted. In spacecraft testing prelaunch, some recalled that an LGA-2 retraction test shook the spacecraft when the LGA hit the stops on the Radioisotope Thermoelectric Generator (RTG) boom on which this antenna is suspended. While the retraction was successful, no change in the HGA configuration was observed.

Alternate theories and possibilities had been put forth and examined. The one that seemed to hold the most promise was Dual-Drive Actuator (DDA) hammering. The DDA includes the motors that are used to drive the HGA open. This theory, extensively modelled with tests on the spare flight HGA in the laboratory at JPL, showed that short on/off pulses of the HGA motors generated force, and could drive the ball-screw up its shaft with a total of about 1.5 revolutions maximum before stalling out again. The force generated on the push rods would be increased about threefold, thereby generating the hope that the antenna would be opened.

Due to the highly critical Earth-gravity assist (EGA), the Project did not want to perform hammering prior to that flyby. However several motors on calibrations were conducted in the April–October 1992 time frame. The first few were just 2-sec turn-ons at various temperatures to measure the DDA performance and to calibrate it against the laboratory measurements. Then in October 1992, a hammer test was performed. This was a shortened demonstration of the extensive hammering planned for late-December 1992 and early 1993.

The DSN supported extensive DDA hammering activities beginning on December 29, 1992. These hammering exercises continued for about 3 weeks. Though some ball-screw movement was detected, the HGA ribs were not freed.

Galileo had an agreement with NASA to declare that the Galileo mission would be supported on the LGA on March 1, 1993, should the HGA still be only partially deployed. Since the aforementioned activities apparently were not successful, the DSN will in fact support the mission at Jupiter only on the LGA. Significant new TDA developments, as well as spacecraft enhancements, are planned to increase the flexibility of, and maximize the supportable, data rates at the Jupiter ranges. These developments include, among other things, DSN antenna arraying, new coding techniques, data compression, and full carrier suppression operations with the Block-V receiver. These developments are planned to be discussed in detail in future TDA Progress Reports.

IV. DSN Support of Earth-2 Flyby

The Earth-2 flyby was essential to the Jupiter mission. If it were not executed properly, the spacecraft would not reach Jupiter. Navigation was near perfect, however, and Galileo is now finally on its way to completion of its prime mission.

DSN support for the flyby was substantial. There were a multitude of requirements to fulfill. These included, but were not limited to, Trajectory Correction Maneuvers (TCMs 14, 15, 16 and 17), the complete Gaspra tape-recorder playback [1], two very critical Probe tests, science instrument calibrations, and the closest-approach science.

TCM-14 was performed on August 4, 1992, and imparted a delta velocity of 21.27 m/sec. This was a deterministic maneuver which would put the spacecraft on course for its second asteroid encounter. That encounter will be with Ida on August 28, 1993.

TCM-15 was performed on October 9, 1992, and imparted a delta velocity of 0.72 m/sec. TCM-16 was performed on November 13, 1993, and imparted a delta velocity of 0.89 m/sec. TCM-17 was the encounter-minus-10-day maneuver. The delta velocity was only 0.03 m/sec.

The sum effect of the targeting was that closest approach was nearly exactly on target and on time. The altitude was only 304 km. The time of closest approach was 15:09:25 UTC (Fig. 2). The targeting was so effective that the TCM-18 planned for December 21, 1992, as a cleanup maneuver was declared unnecessary and therefore canceled.

Complete Gaspra data were played back from the tape recorder on November 23–24, 1992 (Fig. 3). The data were played back twice, and over two Deep Space Complexes to ensure ground capture. They were completely recovered by the DSN on the first attempt.

The highest resolution color image of Gaspra had previously been played back shortly after the asteroid encounter [1]. And when the data rate again supported 40 bps, the highest resolution image (black and white) was relayed to the ground via a Data Management Subsystem Memory Readout (DMSMRO). This occurred over the period between May 18 and June 6, 1992.

Two highly critical Probe tests were supported flawlessly by the DSN in the pre-Earth-encounter period. The first in-flight Mission Sequence Test (MST) was conducted on November 20, 1992. The MST was critical because it will be the only complete MST in the mission if the HGA is not deployed. All Probe data are currently designed for 28.8 kbps data rate. Furthermore, the test is critical in that the Probe ground data processors are fairly intolerant to data gaps.

Some subtle communication problems had been noticed from the Madrid Deep Space Communications Complex (Spain) (MDSCC) in November 1992, which caused the Project some anxiety. Knowing this, DSN and MDSCC personnel spent great energies troubleshooting the communications system, resolving anomalies, and thus ensuring the integrity of the Probe test. A letter of commendation was received by the JPL Assistant Laboratory Director for TDA from the Galileo Project Manager as a result of the DSN support for this test.

Then on December 2, 1992, the Probe Abbreviated System Functional Test (ASFT) was conducted. Again, it was supported flawlessly by the DSN. All test objectives were met for both Probe tests.

The Gaspra playback, Probe tests mentioned above, and the Earth's and Moon's closest-approach activities were conducted with heightened DSN personnel awareness, special support, and NASA Communications Network (NASCOM) special coverage. This support was requested by the Project and was provided successfully by the DSN.

The short range to the spacecraft during the Earth-2 flyby period allowed sufficient telemetry signal-to-noise ratio for all of the Galileo data rates to be exercised. It also allowed the DSN to verify its performance at the higher rates. Some changes since launch and Earth-1 were noted. For example, the type-B Telemetry Processor Assembly (TPA) buffer capacity was reduced during the DSN telemetry system upgrade. The effect of this reduction was that simultaneous recording and transmission of data rates above 80.64 kbps were precluded.

Of more importance than just exercising the high data rate was the ability of the Project to perform science instrument calibrations. If the HGA is not freed, then detailed, high-rate calibrations will not be possible for the duration of the mission. Many science instrument calibrations occurred in the days before closest approach. Then the close Moon and Earth observations were completed to verify the calibrations in preparation for the mission at Jupiter. The DSN supported all these calibrations without incident.

More detail on the closest-approach activities is now noted (see Fig. 4). For this flyby, the Moon's closest approach was at 110,000 km, contrasted with 350,000 km for the Earth-1 flyby. Also, the latitude for the Earth-2 encounter was 61 deg north as opposed to equatorial for Earth-1. This increased the interest in the lunar observations due to this trajectory providing the North Polar Moon coverage. The DSN supported these observations flawlessly beginning about 5 hr before the Moon's closest approach. The closest approach was at 03:47:45 UTC. The lunar observations continued until only a few hours before the Earth's closest approach.

At the Earth's closest approach, Galileo began to concentrate on Solid State Imaging (SSI) of the Andes, Antarctica, Hawaii, Indonesia, and other places. The Andes data were placed on the tape recorder for later playback, as the DSN was not in view during this time. The next section discusses special, non-DSN coverage during the DSN tracking gap. This coverage was limited to carrier tracking only.

After the closest approach, the LGA-1 aspect angle to the DSN antennas was more than 100 deg. Poor telemetry performance was noted. It was most noticeable as black streaks in the real-time images that the Project was displaying on the JPL monitors. As noted earlier, the LGA-2 had been stowed in July 1992; and with the HGA anomaly, the only available antenna was the LGA-1. Also, the sequence on board the spacecraft assumed a margin to support the highest possible telemetry data rate, i.e., the data rate was lowered only when the higher data rate was not deemed to be supportable.

This condition lasted for several days. It was determined quite early that the high aspect angle was likely reflecting the signal through the magnetometer boom, thus causing the unpredicted poor performance. The Project had little choice but to accept this anomalous condition until the aspect angle became much better, as a modified sequence was unattainable. The DSN had to provide support through these periodic data gaps.

The Galileo Optical Experiment (GOPEX) was very successfully supported from December 9–16, 1992. The DSN provided special pointing predictions to the Table Mountain Observatory and the Starfire Optical Range. The DSN also provided special communications equipment and arranged for communication lines for these activities. More detail on the experiment is provided in [2].

V. Special Non-DSN Support During Earth-2 Closest Approach

A trajectory anomaly was observed during the Earth-1 encounter. It coincided with the closest approach, which was out of view of the DSN. After intense examination by the Galileo navigation and science teams, no plausible argument could explain the trajectory anomaly, a 3- to 4-mm/sec velocity increase, at the Earth-1 closest approach. The trajectory for Earth-1 flew almost directly over Madrid, Spain, with a closest approach at 25 deg north latitude and 63 deg west longitude. The minimum altitude was 960 km. Goldstone rise was then 15 min after Madrid set, thus leaving this flyby with a short DSN tracking coverage gap.The Earth-2 closest approach was at 34 deg south latitude, 6 deg west longitude, and only 304 km altitude. This led to a DSN tracking gap of about 2 hr.

A Galileo celestial mechanics investigator, John Anderson, convinced the Project that there was reasonable probability that the answer may have been of fundamental science significance, i.e., gravitation or general relativity related. In April 1992, the Project requested that the TDA team pursue options available for closing the DSN tracking gap during the Earth-2 flyby.

Many ground sites were considered, along with NASA's own TDRSS. After some deliberation, it was decided to enter into negotiations with NASA and Goddard Space Flight Center for use of a TDRSS satellite; with the University of Chile for a Santiago tracking station; with the European Space Agency (ESA) for its Perth, Australia, tracking station; and with the National Space Development Agency of Japan (NASDA) for an Okinawa tracking station.

Ultimately, TDRS-3 at 62 deg west longitude was used for support. Also utilized were the 9-m antenna at Santiago, Chile, the 15-m antenna at Perth, Australia, and one of two 18-m antennas at Okinawa, Japan (Fig. 5).

The TDRSS operations were made easier by transporting a special receiver called the Experimental Tone Tracker (ETT) to White Sands, New Mexico, to communicate with the TDRS-3 (Fig. 6). This receiver was developed by the JPL Tracking Systems and Applications Section 335, for use with the Orbiting Very Long Baseline Interferometry (OVLBI) experiment, and so had previously been installed and operated at White Sands. The Galileo Doppler data were recorded from the ETT and transported to JPL.

The Santiago interface was the only real-time interface for the non-DSN supporters and was conveniently connected into NASCOM. The Perth data were sent electronically to Darmstadt, Germany, from where the ESA personnel forwarded them electronically to the JPL navigation team. The Okinawa data were formatted onto a floppy disk and mailed to JPL.

The time line shows that 3-way Doppler was recorded by the non-DSN stations until DSS 42 had the transmitter off at 1340 UTC. Then they reacquired 1-way until their respective set times. Thus there was a 22-min ground gap until Santiago had an acquisition of signal (AOS) at 1513 UTC. The link from Galileo to TDRS-3 to the ETT at White Sands maintained lock during this time. Goldstone acquired the signal before Santiago lost the signal. In fact, DSS 12 established an uplink at 1555 UTC and Santiago was in 3-way lock at 1556 UTC. The DSN tracking gap was thus completely covered by the non-DSN resources, and the operation was a complete success. Analysis of the data did not reveal an orbit anomaly.

References

[1] P. E. Beyer, R. C. O'Connor, and D. J. Mudgway, "Galileo Early Cruise, Including Venus, First Earth, and Gaspra Encounters," *The Telecommunications and Data Acquisition Progress Report 42-109*, vol. January–March 1992, Jet Propulsion Laboratory, Pasadena, California, pp. 265–281, May 15, 1992.

[2] K. E. Wilson, J. R. Lesh, T.-Y. Yan, J. Schwartz, M. D. Rayman, and S. Wee, "GOPEX: A Deep-Space Optical Communications Demonstration With the Galileo Spacecraft," *The Telecommunications and Data Acquisition Progress Report 42-103*, vol. July–September 1990, Jet Propulsion Laboratory, Pasadena, California, pp. 262–277, November 15, 1990.

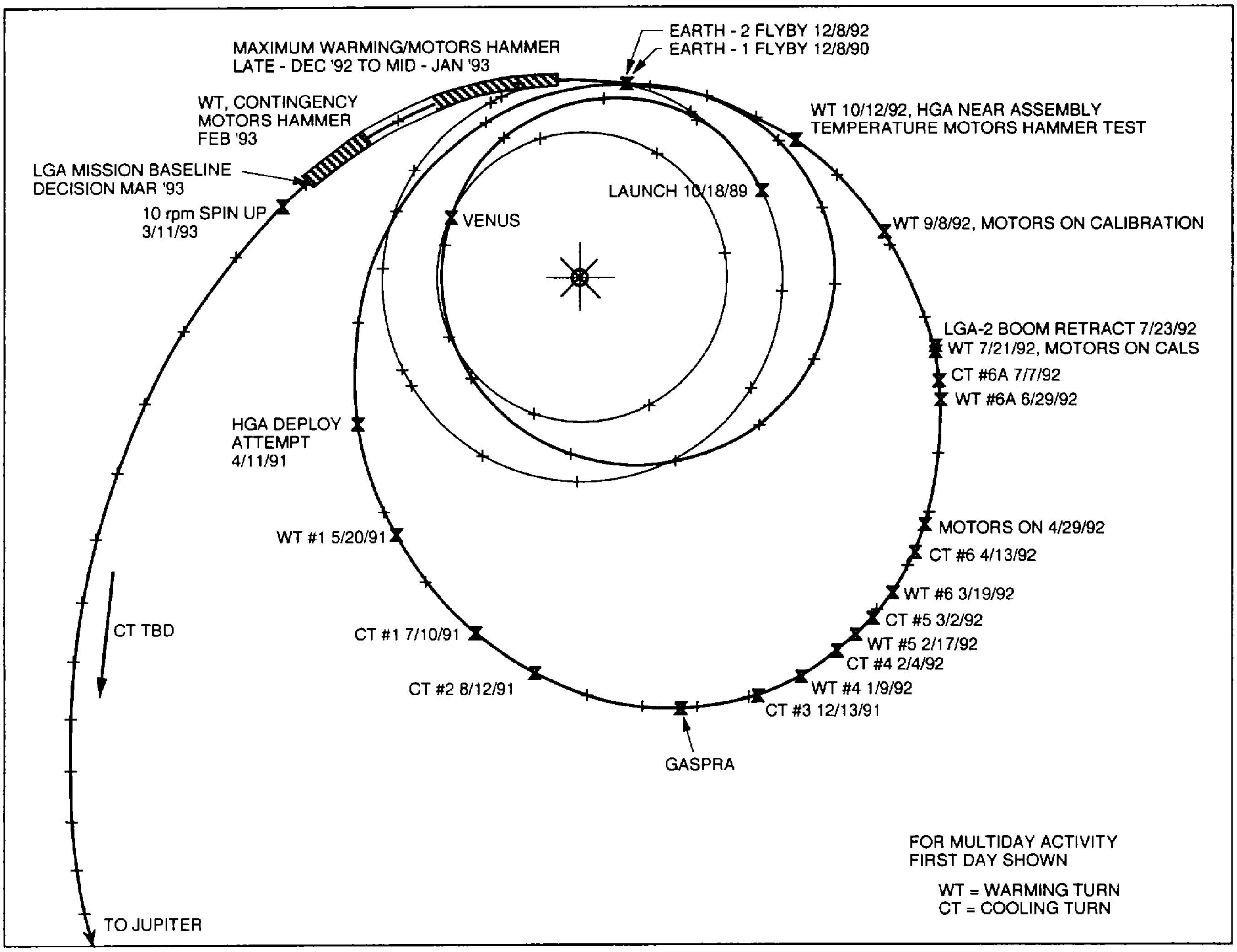


Fig. 1. Galileo HGA events.

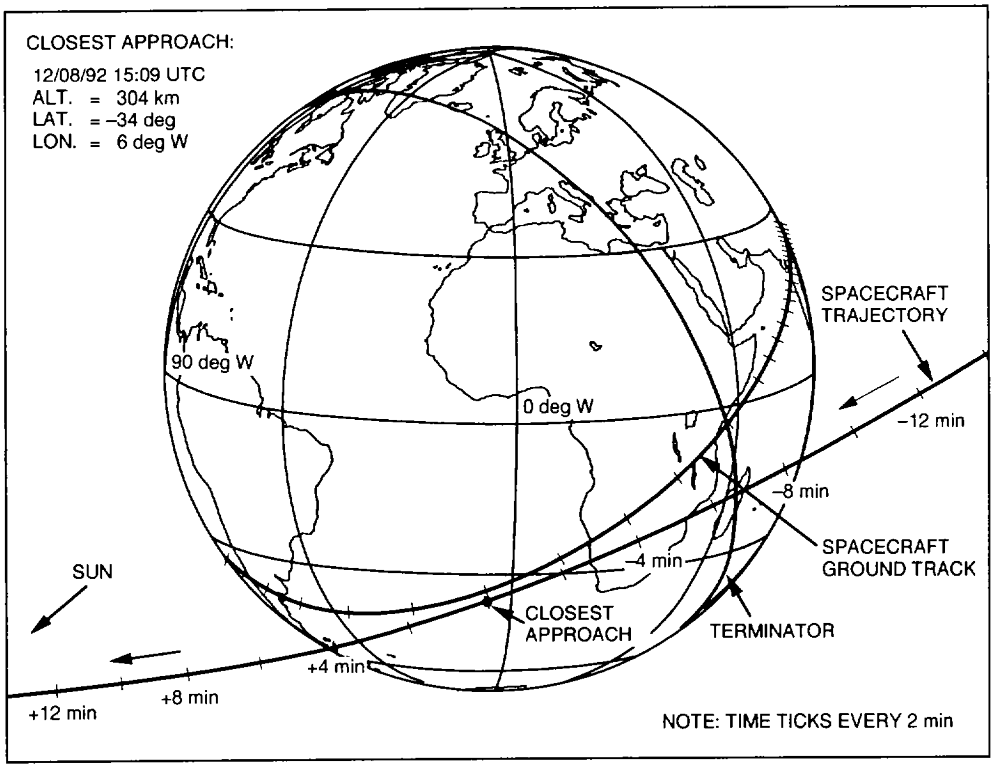
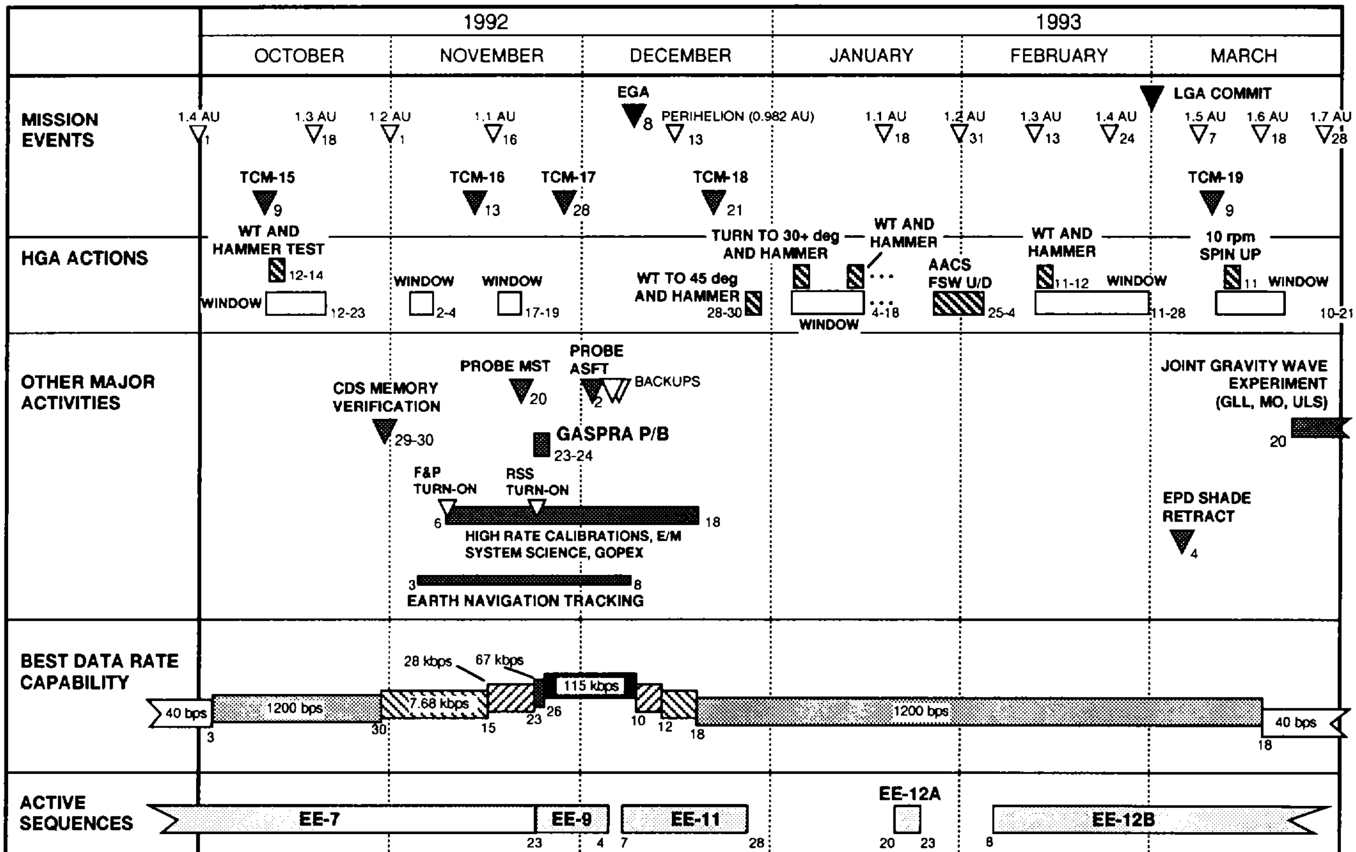


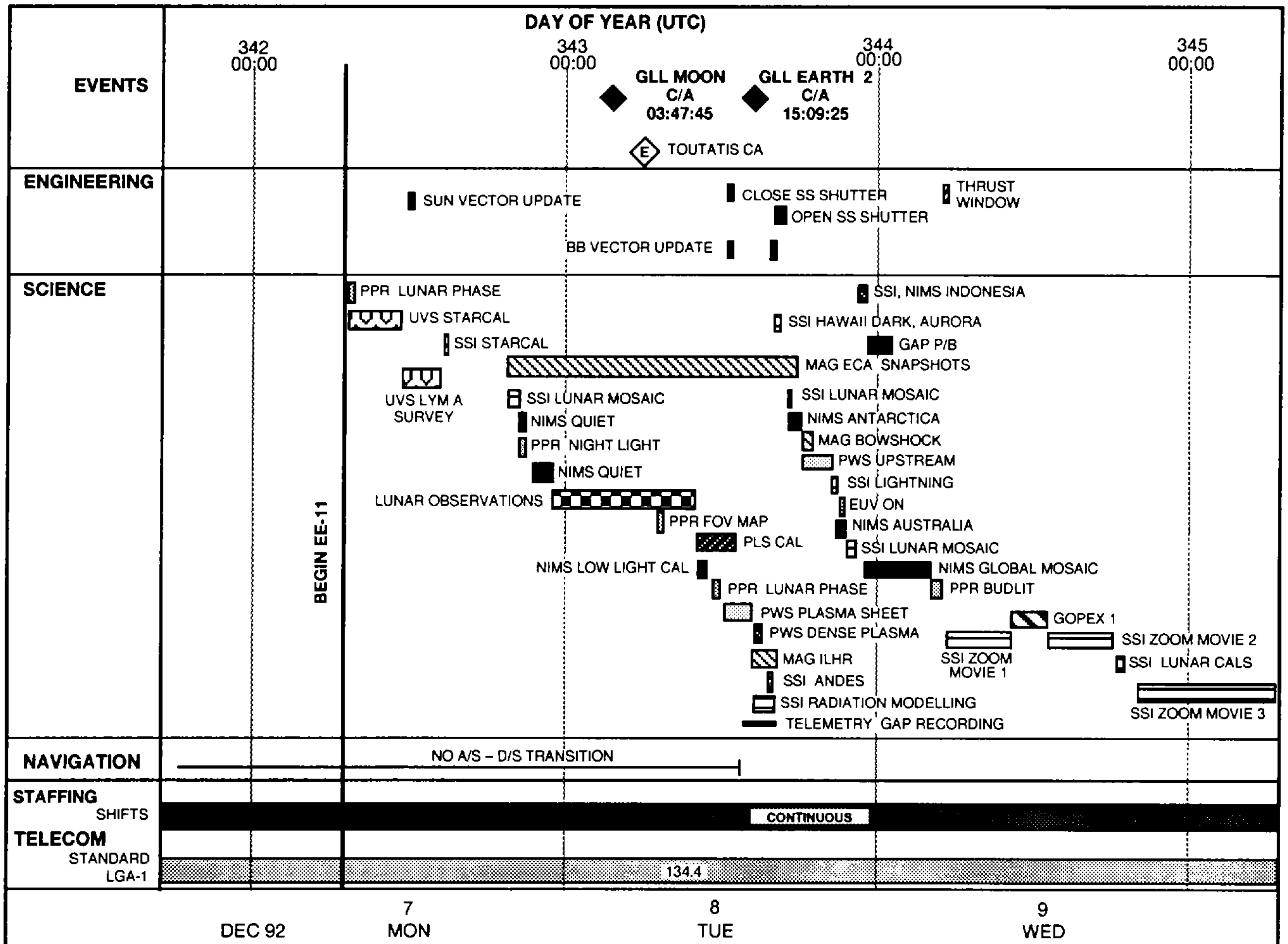
Fig. 2. Galileo ground track of Earth-2 flyby.



LEGEND:

AACS	ATTITUDE AND ARTICULATION CONTROL SUBSYSTEM	F&D	FIELDS AND PARTICLES	RSS	REMOTE SENSING SCIENCE
CDS	COMMAND AND DATA SUBSYSTEM	FSW	FLIGHT SOFTWARE	U/D	UPDATE
EE	EARTH TO EARTH	GLL	GALILEO SPACECRAFT	ULS	ULYSSES SPACECRAFT
E/M	EARTH/MOON	MO	MARS OBSERVER SPACECRAFT		
EPD	ENERGETIC PARTICLES DETECTOR	P/B	PLAYBACK		

Fig. 3. Galileo time line of events.



LEGEND: A/S	ALL SPIN	FOV	FIELD OF VIEW	PWS	PLASMA WAVE SUBSYSTEM
BB	BRIGHT BODY	LYM A	LYMAN ALPHA	SS	STAR SCANNER
C/A	CLOSEST APPROACH	MAG	MAGNETOMETER SUBSYSTEM	UVS	ULTRAVIOLET SPECTROMETER SUBSYSTEM
CAL(S)	CALIBRATION(S)	NIMS	NEAR INFRARED MAPPING SPECTROMETER		
D/S	DUAL SPIN	PLS	PLASMA SUBSYSTEM		
EUV	EXTREME ULTRAVIOLET	PPR	PHOTOPOLARIMETER RADIOMETER SUBSYSTEM		

Fig. 4. Earth-2 encounter overview Earth closest-approach activities.

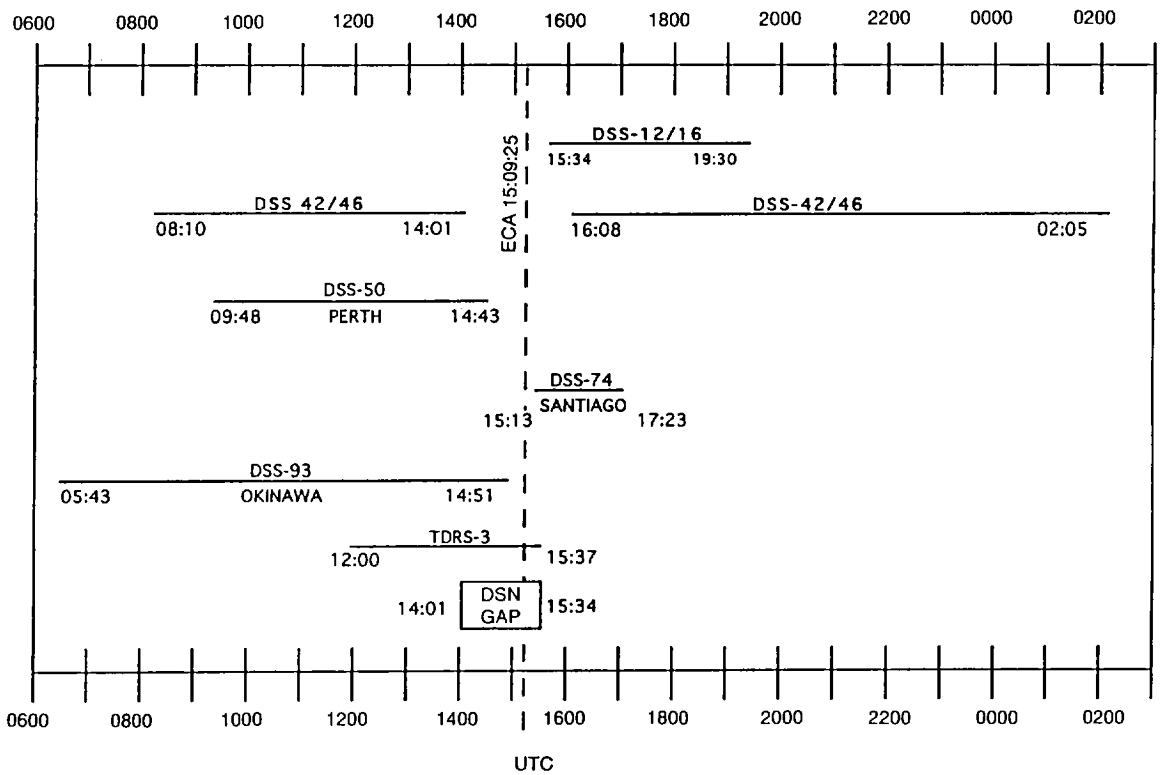


Fig. 5. Galileo tracking time line for Earth closest approach.

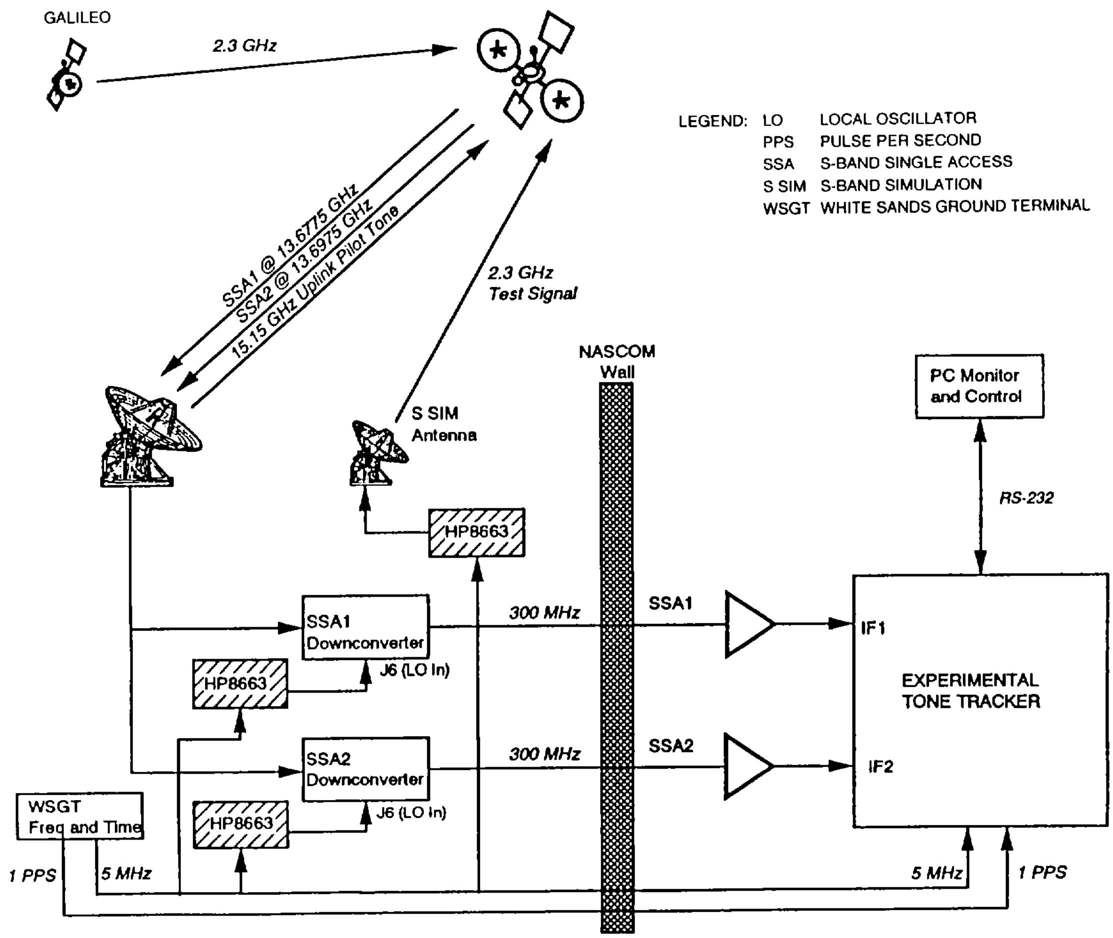


Fig. 6. Galileo Earth-2 TDRSS tracking.