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Completing Its Primary Mission

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Abstract

During this past year, the Galileo Orbiter has performed the large majority of its primary scientific mission in the Jupiter System—eight of the eleven orbits and seven of the ten close satellite encounters and the deep penetration of the magnetotail. Only the tenth encounter remains ahead. This paper will as in past years[1-6] provide a summary of the salient Galileo activities throughout the year. Galileo has indeed been fulfilling its promise in the Jupiter System in an exemplary manner.

Also, a summary of the approved follow-on Galileo Europa Mission (GEM) will be given. The GEM will extend Galileo's orbital operations at Jupiter an additional two years to the very end of this century.

1. Introduction

Project Galileo marks the 20th anniversary of its start this Month. Galileo was a FY78 new start in October 1977. This 20th anniversary follows a terrific year of outstanding Galileo achievement. All seven of the satellite encounters this year were grandly successful—2 with Europa, 2 with Ganymede, and 3 with Callisto. Galileo is now nine for nine. The first two encounters—Ganymede-1 &2—occurred last year and were equally successful.[7] Only one primary mission encounter is yet to be performed—Europa 11 on November 6th. An absolutely tremendous bounty of science has been obtained for which Galileo is acclaimed worldwide. Galileo is also widely acclaimed for its stunning recovery from the High Gain Antenna deployment failure---particularly for the use of new concepts and technologies that have broad application for future deep space missions. Project Galileo's performance this past year has spectacularly demonstrated the success of this remarkable recovery. Spacecraft health has been scrupulously maintained.

The heliocentric path of Jupiter now in its second year possessing its first artificial satellite—the Galileo Orbiter– is shown in Figure 1. Highlighted is the path over the past year, i.e., between the 47th and 48th IAF Congresses. Figure 2 shows the journey of Galileo through the Jovian System, again, with the past year highlighted. A closeup view of all the Galileo primary mission perijove passes is presented in Figure 3. The targeted, gravity assist, satellite encounter is indicated for each orbit, Also shown are the four "non-targeted"

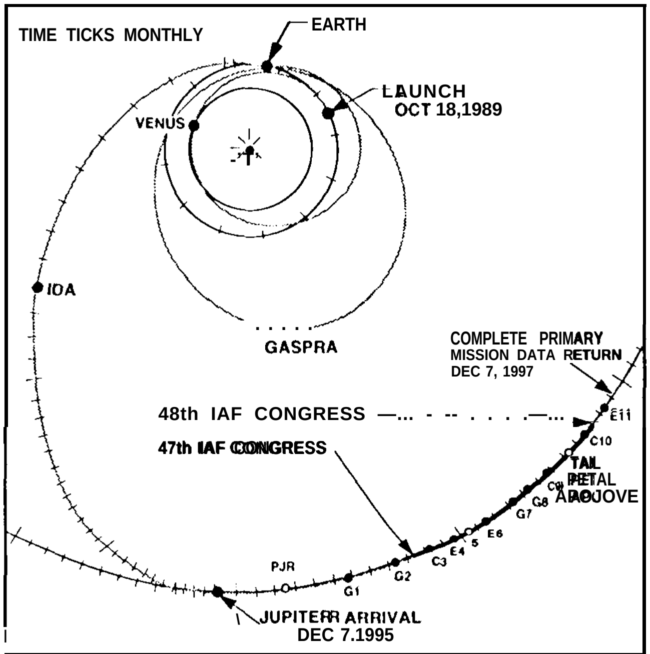


Figure 1. Heliocentric Progress

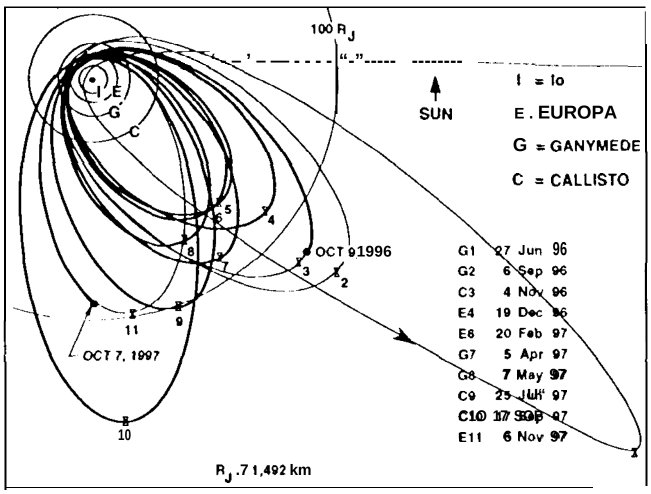


Figure 2. Orbital Tour of the Jupiter System

[1]Galileo Project Manager, Member, AIAA, [2]Galileo Science and Sequence Office Manager, [3]Galileo Flight Control and Support Office Manager, [4]Galileo Engineering Office Manager, [5]Galileo Mission Planning Office Manager, [6]Galileo Mission Director, [7]Galileo Deputy Mission Director.

[illegible] the International Academy of Astronautics satellite cncorrntcrs—encounters designed into the Tour for moderate resolution global coverage of a satellite coming within 100,000 km flyby range; these do not provide any orbit shaping and cannot bc controlled independent of the targeted satellite flyby. The first encounter of this past year, Callisto-3, also provided the first non-targeted encounter, Europa-3A ("A''dcsignates non-targeted). Figure 4 illustrates this beautiful chorcgraphy and shows the closest approach points for all the satellites. Indeed, at every perijove (except #5 in solar conjunction), observations arc generally made of all the Galilean satellites and of Jupiter in addition to the emphasis on the targeted satellite. The high-level calendar of Galileo activity this past year is given in Figure 5.

One of the best measures of a Project is its ability to diagnose and overcome immediate and unforeseeable anomalies. Project Galileo continued to bc superb in this. At four of the seven encounters, realtime contingency actions were performed to overcome serious anomalies. Most notably, at Europa-4 just one day before the first scheduled recording, the Tape Recorder was locked out by CDS fault protection. In another stunning effort, the Team recovered the Rccordcr one hour before the first scheduled recording. A very slight misalignment of the ncw track markers coupled with removal of now superflous "unsticks" on forward tracks had fooled the CDS into anomalously detecting end of track. Again, the FSW fault protection response was perfect and the subsequent Team response was stunning indeed.

All eleven Galileo Orbiter science instruments and the two radio science investigations have produced excellent results throughout the year even though the Near Infrared Mapping Spectrometer (NIMS) has two of its seventeen detectors now failed and the Photopolarimeter-Radiometer (PPR) filter wheel is somewhat impaired. In addition to the spectacular images and other remote sensing, the six fields and particles instruments gathered extensive data on Jupiter's magnetosphere including its interaction with the satellites. And the kcy objective of measuring the deep magnetotail has been accomplished,

Galileo has produced extensive scientific publications and very positive media coverage. Of particular note, through the support and participation of the late Dr. Jurgen Rahc (NASA Code S) and initiative and hosting of Prof. Cesare Barbieri of University of Padova, Italy, an excellent Three Galileos Scientific Confcrcncc was held in Padova, which culminated in the Galileo Project Manager and Project Scientist presenting Project Galileo imaging results to Pope John Paul II in Rome on January 1 1th.

The most significant Galileo finding to date is the strong evidence in the high resolution images of Europa that liquid water may indeed presently exist under the Europa water ice crust. A summary of science highlights is given in the next section.

Coordination of the virtually continuous tracking support by the DSN (including the Australia 64m Parkes radio astromony antenna augmentation) with the spacecraft sequence with its multiple telemetry rate changes each day and periodic special tracking needs (e.g., occultation scicncc experiments) continues to bc superb. Array support began right on schedule

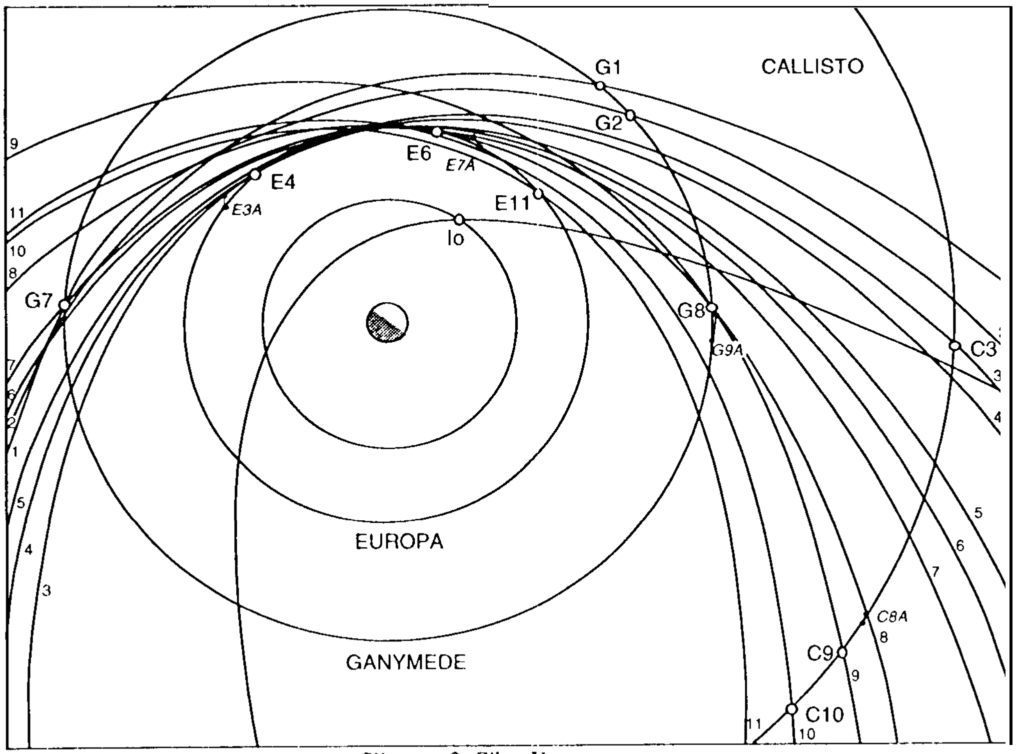


Figure 3. The Encounters

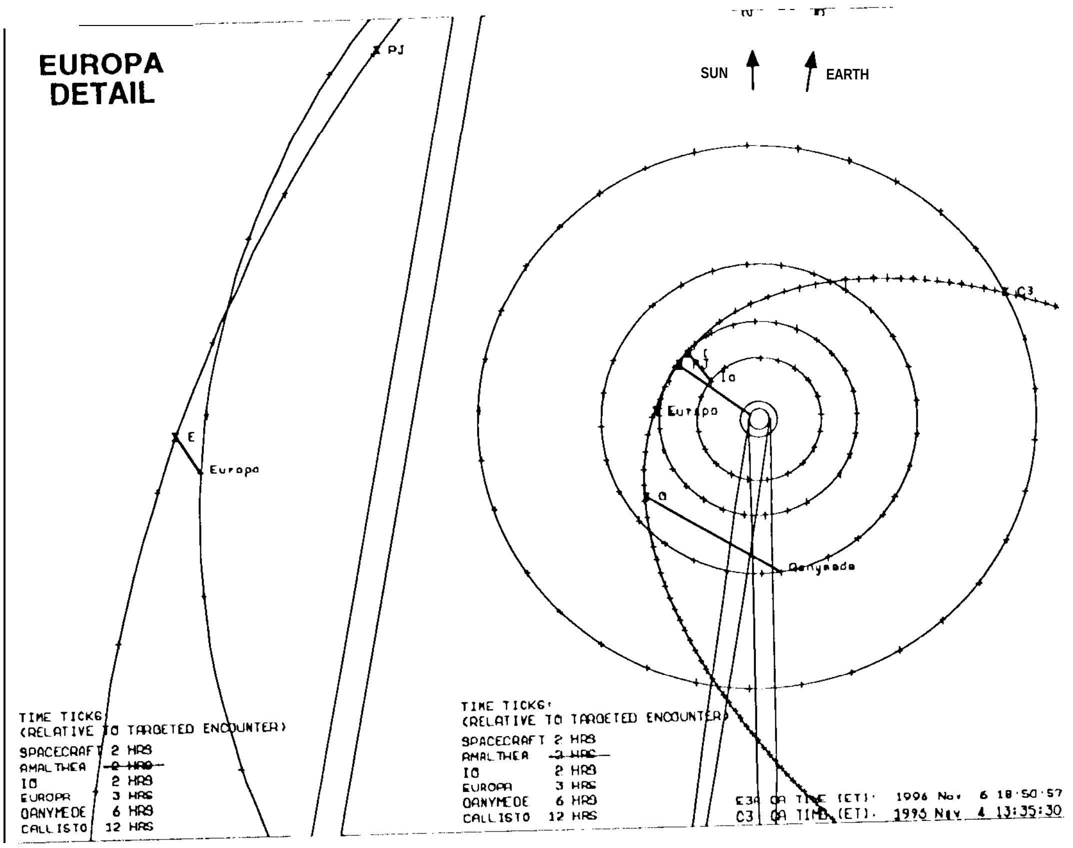


Figure 4. The Callisto 3/Europa 3A Ballet

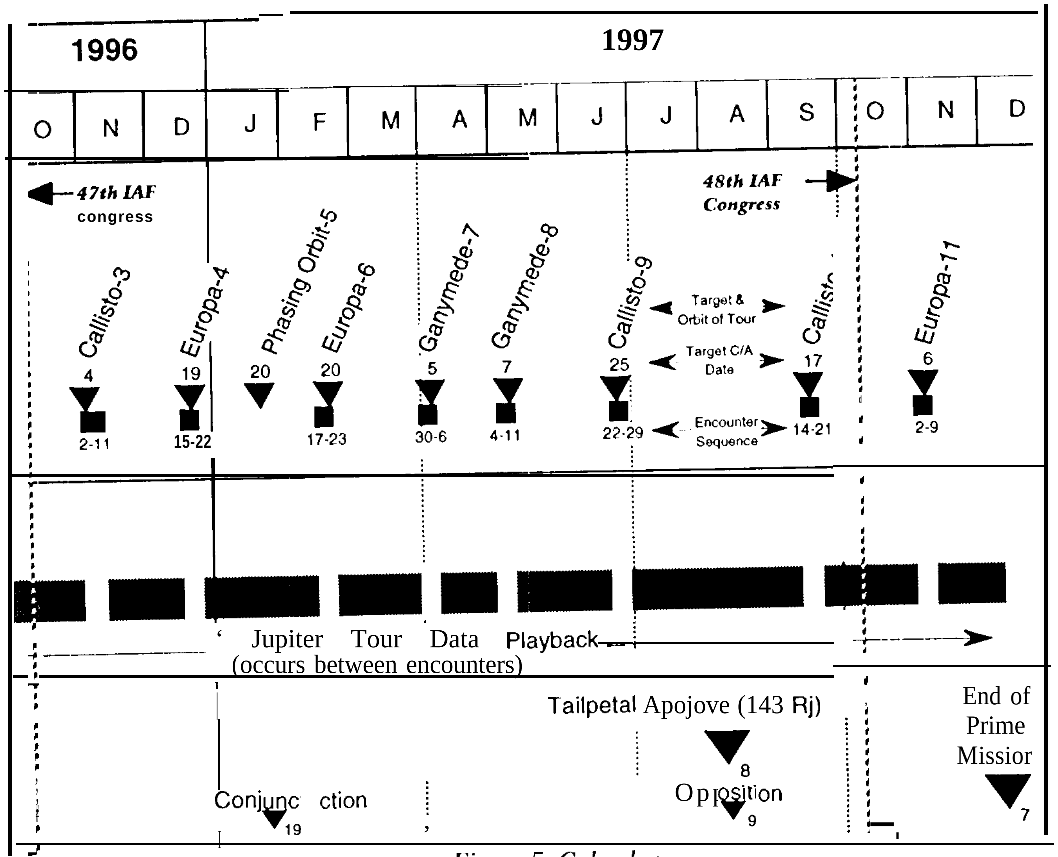


Figure 5. Calendar

in November and after procedural growing pains and with continuing quite frequent selected post-pass processing including sending Full Spectrum Recorder (FSR) tapes to JPL for-data extraction, data capture is now exceeding a phenomenal 98 percent. This is so remarkable considering received signal strength is 10,000 times less than the spacecraft High Gain Antenna was to have provided.

The overall performance of the spacecraft including all its new FSW has been outstanding throughout the year. The sequence development and execution have been remarkably smooth for both science acquisition and playback especially considering that this is one of the most complex deep space mission operations ever. The harmony in achieving the best science safely is absolutely extraordinary. And the new technique of Record During Cruise (RDC) was very successfully used in the magnetotail orbit between the Callisto 9 and 10 encounters. Also this year, the new contingency version of FSW has been completed that can be used to enable imaging without the Tape Recorder in the event of a Recorder failure. Far fewer images would be possible, but this FSW does provide for fast CCD read to the CDS buffer (pre-compression) to allow imaging in the radiation environment at Europa and Io.

Navigation continues to be superb. The now Galileo-based Galilean satellite ephemerides arc so accurate that optical navigation was eliminated after Ganymede-7. This reduces cost and complexity and provides more downlink for science. The superb navigation has resulted in an end of primary mission usable propellant estimate (90%) of nearly 60 kg, which is nearly twice the amount predicted just before arriving at Jupiter. The actual navigation delivery accuracy is now typically better than 10 km in altitude and one second in encounter time.

Project Galileo is operating with 25% less work force than was planned for this period just one year ago (-224 vs. 294 people). The Project will save about 15 M$ in FY97 to apply to FY98 science data analysis and the extended mission. This was achieved with spacecraft and ground systems maturation and considerable process improvements.

Entirely within the last two fiscal years (i.e., post-Jupiter arrival) the Project conceived, developed, and obtained NASA approval and funding for an outstanding two-year extended mission called the Galileo Europa Mission (GEM). GEM consists of eight consecutive Europa encounters followed by a perijove reduction campaign using four Callisto gravity-assist encounters to provide for one or two close Io encounters in late 1999, all subject, of course, to radiation survivability. The aforementioned propellant reserves arc more than adequate to complete the GEM. The GEM preparations are very wel I along and the Mission Plan and Orbit Planning Guide are already published. The GEM is described in the last section of this Paper. Pursuant to very recent discussions with NASA Headquarters, Project Galileo has developed a strawman plan to continue very limited Galileo Orbiter operations after GEM for as long as the spacecraft survives and the current Galileo lands can support. The objective of this continued operation is to learn as much as possible about the radiation affects on Galileo in order to best design the radiation protection for future missions to the Jovian System such as the Europa Orbiter now under serious consideration by NASA.

Galileo Outreach continued to be exemplarly throughout the year including a new image presented to the public on the World Wide Web Galileo Homepage (http://www.jpl.nasa.gov/galileo) virtually every working day on average. Tremendous leverage was obtained with several Educator Workshops wherein the capacity attendance of -200 teachers in JPL's von Karman audi tori urn at each workshop multiplies by hundreds fold in number of students reached. These are always early "sellouts" with enrollme nt applications twice capacity.

The U.S. National Space Club presented its Nelson P. Jackson Aerospace Award to "Project Galileo Mission" at the Annual Goddard Memorial Dinner in Washington on April 4th. The Galileo Team also received the AIAA Space Operations and Support Award for 1997.

2. Orbiter Science Highlights

From Project inception in 1977, Galileo has had three co-equal primary science objectives, namely, to investigate the Jupiter 1)atmosphere, 2)satellites, and 3)magnetosphere. As reported at last year's IAF Congress[1], the Galileo Atmospheric Entry Probe was tremendously successful in performing the tirst-ever direct sampling of the Jupiter atmosphere reaching a pressure depth of 23 bars-over twice the 10 bar mission requirement--before high temperature silenced the transmitters. This past year the Galileo Orbiter has performed the bulk of its primary orbital mission at Jupiter. The Probe and Orbiter have produced a tremendous bounty of science to date. About two-hundred science publications have already been produced, including the interplanetary cruise science.

The most significant finding of Galileo to date is the strong evidence in the high resolution images of Europa that liquid water may indeed presently exist under the ice crust. Images taken at the Europa-6 encounter in February at 50-meter resolution show icebergs in a frozen sea (see photo section). These icebergs (also, perhaps more descriptively, called ice rafts) arc displaced from one another in a manner that clearly indicates they have broken apart and been moved and rotated into these positions as this particular surface formed. With no significant slopes or winds, it is logical that ocean currents produced the displacements, The paucity of craters indicates this particular surface is geologically very young, perhaps just 10's of millions years old, Therefore, given the age of the system at 4.6 billion years, if liquid water existed there so recently, it is inconceivable that it has all frozen out in the "instant" of geologic time since the imaged surface was formed.

The Probe did the detailed in-situ measurements of Jupiter's atmosphere in its entry and descent region. The

Orbiter also has a very significant role in the atmosphere investigation, namely, the global characterization of the atmosphere by remote sensing and radio occultation experiments. Correlation of the remote and in-situ measurements is a key feature of the Galileo Mission. For example, a major finding by the Orbiter's Near Infrared Mapping Spectrometer (NIMS) is that water vapor abundance varies by orders of magnitude from "dry" to "wet" regions in Jupiter's upper atmosphere. This is consistent with the dry Probe entry region while other regions can be factors above solar relative abundance.

Images of Jupiter show clear evidence of thunderstorm-like activity. Three dimensional models of cloud structures and winds have been constructed using the imaging data. Ground and Hubble Space Telescope observations arc being effectively combined with the Orbiter's atmosphere observations.

There have been many exciting findings for the Jupiter satellites. Distant Io imaging is performed in every encounter sequence to do volcano monitoring. Large changes in volcanic activity are seen since the Voyager imaging in 1979. At least nineteen hot (>700K) volcanic areas have been located by Galileo. Silicate volcanism is implied. There is evidence of some very high lava temperatures (>1800K) suggesting extreme chemistry. Fewer plumes arc visible than in 1979; perhaps there arc more pure gas "stealth" geysers. Io's plumes may be the source of high speed dust streams seen by both Ulysses and Galileo. Six precisely designed distant Io occultations have provided the first global picture of Io's complex ionosphere. Last year it was reported that Io gravity field measurements during the arrival day close flyby indicate a large iron/iron-sulfide core about half Io's radius.

In addition to the aforementioned compelling evidence of liquid water, Galileo has found complex systems of faults and ridges covering Europa's surface. Galileo images show the first evidence for volcanic ice flows. Radio occultation measurements have discovered an ionosphere at Europa. Gravity measurements and other observations indicate Europa has three structural phases: a large metallic core , a rock mantle, and an outer shell of liquid and solid (ice) water perhaps 150 km thick.

Measurements during the Ganymede encounters this year confirmed the discovery by Galileo last year that Ganymede has a nlagnctospbcrc--the first moon in tile solar system determined to have a magnetic field. Gravity field measurements show Ganymede to be differentiated. The preferred model has three phases: a metallic core, rock mantle, anti large icy outer shell. Galileo also discovered a tenuous hydrogen atmosphere at Ganymede and a large outflow of protons; also that ozone in Ganymede's surface icc is concentrated at high latitudes.

The first encounter of the year was with Callisto in November. It produced two big surprises. First, Callisto has extensive blanketing by an apparently powder-like debris covering small craters. The origin and make-up of this material is a mystery under investigation. Second, gravity measurements show Callisto is an essentially homogeneous body unlike the other big Jupiter satellites. Galileo's fields anti particles measurements also show Call isto has no significant magnetic field.

Exciting new measurements of the great plasma torus along 10's orbit and its plasma disk have been obtained by the Galileo Orbiter during the cruise phases of the tour. The disk was observed to extend as a thin sheet to radial distances of 100 RJ and beyond. The location of the Orbiter near equatorial latitudes has allowed the detection of global changes in the geometry of this rapidly rotating, undulating plasma disk. That is, the geometry of the disk is observed to quickly—within one day or so—change in thickness and to exhibit distortions in its geometry. The reasons for this remarkable behavior arc probably due to variations of the injections of plasmas from Io's volcanic activity and/or the action of a variable solar wind. The magnetic signatures which suggest the merging of magnetic field lines in tbc plasma sheet which provides the release of large amounts of energy have been tentatively identified. Such processes arc responsible for the magnetic substorms which cause intense auroral light activity at Earth. From remote Earth-based images of the polar regions of Jupiter, it is now known that Jupiter also exhibits great increases in auroral light intensities, which are suggestive of global changes in the magnetosphere of Jupiter. In order to produce these dramatic displays of light, it is necessary to force the flow of charged particles into Jupiter's atmosphere. I'article detectors onboard the Galileo Orbiter have recently detected these beams flowing along the magnetic field in the direction of Jupiter's atmosphere. And there is every reason to believe that the mysteries of the aurora will be unraveled with the in-situ measurements of fields and particles in combination with the remote imaging of the auroras with the remote sensing "cameras" onboard the Galileo Orbiter and those at Earth. Measurements of the charged particles environment in the Jovian magnetosphere show that there have been great changes since the Voyager epoch of 1979. There arc very puzzling decreases in tbc hot plasma densities and changes in the composition of the ions during this current "Galileo epoch." Is it possible that all of these dynamical effects arc due in large part to the variable volcanic activity of 10'? The answers to ail of these above mysteries arc anticipated to be found with vigorous analyses of the wealth of data from the current prime mission and from the two year extended mission ultimately reaching into the near-Jupiter "core" of the torus and plasma sheet.

3. Summary of Encounters

3.1 Callisto 3

The first of the seven satellite encounters occurring within tbc last twelve months was the third encounter of the tour, and the first with Callisto. It occurred on November 4, 1996, at a closest approach altitude of i, i 36 km at 13:34 GMT.

The perijove pass on which this encounter occurred also provided the first "nontargeted" encounter of the tour, a 34,800 km pass of Europa (Figure 4). A nontargeted encounter is a secondary, more distant satellite encounter on any given pass through perijove, up to 100,000 km distance. It is "targeted" in the sense that it was deliberately designed into the original tour design, but is untargeted in the sense that while actually flying the tour, no effort is made to control the encounter conditions. This is because, with the propellant available and the maneuver placement schedule, it would be very difficult, in most cases impossible, to control the encounter conditions of two satellites in a single perijove pass and still achieve the necessary gravity effects to reach the next encounter in the tour. Hence, the terminology "nontargeted" One of the primary science objectives that is accomplished with nontargeted encounters is global coverage, which is possible because of the greater ranges to the body.

The geometry of the Europa encounter led to a "tweak" of the C3 encounter sequence. "Tweak" is the terminology used to refer to the process of overwriting observation parameters that are already stored in spacecraft memory, as opposed to loading a complete sequence. Because the Europa closest approach point occurred a little over two days after the Callisto close encounter, the normally occurring navigation delivery errors at Callisto would project to much larger dispersions by the time of the Europa encounter. If left unaccounted for, these dispersions would have degraded, if not missed entirely, some of the planned observations of Europa. By tracking the spacecraft through the point of closest approach to Callisto, it was possible to determine more accurately what the actual trajectory would beat Europa, and the point ing parameters for 16 Europa observations were updated and sent to the spacecraft.

A high level indication of the science observations that were made during the C3 encounter sequence may be seen in Figure 6a, a tape map of the recorded observations. Recording for C3 started on track 2 as indicated, about 2/3 of the way through the track, measured from right to left. Recording then proceeds to track 3, track 4, track 1, then finishes with the remainder of track 2. The rules for operating the tape recorder vary with track, depending on whether it is a forward running track or a reverse running track.[1] The record starting location is selected so as to place the closest approach events on a forward running track, since wait times arc not required and it is possible to record nearly continuously, but at varying record rates. The abbreviation "IT" seen in this and subsequent tape maps refers to feature tracks, that is, observations which track features in Jupiter's atmosphere from orbit to orbit, such as the (it-cat Red Spot, white ovais, brown barges, etc.

The standard seven day encounter sequence for this encounter ran from November 2, i 996, 16:00 GMT to November I i, 1996, 02:00 GMT. Two sets of spacecraft [urns were required to implement the science observations. The first set, on November 7, was for the feature track observations. At this time, about a day after perijove passage, the spacecraft had moved behind Jupiter--in the hemisphere opposite Earth and Sun, but not in occultation--so that the line-of-sight from the scan platform to the target passes through the plane of the booms (the magnetometer boom, the two RTG booms, and if the phase angle is large enough, the two thruster cluster booms). To avoid this interference, the spacecraft was turned about i 6°. The second set of turns was needed for a feature of the Callisto-3 encounter that was of particularly high interest to the scientific community, the solar occultation that occurred about five days after the Callisto closest approach, as seen in Figure 7a. The spacecraft was turned about 99° this time, again to avoid the booms. This allowed observations of the dark side of Jupiter, and of the rings in a back-lit lighting configuration, while the spacecraft was in the shadow of Jupiter. This is possible only in shadow, because of the damage that would occur to the instruments if pointed this close to the sun direction and not shaded by Jupiter. About four hours of highly successful observations were made during this period, Occultations of the. sun by Jupiter were not unique to the C3 orbit, but this one provided the best observing opportunities because of its long duration and relatively short range to Jupiter.

3.2 Europa 4

The fourth encounter of the tour, the first close encounter with Europa, occurred on December 19, 1996, at an altitude of 692 km at 06:53 GMT. Scientific interest in this encounter was very high, because Europa had iong been a high priority target for the scientific community. This interest was further heightened after images returned from the C3 distant flyby of Europa showed long features in the icy surface not previously seen. The primary scientific objectives of this encounter were remote sensing observations of the surface of Europa, observations of the interactions of Europa with Jupiter's magnetosphere during the satellite flyby period, and several observations of features within Jupiter's atmosphere. Additional details may be seen in the encounter period tape map shown in Figure 6b. Observations of 10, albeit distant, are seen in the tape maps for every orbit, These are in support of an 10 monitoring campaign to determine variations in 10's surface due to volcanic activity over the time period of the Galileo mission.

The encounter sequence started on December i5, 00:00 GMT, and ran until December 22, 13:00 GMT. Highlights of the encounter period include an 80° turn to clear the booms for the Jupiter atmospheric feature tracking observations, and occultations of the sun and Earth by both Europa and Jupiter. The Earth occultations provided the opportunity to look for evidence of an ionosphere/atmosphere at Europa, and to obtain atmospheric structure profiles on Jupiter. Although the closest passage points to the other three Galilean satellites were quite distant, Io being the closest at 320,000 km, observations were made of each on this orbit, as well as of three of the minor satellites. The observations of Ganymede and Call isto were primarily for the purpose 01' measuring the surface composition, while the 10 observations were par(of the continuing Io monitoring program. Magnetospheric investigation priorities in this sequence included measurements in Europa's wake, the only opportunity in the tour where the geometry allowed this; measurements of the interactions between the magnetosphere and Europa; and continuous magnetospheric survey data inside of 50 R_J.

The return of the data acquired during this encounter was limited try the occurrence of solar conjunction on January 19, 1997, approximately midway between the E4 and E6 encounters. The proximity of the sun to the signal path between Jupiter and Earth prevented data return completely for a period of about ten days, and the combination of solar scintillation effects and the maximum Jupiter-to-hrth range kept the data rate low for many days on either side of conjunction. The total science return of about 69 megabits during the two orbits between E4 and E6 was by far the least of any of the orbits in the tour. Nevertheless, the data return went well, and new and very exciting insights into Europa were gained from this first close encounter.

3.3 Europa 6

The next encounter was also with Europa, and occurred on February 20, 1997, at an altitude of 586 km at 17:06 GMT. There was no close satellite encounter on orbit 5 because Earth and Jupiter were in solar conjunction around the time of perijove on that rev. Thus, not only would [here have been little to no communication capability with tbc spacecraft daring such an encounter, there also would have been insufficient downlink capability to return data from a fifth encounter. Europa 4 data return, using both revs 4 and 5 to accomplish it, was the most limited of all the encounters due to the limitations imposed by the proximity to conjunction. Scientific objectives for the Europa 6 encounter were similar to those of Europa 4. The encounter geometry was slightly different, which allowed observing of some new terrain, but mostly it was an additional opportunity to collect more dataon the entire system, since on any given encounter, data collection was limited not by opportunity but by space on the tape to record it and by telecommunications capability to return it prior to the next encounter and rewriting of tbc tape. During each encounter period when data arc being recorded, there is no playback of recorded data, but rather the time is used to return realtime magnetospheric data at rates ranging from 20 bps up to nearly 160 bps, depending on the telecom capability for that orbit.

The E6 encounter sequence started on February 16,23:05 GMT, and ran until February 23,01 :30 GMT. Magnetospheric science observations in this period, in addition to the continuing RTS (Realtime Science), included high time resolution recordings during the period of closest approach to Europa and during the magnetic equator crossing occurring at perijove, and remote sensing, of the Io torus region. For this encounter, the spacecraft path crossed behind Europa, relative to Europa's orbital motion, and hence upstream of the satellite's wake. This was the opposite of the E4 geometry, and provided a pair of highly complementary wake observations. Satellite science objectives were primarily global and high resolution coverage of Europa and continued Io monitoring. The closest approach to 10 in this orbit was about 400,000 km. The Jupiter atmosphere campaign in this orbit was a coordinated activity among all of [he remote sensing instruments to observe white oval features in thermal to ultra-violet wavelengths. Four occultations of Earth occurred in this orbit—one by Europa in the encounter sequence, and one each by Europa, Io, and Jupiter in the cruise sequence. Radio science occultation measurements were made at each of these events. A second radio science objective during this period was to acquire two-way coherent tracking data for the purpose of determining Europa's gravity field. The Earth occultation started 16 seconds after Europa closest approach and lasted for about 12 minutes. This was undesirable from the viewpoint of the gravity experiment and the desire to acquire continuous Doppler data in this period, but it was an unavoidable consequence of the encounter geometry, and did not seriously impact the gravity experiment. A solar occultation also occurred during the cruise sequence, and original plans were to do a spacecraft turn and make observations during the event as bad been done in C3. However, as the observation planning continued, this plan was abandoned, The costs in propellant usage for the turn pair and the impact to the downlink capability due to this activity were judged to outweigh the science benefits, which were waning anyway as the opportunity was further studied.

3.4 Ganymede 7

The next encounter was with Ganymede on April 5,1997, at an altitude of 3,102 km at 07:10 GMT. The second nontargeted encounter of the tour, a 23,500 km pass of Europa, also occurred on this orbit. Observations were made of all four of the Galilean satellites on this pass—the closest approach to 10 was just over half a million kilometers, and Callisto closest approach was at 636,000 km. The primary science objectives on this orbit were global observations of Europa and the two more distant satellites, high resolution observations of high energy impact regions on Ganymede, continued Jupiter feature track observations, and recording of fields and particles instruments' data during the Ganymede closest approach and during the plasma sheet crossing.

The encounter sequence began on March 30, 16: 00 GMT, and ended on April 6, 1600 GMT. This encounter was the only outbound (post perijove) encounter with Ganymede in the mission, thus providing a unique geometry and the opportunity to observe regions of the surface not available in any of the other three Ganymede encounters in the tour. No occultation events occurred in the entire G7 orbit, However, even with uninterrupted two-way Doppler tracking through closest approach and the unique geometry, no significant gravity information was expected, or obtained, beyond what was learned in the G1 and G2 passes, primarily due to the relatively high altitude.

A late update to the encounter sequence was required to insure the successful acquisition of the observations of Europa. This was necessary because, when the approach orbit trim maneuver was designed to null trajectory dispersions at Ganymede closest approach, the conditions at Europa just over one day earlier would be off-nominal enough to affect the observations. Consideration was given to "tweaking" the sequence after it was loaded on the spacecraft, but it was determined that a last-minute update to the sequence before uplinking it was feasible and operationally safer. Accordingly, after the maneuver design was complete and thus the new nominal flight path known, but prior to the execution of the maneuver, the sequence was modified to match the new trajectory and sent to the spacecraft. This procedure was

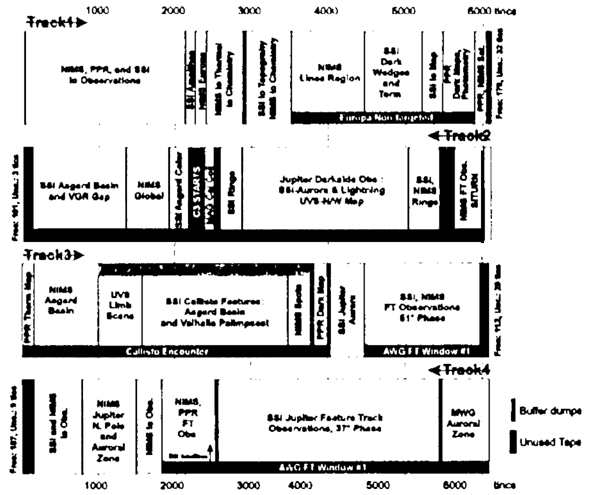


Figure 6a. C3 High-Level Tape Map

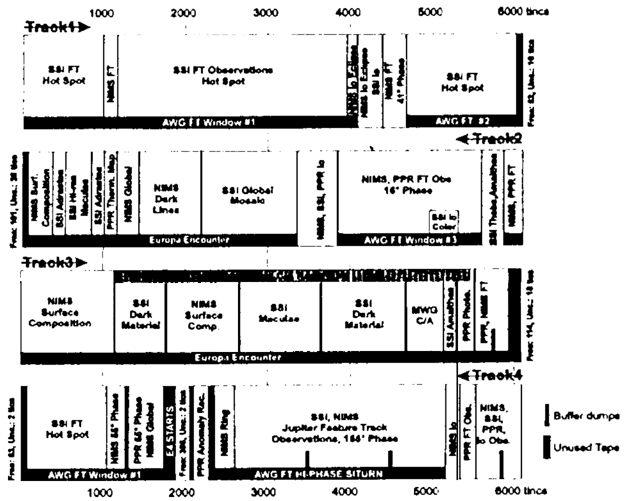


Figure 6b. E4 High-level Tape Map

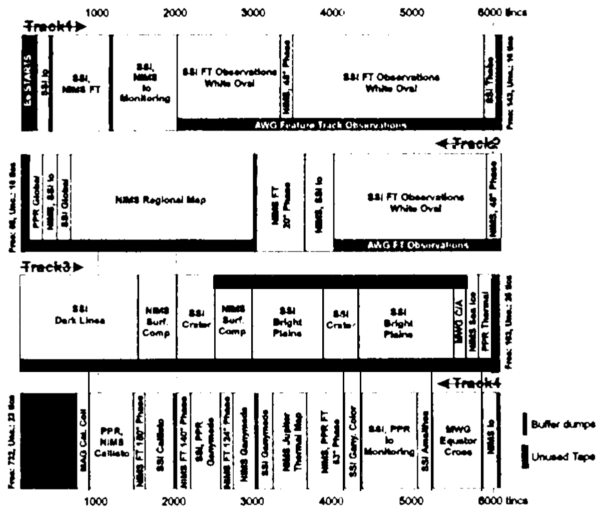


Figure 6c. E6 High-Level Tape Map

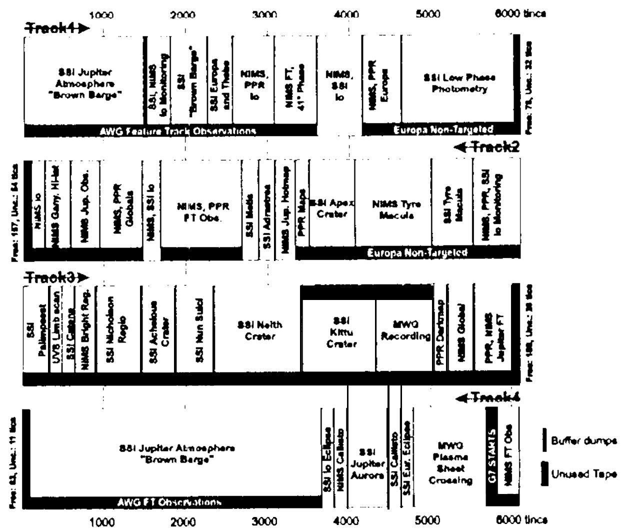


Figure 6d. G7 High-Level Tape Map

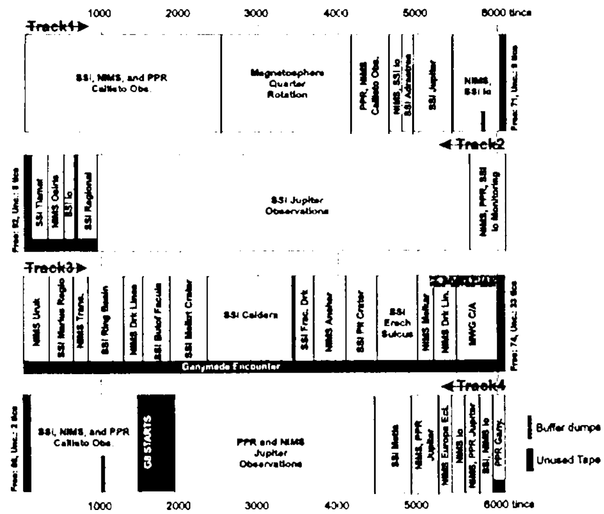


Figure 6e. G8 High-Level Tape Map

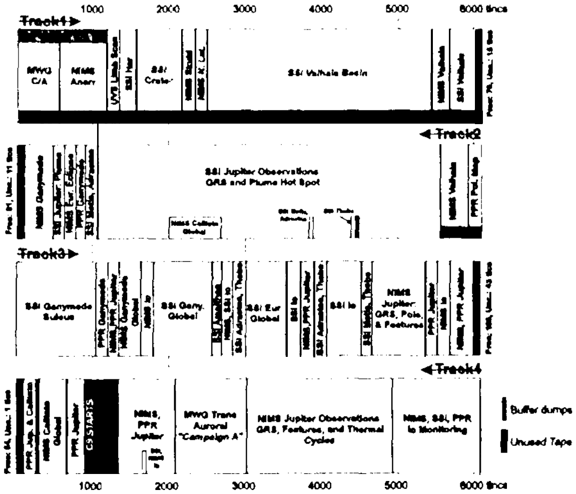


Figure 6f. C9 Encounter High-Level Tape Map

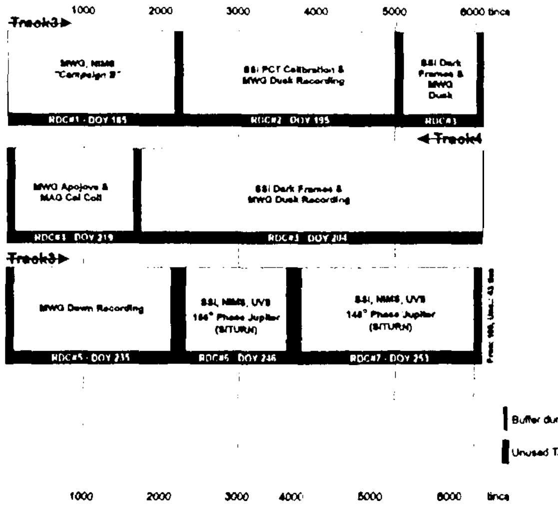


Figure 6g. C9 Cruise High-Level Tape Map

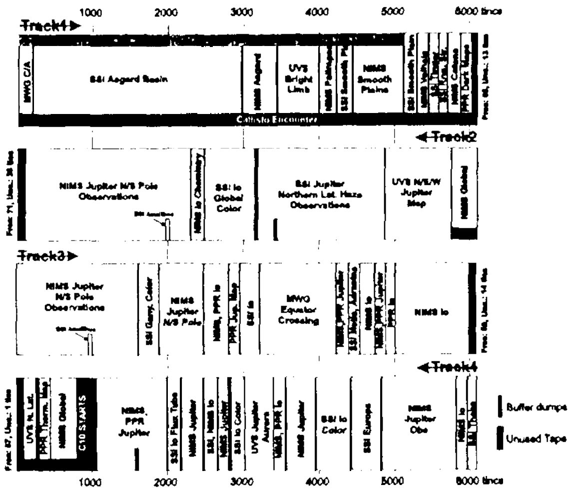


Figure 6h. C10 Encounter High-Level Tape Map

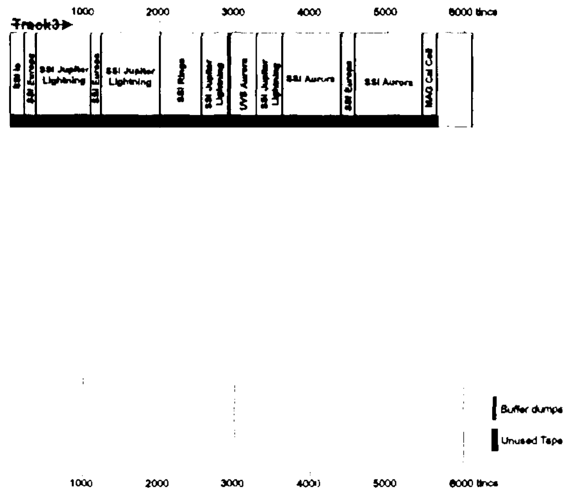


Figure 6i. C10 Cruise High-Level Tape Map

successful and all of the planned Europa observations were acquired.

Since the G7 encounter occurred more than two months after solar conjunction, the decreasing Earth to Jupiter range permitted increased data transmission rates which worked to the advantage of the magnetospheric observations. Data rates of up to 120 bps permitted increased RTS rates that were used throughout the encounter sequence. In addition, continuous RTS data were acquired in the G7 cruise period up to about the apojove region. Following this, after about a two week gap, the second "mini-tour" of the magnetospheric survey began. Sec *Section 3.8* below for additional details. Recorded magnetospheric observations in the encounter period included 45 minutes during the plasma sheet crossing, nearly an hour of data during the region of closest approach to Ganymede, observations of the plasma tori of Callisto, Ganymede, and Io, and measurements of the Jupiter aurora.

Satellite observations were made of each of the Galilean satellites, as well as of three of the minor satellites. Global observations of Callisto and Europa were made of regions not previously observed by either Galileo or Voyager. The relatively close nontargeted encounter with Europa also was used to make small phase angle observations of the surface that had previously been observed only at higher phase. Io monitoring continued, with the emphasis on three of the more active volcanoes. SS1 and UVS observations were made to study the thermal properties of Io while it was in solar eclipse behind Jupiter. Atmospheric observations were particularly limited during this encounter, since the allocation of downlink bits to this objective on this orbit was the second lowest of the entire tour. Continuation of the feature tracking campaign was the principal atmospheric activity.

3.5 Ganymede 8

The fourth and final encounter of Ganymede occurred on the eighth orbit on May 7, 1997, at an altitude of 1,603 km at

15:56 GMT. A nontargeted encounter with Callisto also occurred on this orbit at an altitude of 33,100 km. The encounter geometries for G7 and G8 were very different. G7 was a high latitude, outbound encounter, while G8 was amid-latitude inbound encounter, and the closest approach longitudes were about 180° apart. So the pair of encounters was very complementary, and provided ample opportunity for viewing different regions of the satellite. In addition to the Ganymede observations, feature tracking of Jupiter's atmosphere to measure the time-varying properties of atmospheric features was a key science objective, as well as fields and particles instruments' data recording for satellite closest approach and over a full quarter rotation of the magnetosphere.

The encounter sequence began on May 4, 1997 at 1600 GMT, and ended on May 11 at 1600 GMT. Although the closest approach to Io was nearly one million kilometers on this orbit, the otherwise favorable geometry and the still

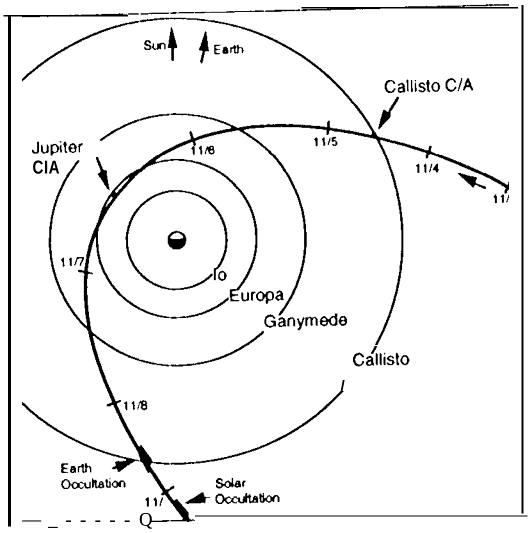


Figure 7a. C3 *Encounter Trajectory*

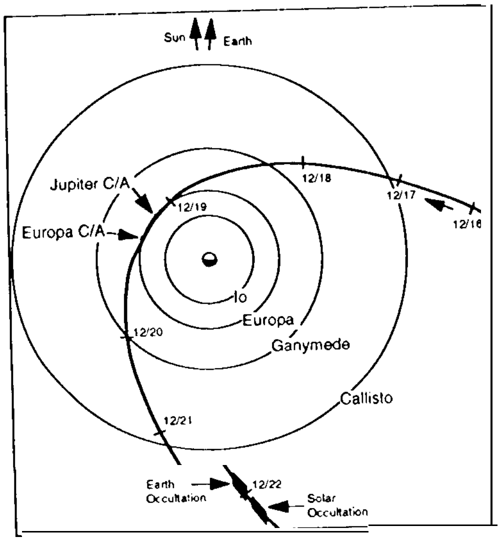


Figure 7b. E4 Encounter Trajectory

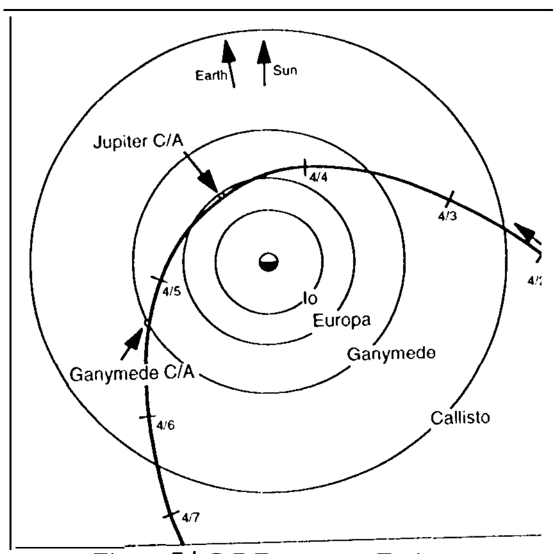


Figure 7d. G 7 *Encounter Trajectory*

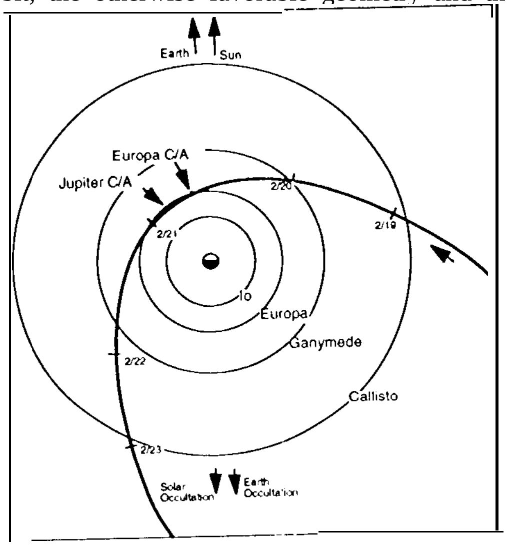


Figure 7c. E6 Encounter Trajectory

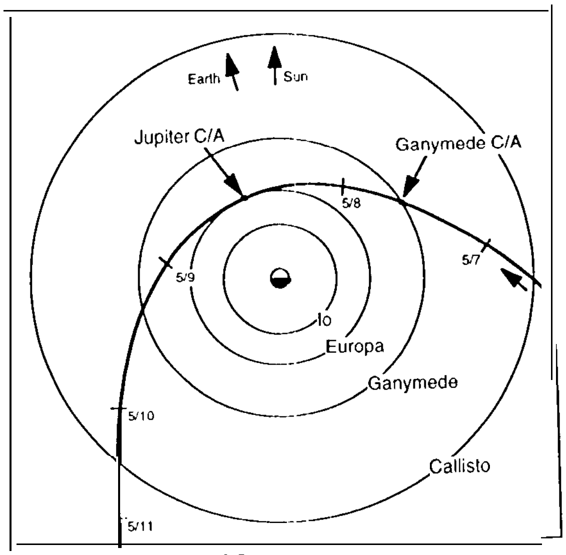


Figure 7e. G8 Encounter Trajectory

increasing ability to return recorded observations led to a number of' Io observations being made. Both dayside and nightside measurements were possible. Dayside observations focused on surface compositional changes, volcanic activity and plumes, and polarimetry. Nightside observations were primarily thermal maps made by SS1 and NIMS of hot spots. Europa, at well over one million kilometers minimum distance, received minimal attention on this orbit, with only NIMS and PPR making limited observations.

Numerous observations of Ganymede were made, with each of the remote sensing instruments participating. SS1 concentrated on single color high resolution images of several specifically targeted features. The NIMS focus was on surface compositional studies, some of which were coordinated to coincide with the SS1 images. PPR and UVS/EUV also concentrated on high resolution feature observations. The Callisto nontargeted encounter, at 42 degrees South latitude, provided unique viewing opportunities of the south polar region. In addition, observations were made to fill in gaps in regions not observed previously by either Galileo or Voyager, to more nearly obtain a full global map of the satellite.

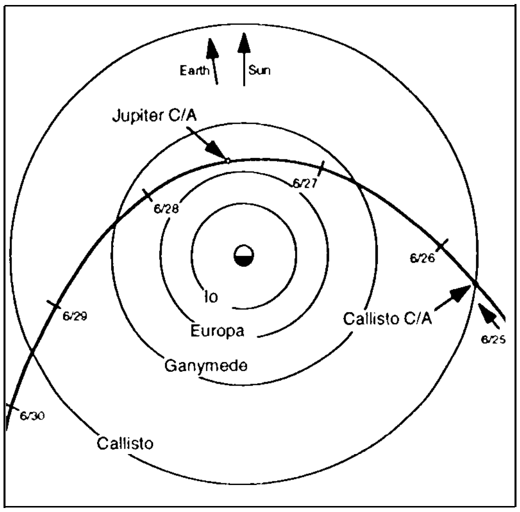


Figure 7f. C9 Encounter Trajectory

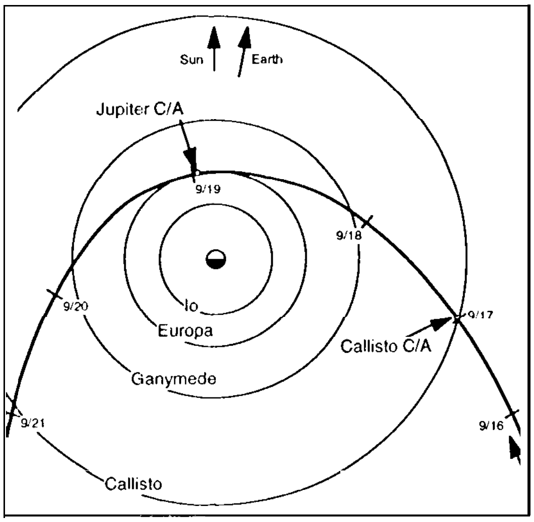


Figure 7g. C10 Encounter Trajectory

The bits-lo-ground allocation to Jupiter atmosphere observations was relatively large in [his orbit, and numerous observations were made in addition to the standard feature tracking activities. Some of the more salient ones were NIMS and PPR full North-South strip measurements, SS1 mosaic observations of atmosphere features under varying lighting conditions, and UVS Jupiter auroral measurements.

One new observation made by the magnetospheric instruments on this orbit is one referred to as the Quarter Rotation Sample. This observation was a recording of somewhat over two hours duration done at around 25 R, inbound to perijove. The duration corresponds to one quarter of a full rotation of Jupiter. The objective of this observation was to characterize the local plasma and electromagnetic field conditions in this segment of the magnetosphere which is thought to be linked to the aurora. Previous recordings in this region have been of shorter durations and produced limited characterizations. Simultaneous remote sensing of the auroral regions by UVS and NIMS complemented this observation. A 45 minute recording of the magnetospheric instruments' data was made during the Ganymede encounter. In this case, the spacecraft crossed Ganymede's orbit upstream of the wake, behind Ganymede, producing complementary results with the G1 encounter, where the spacecraft passed in front of Ganymede, prosing through the wake.

The magnetospheric survey was continuous throughout all of the G8 orbit, many times exceeding the 20 bps minimum requirement, at times in the encounter period ranging up to I 10 bps of RTS science data.

3.6 Callisto 9

The second encounter with Callisto occurred on the ninth orhit on June 25, 1997, at an altitude of 418 km at 13:48 GMT. The fourth and final nontargeted encounter of the tour, a 79,700 km pass of Ganymede, also occurred on this orbit. The C9 orbit was tbe one in which the fields and particles science objective of passing deep into the magnetotail region was met. This was accomplished by having the cruise orbit of C9 extend to an apojove of 143 R_J, and approximately in the anti-solar direction. The corresponding orbit period was about three months. This long duration, combined with the fact that the Jupiter to Earth range was at a minimum during this period, led to a large total downlink capability during this orbit, significantly beyond what was necessary to return one tape load of data, plus the on-going RTS data. However, since this orbit was designed specifically to acquire high data rate measurements in the ma, netotail region, this increased downlink capability was essential. To meet this mission objective, the cruise sequence was designed to do additional recordings on portions of the tape that had already been cleared of encounter data to record additional data during cruise, referred [0 as RDC. Tape maps for the C9 encounter data acquisition and for the data recorded during the RDCs are shown in Figures 7f and 7g.

One aspect of the RDC strategy was that not all of the encounter data would have two opportunities to be selected for return, as was the case for orbits without RDC. Playback of the recorded encounter data was initiated at the beginning of track 3, and proceeded through the tape, track 4, track 1, and track 2, interrupted as nccdcd to record the first four RDCs. By the time the end of track 2 was reached, tracks 3 and 4 had been recorded on again with the first four RDCs. At this point, which was reached on August 10, play back continued on track 3, beginning the return of recorded cruise data, Playback continued again through all four tracks in order, interrupted as nccdcd to complete RDCS 5,6, and 7 on track 3, the third time data had been recorded on this track in C9. After completion of the second full pass through the tape, playback cent inued on track 3 for the third time to complete the playback process. C9 data recorded on tracks 1 and 2 had the usual two tape passes available, but the encounter data recorded on tracks 3 and 4, as well as all of the RDC data, had only one pass for data return. One exception to this arose in the case of some PPR calibration data that was recorded in RDC 4, but was not successfully acquired on the ground due to some problems at the tracking station. Due to the special value of this data in interpreting other PPR data, efforts were made to return to this point on the tape prior to doing RDC 7, which would have overwritten this data, and return it a second time. This effort was successful.

The C9 encounter sequence started on June 22, 1997, at 1600 GMT, and ended on June 29, 16:00 GMT. During this period, RTS data were acquired at rates of at least 40 bps throughout, and fields and particles recordings were done for about 45 minutes around the Callisto closest approach, and for about an hour in the trans-auroral crossing region. The spacecraft passed behind Callisto as seen from the sun and Earth, providing an opportunity for an occultation experiment by the Radio Science Team. This was the only occultation of Earth by Callisto in the tour. Remote sensing observations of Jupiter's atmosphere focused on the Great Red Spot, a plume head feature in the northern equatorial belt, and both north and south polar auroral measurements. Observations were made of all four of the Galilean satellites as well as of four of the smaller satellites. Io, at its closest point just over 0.6 million km from the spacecraft, continued to be a target of much interest due to its dynamic features even on the time scale of the Galileo orbit periods. Both Io and Europa provided special observation opportunities as they passed through eclipse in the shadow behind Jupiter.

The C9 cruise sequence began on June 9, 1997, and continued until September 14. In addition to the emphasis placed on fields and particles data collection in this cruise period, it was also particularly significant for the Radio Science Team because of the unusually large number of occultations of Earth that occurred. A total of nine such occultations occurred—one by Jupiter, three by Ganymede, and five by Io. Of the five by 10, four were solid, behind the body, events, while the fifth onc was a grazing event in which the radio signal was not lost, but still passed deep enough in the atmosphere that useful scientific data were obtained.

The uniqueness of this orbit for making magnetotail observations may be seen in Figure 8, which shows the paths followed in the near-Jupiter environment by Pioneer 10, Voyagers 1 and 2, Ulysses, and Galileo on its path from 50 R inbound to the Callisto-9 encounter around to the 50 R point inbound to the Callisto-10 encounter. While each spacecraft's path passed through a different region of the magnetosphere, Galileo's path was particularly significant, by design, in that it passed through the anti-solar region, or the magnetotail region, for the first time. Galileo's continuous RTS survey data returned on this orbit, at rates as high as 140 bps, combined with the high rate data recorded over five different intervals in this orbit, combined to give valuable new insights into the interaction of the solar wind with Jupiter's magnetosphere.

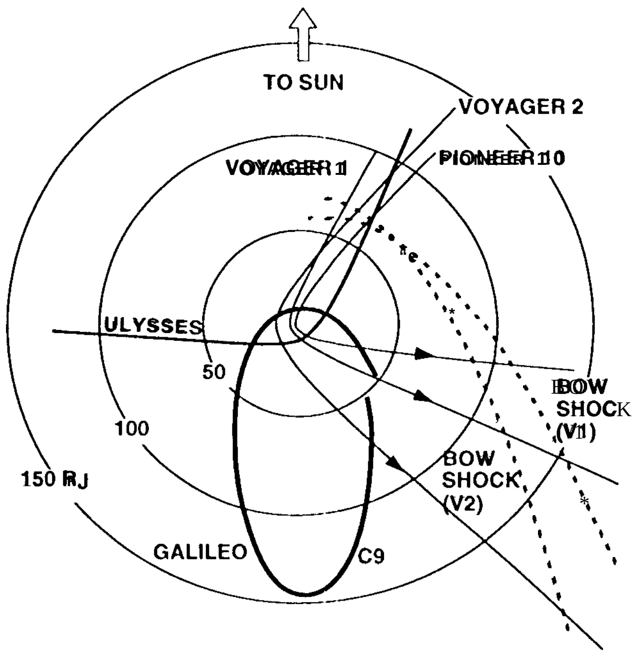


Figure 8. Galileo Exploratory Orbit Into The Magnetotail—Equatorial Plane

3.7. Callisto 10

The third and final encounter with Callisto in the prime mission occurred on September 17, 1997, at an altitude of 539 km at 00:19 GMT. This orbit also will have a solar occultation by Jupiter in the cruise phase, similar to the onc in C3, although at a considerably greater distance from Jupiter. This opportunity is planned to be used for additional observations of the backlit rings of Jupiter, as well as observations of Io, Europa, Jupiter, and its aurora while the spacecraft is in the shadow of Jupiter. Only this one event of recording during cruise is planned for the C 10 orbit. It is made practical by the relatively long six week cruise duration and the still small but increasing Jupiter to Earth communication range. No further recordings during the cruise periods are planned for the Galileo mission.

The C 10 encounter sequence started on September 14, 00:00 GMT, and ran until September 20, 14:30 GMT. Tape maps of recorded data are shown in Figures 7h and 7i for encounter and cruise recording during the solar occultation, respectively. The encounter record plan was implemented as shown without incident, but as of this writing, the cruise recording has yet to be completed. The magnetospheric instruments recorded data for about 60 minutes around the satellite closest approach, and again for about 45 minutes at the magnetic equator crossing near perijove. The remainder of the magnetospheric data collection during the encounter period was the continuous RTS survey data, which for about 90% of the encounter period was available at rates of 40 bps or greater. A long period of occultation of Earth by Jupiter is planned to be used by the Radio Science Team to acquire additional atmospheric data. During the encounter period there were no occultations, but the continuous uninterrupted Doppler data were used to further understand Call isto's internal structure.

A Jupiter atmospheric observation, coordinated among all of the remote sensing instruments, was made of the north polar haze and the north auroral region. Additional observat ions by the individual instruments provided coverage at various phase angles, investigated cloud structure, and observed atmospheric dynamics over one full Jupiter rotation. Observations were made of each of the Galilean satellites, with emphasis, beyond Callisto, being on the ongoing Io monitoring campaign. Closest approach to Io was a relatively close 318,000 kmon this orbit. Images were also taken of four of the smaller satellites as well.

3.8 Realtime Magnetospheric Science Survey

One of the original objectives of Galileo's magnetospheric science investigators was to have continuous data acquisition from the fields and particles instruments over the entire duration of the tour in order to provide both spatial and temporal coverage of the magnetosphere. With the loss of the high-gain antenna, and the allocation of the reduced downlink resource to each of the three science working groups (atmospheres, satellites, and magnetosphere), the continuous survey was no longer possible. In its place was developed a new objective of continuous coverage of at least 20 bps whenever the spacecraft was within 50 R, of Jupiter, and as much coverage as possible within the bits allocation elsewhere. One place where continuous coverage clearly could not be supported was in the orbits around solar conjunction, where the telecom capability was at its lowest. This led to the notion of two "mini-tours", one before conjunction and one after, where the survey requirements could be met, Figures 9a and 9b show the regions where continuous coverage was achieved for orbits G 1 through E6, and G7 through C 10, respectively. The pre-conjunction "mini-tour" went from about 65 R, inbound to the G2 encounter through to about 90 R_J inbound to C3, withone brief gap just after the G2 encounter. The post-conjunction continuous coverage runs from about 50 R, inbound toG8 through to the beginning of the E I 1 encounter sequence. However, there is little doubt that the continuous coverage will be realized through the E 11 encounter sequence, since the telecom performance analysis is complete and the sequence to implement this is already built. Short outages in the continuous survey resulting from weather, station outages, etc., are not considered to violate the continuity requirement, and are not included in the figures showing the regions covered.

The survey performance was not as good in the first part of the tour as in the second for at least three reasons, all of which combined to favor the later time period. First and most significantly, the conjunction period and corresponding long communication ranges occurred in the first part of the tour, leading to lower data return capability to be shared among the different science teams. A second factor was the timing of the implementation of the array capabil ity, including the Parkes radio astronomy antenna, at the Australian facility.

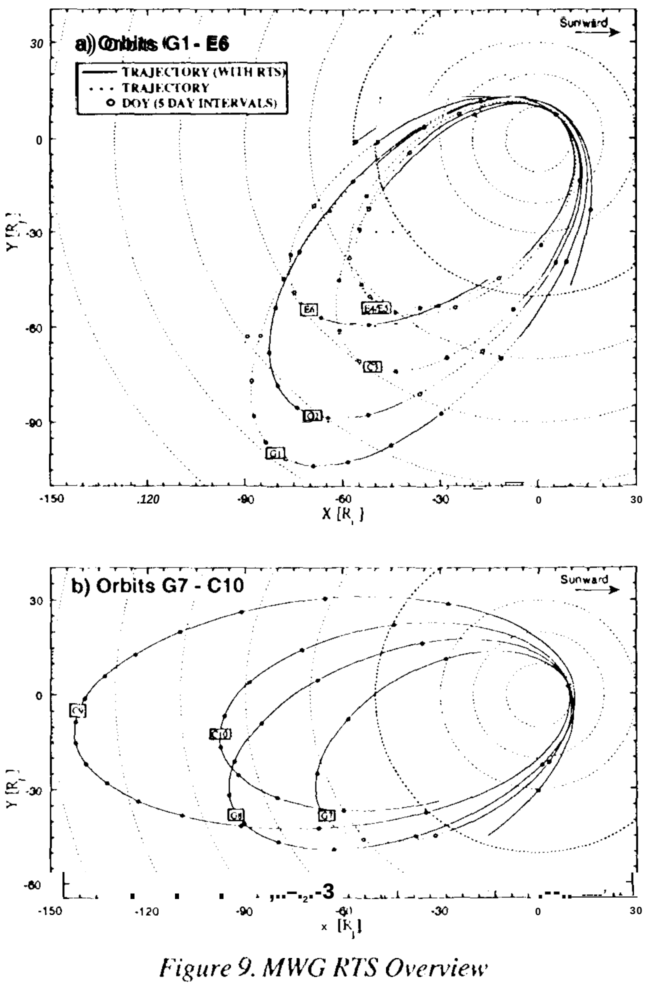


Figure 9. MWG RTS Overview

Although the array capability came on line November, 1996, this was too close to the conjunction period to sustain the pre-conjunction survey. The final factor was that the telecommunications capability using the new DSN systems specifically upgraded for Galileo was deliberately estimated conservatively until some actual experience had been gained. The new performance had been estimated and tested, but was not known very accurately. The loss due to underestimating the new capability was the difference between the actual and assumed performance. However, the loss due to overestimating the performance would be all of the data transmitted during those periods where the stations were unable to lock onto the signal at the higher data rate. By the time the DSN capability was fully measured and understood, and the lead time in the sequence development process was accounted for, Galileo was approaching the E6 encounter, the first after conjunction. The increase in downlink capability due to the gains from moving away from conjunction, the array, and the then known actual performance, was shared among the three science working groups, and the MWG's share is reflected in the increased period of continuous survey.

4. Instrument Status

Overall, the eleven Orbiter science instruments arc working splendidly. Only one instrument has a major limitation on its data taking capability and that restriction is being accommodated.

The ***Solid State Imaging Subsystem (SSI)*** has performed exceptionally well throughout the mission producing amazing images. An anomaly detected during the Ganymede-1 encounter playback showed some exposure settings actually produced shorter than desired exposures. This problem originates in a Phase 2 software bug, but insufficient memory and processing speed remain in the camera for this problem to be fixed. Ground software now selects exposure settings knowing the true exposures that will result. This procedure is reliable, and will be used throughout the rest of the mission.

The ***Near Infrared Mapping Spectrometer (NIMS)*** has provided a wealth of new data, even while struggling through a set of problems. The software halts that first appeared in the Ganymede- 1 encounter have continued periodically throughout the subsequent orbits. These have been successfully mitigated through the use of periodic onboard memory loads to the NIMS, followed by restarts.

At the Callisto-3 encounter, one of the 17 NIMS detectors failed. Previously, "cycling-on" a shield beater to minimize any contamination of the NIMS cooling radiator shield by propellant byproducts at thruster firings was the protocol. After the detector failure it was decided to accept the risk of some small levels of contamination, and to eliminate the temperature cycling, because the temperature excursions may have damaged the sensor signal circuitry. At the Europa-6 encounter, another detector began operating anomalously. It now appears both failures may have the same root cause, namely, an amplifier type used in each detector signal chain.

During the Ganymede-1 encounter playback, it became apparent that the ***Photopolarimeter/Radiometer (PPR)*** filter wheel was no longer cycling between positions as planned. It had stuck in one position (position 20), and could not be moved. Investigation eventually showed that position 20 was erroneously reporting its position as position 21. Due to the filter wheel's motor control logic, it would be unable to move the wheel. As a result of ingenious heating and cooling of the instrument, the filter wheel was able to correctly report its position and be moved out of the stuck location. Subsequent sequences up through (he Callisto-9 encounter have been planned to cycle slowly through the filter positions, taking data at different positions for each encounter. At the end of the nominal mission the wheel location should be back at position 20. At that time, a cooling cycle should enable the instrument to cycle over position *20* again.

During the Ganymede-8 encounter playback, it was discovered that the filter wheel was getting stuck in a new location. It stuck momentarily at position 4 for numerous occasions, successfully resuming cycling on its own. One of the recoveries did cycle the entire filter wheel through a full rotation including position 20. This was both bad news and good news. The filter wheel can get stuck in other positions, but probably not permanently.

During approach to the Ganymede- 1 encounter, the ***Ultra-Violet Spectrometer (UVS)*** grating motion was anomalous. It appeared to be acting similarly to a behavior noticed pre-launch at low temperatures. This problem in flight was ameliorated by turning on a supplemental heater but has shown some signs of returning in later encounters. At the present level of occurrence this poses no significant problem to the data taking.

The ***Extreme Ultra- Violet Spectrometer (EUV)*** has had no problems and continues to perform well.

The ***Magnetometer (MAG)*** has had one apparently radiation-induced processor halt. During the fifth orbit perijove (while the spacecraft was not "radio-visible" to the ground because of conjunction), the MAG suffered a processor halt, preventing data taking during the Europa-6 encounter. The instrument was successfully reloaded and restarted and has not suffered a recurrence. A plan is now in place to monitor the instrument and restart it by real-time ground commands in the event of any future processor halts.

MAG has also experienced problems with the capability to flip sensor arrays. This capability is used to rotate either of its arrays of 3 sensors to a different orientation to allow cross calibration. Its outboard nip capability seems to require excessively long heating of a hi-metallic spring to flip from one position to the other. In addition, when the inboard sensor array is flipped, the outboard array may also flip. During the Callisto 10 encounter the sensor heads were flipped to the preferred configuration, and the plan is to leave them there for the duration of the mission. This should prevent any further such difficulties.

The *Plasma Subsystem (PLS)* instrument is in good health, returning exciting results from each encounter. Early in the tour, one electron detector was slow to begin counting, but this eventually corrected itself as expected. A stuck bit in one location of memory has occurred, but ground data processing by the investigation team easily interpolates over this problem.

The *Plasma Wave Subsystem (PWS)* instrument is operating nominally, with no problems. Data returned contains modest noise from two sources, both the UVS grating stepper motor and the EPD stepper motor. The magnitude of the EPD noise has gradually increased since the beginning of the tour. The instrument team timeshares important data taking intervals with UVS to avoid the conflict.

The *Dust Detector Subsystem (DDS)* is operating nominally. This instrument is showing dramatic evidence of a dynamic dust environment near Jupiter.

An initial problem with the Phase-2 software load turned the *Energetic Particles Detector (EPD)* instrument off periodically. This was corrected by special commanding for Ganymede-2 and the flight software was corrected in time for the Callisto-3 encounter, and the instrument has performed nominally since then.

The *Heavy [on Counter (HIC)* was the last instrument to have its processing capability correctly coded into the Phase 2 CDS flight software. The processing was not completely correct until the Ganymede-2 encounter. Subsequent to that correction, instrument operation has been completely nominal and continues to return excellent data.

5. The Playback Process

The process for controlling the playback of recorded data acquired by the Galileo spacecraft was developed in concert with the development of the new flight software. It meets the objective of maximizing the scientific information content of the data returned. The flight soft ware provides for compression of the data prior to returning it, as well as allowing the ground team to select which data is to be returned and which is not. It is neither possible nor beneficial to return every bit of the recorded data, and the ability to choose the data to be returned, as well as to update these decisions as the process runs is very important.

The now standard practice in returning recorded data is to pass through the tape two times, with usually different, but sometimes redundant, data selected for return on each pass. This considerably improves the likelihood of successfully returning ng all of the highest priority data. The amount by which data will compress is uncertain, and hence the number of observations that can be returned is not well known at the start of the process. Also, from time to time data transmitted from the spacecraft will not be captured on the ground duc to reasons such as weather, tracking station problems, an emergency declared by another project resulting in the loss of the station to Galileo, etc. The strategy in designing the playback instruction segments to be sent to the spacecraft that control the data selection is generally to select the highest priority data for the first pass through the tape, allowing the insurance of the second pass for second attempts as necessary. Data for which the compression performance is highly uncertain, or images where the location of the target within the frame is unknown, may be sampled sparsely during the first pass in order to specify the parameters on the second pass more effectively, Another example of a replay occurs when the compression algorithm may have compressed the data to such an extent that compression artifacts limit the scientific value of the data. In these cases a decision can be made to play these data back a second time at lower compression at the expense of presumably lower priority data. The a'priori uncertainty in image compressibility can vary from a few percent to factors of two to three.

The initial selection of recorded data to be returned during each orbital cruise period is made as the corresponding encounter recording sequence is being developed. Then the full set of segments for the orbit is delivered with the cruise sequence, and the first four segments arc transmitted to the spacecraft with the cruise sequence load. The CDS software limits the number of segments that can be onboard at any given time because there arc only four memory "slots" used for this purpose. Any segment already on board can be overwritten with an updated one so long as it has not yet been pulled into active memory in the playback process, and as long as its segment boundaries remain the same. If all of the segments onboard have been completed before more have been sent, the playback process autonomously pauses, and then resumes normally when new segments have been received. Such pauses are highly undesirable because, other than the low rate Realtime Science data (RTS) which continues through a pause, they waste the downlink capability available for recorded data return. In the 14 months that Galileo has been operating in this mode, two such pauses have occurred for brief periods. Pause and resume commands are built into the sequences to pause playback during maneuvers and other activities that are incompatible with playback. Pause and resume commands have also been sent in realtime to prevent loosing playback data in contingencies when a tracking station could not support Galileo as scheduled.

The update process operates on a weekly schedule. Starting on Monday, each science team reviews the data received, or missed, over the past week. The total downlink bits received and missed for each team for that week are provided by the playback coordinator responsible for that orbit, Any changes to the margin policy are announced. Armed with this information, each team develops its strategy for at least the next week. Data selections are modified depending on ground receipt performance, compression performance, data content, and any other knowledge that becomes available as playback progresses. Each team del i vers its updated inputs to the playback coord inator, who then develops the updated segments. A Project review of the process is held on Thursday afternoon, and ncw segments may be scat as soon as Thursday evening. Ncw segments arc sent throughout the week as appropriate to stay within the CDS limit of four on board, and yet insuring that the process dots not run out of segments.

The two passes through the tape strategy has introduced some inefficiency in the process due to the additional slewing time between observations to be played back. The larger the amount of tape slewed across without playback, the larger the ineffiency in the process. This can be estimated up front and typically has been about three to five megabits pcr orbit. (Typical return from an orbit is 200 mb) The playback coordinator reserves a 4% margin of the downlink capability from the teams participating in playback at the start of the playback development. As the inefficiency is realized and tracked during the orbit, the margin is gradually released back to the teams as it bccomcs available. If the inefficiency remains near the 4% level, none is returned. On most orbits, some of this margin has been released back to the science teams.

At the beginning of playback for each orbit, some margin in downlink bits is also hcid by the Project to insure against reaching the end of the playback period with high priority observations at the end of the tape unreturned. This margin is gradually released as each orbit progresses, attempting to strike a balance between unused capability and unreturned high priority data. As this playback management process was being developed, prior to any actual inflight experience with it, it was feared by some that it was too complex to be reliable, and described by others as straightforward but tedious. In fact it has turned out to be neither, and has worked out exceptionally well in providing the maximum utilization of the available downlink performance.

6. Deep Space Network (DSN) Performance

The DSN capability to receive Galileo's very weak signal was improved substantially this past year as planned. Delivery of the 'Arrayed Antenna' capability of the Deep Space Communication Complex (DSCC) Gai ilco Telemetry (DGT) unit was a major step forward. The usc of the Full Spectrum Combiner (FSC) of the ncw DGT allows the signals received at several antennas to be combined into a stronger signal to provide a substantial increase in the telemetry bit rate ground receive capability (bps). In addition to enabling the arraying of DSN antennas, this ncw capability enabled adding the 64m Australian CSIRO (Commonwealth Scientific and Industrial Research Organization) Radio Telescope at Parkes, Australia to the Galileo array in accordance with agreements between CSIRO and NASA to improve Galileo's data return, which included major augmentations to Parkes (i.e., frequency agility) and daily tracking for onc year. The full rnuiti-antenna array, consisting of the DSN 70m and two of the DSN 34m antennas at Canberra, Australia; Parkes; and the DSN 70m at Goldstone, California (during the California-Au stralia view overlap) was available for the first time for the Callisto-3 encounter in November 1996, as planned. The Arrayed Antenna capability permitted the Project to increase the downlink data rate from the spacecraft to 120 bps during some of the Callisto 3 encounter as the effective gain in signal strength was as high as 3.8 db. This represented a three-foid increase in the data return as the previous high data rate was 40 bps. The downlink data rate changes designed into the onboard spacecraft sequence became more frequent duc to the array enabling a broader number of rates and time variability. With the array capability in place and operating well and the spacecraft performing a satellite encounter nearly every month, operations took *on* an even more strident note. As sequenced, data replay from the Callisto 3 encounter completed onc week before the Europa 4 encounter. The percentage of data capture for Callisto 3 reached 95.2% and the total number of normal transfer frames (i 6,384 bits pcr frame) acquired was 9,838.

The closest approach for the Europa 4 encounter occurred on December i 8, i996 at i i :43 PM Pacific Standard Time over the Canberra Tracking Site (All times in this section are Earth Receive Time (ERT)). The playback of the Europa 4 recorded data started when the encounter sequence completed three clays later and continued through February 16, 1997. This longer playback period was related to the Solar Conjunction event. The spacecraft was approaching a Solar Conjunction period where the Sun-Earth-Craft (SEC) angle gradually decreased over time to essentially zero and then gradually increased. As the SEC angle reduced to about 7°, Solar noise interfered with the receipt of the S/C telemetry making it impossible to receive valid data, This angle was reached on January iO, 1997. Even though telemetry data were unavailable because of the Solar noise, science continued. It is during these periods that some of the Galileo Radio Science experiments are conducted and data collected. The DSN supported the Radio Sciencc without incident. Aiso at this time, a close encounter with Jupiter (Orbit ##5) occurred, but by design, no data were taken because of the Solar Conjunction effects. On January 28, i 997, the telemetry data link was once again established and the Europa 4 encounter data replay was resumed. It completed on 16 February 1997 with a 93.3 percentage of data captured. The total number of normal transfer frames received was 6,226.

On 20 February i997 the second close encounter with Europa (designated Europa 6) occurred at 9:56 AM Pacific Standard Time over the Goldstone Tracking Site. Playback of the data recorded during the encounter commenced on 22 February i997 and completed on 28 March 1997. It was at this point in the year that the brand ncw 34 meter Beam Wave Guide (BWG) antenna at Canberra became available and joined the array adding about 0.3 db to the received signal capability. It was aiso at this point that the 34m HEF left the array to support the Voyager Project. The DSN captured

11,016 normal transfer frames--97Yo of the downlinked data–– during the Europa-6 orbit.

Following closely upon the completion of the Europa-6 data replay, the third Ganymede encounter (Ganymede-7) was executed. Closest approach occurred on 4 April 1997 at 11:56 PM Pacific Daylight Time over the Madrid Tracking Site. The spacecraft tape recorder playback started on 6 April 1997 and completed on 3 May 1997. Data capture amounted to 11,814 normal transfer frames—98.5% of the data transmitted.

The spacecraft flew by Ganymede for the fourth and final time in the eleven orbit primary mission on 7 May 1997 at 9:38 AM Pacific Daylight Time. This encounter was designated Ganymede 8. Playback of the data recorded for this encounter commenced on 11 May 1997 and completed 22 June 1997; 22,274 normal transfer frames (98. 1% of the transmitted data) were captured.

The Callisto 9 encounter sequence commenced on 22 June 1997 with the closest approach occurring at 7:23 AM PDT 25 June. On closest approach day, procedural problems in the transmission of telemetry signal prediction values to the Parks antenna caused the Full Spectrum Combiner (FSC) located at the Canberra complex to fault. The predicted signal frequencies are used by the FSC to track the received signals from the spacecraft. If all antennas sending their inputs to the Full Spectrum Combiner are not within the predict tolerances, no signal combination can occur and no data can be extracted. Operational steps were implemented that aligned the frequency and enabled combining. Data flow resumed in a little over an hour. This problem only precluded the extraction of-data in real-time. These data are recoverable through the reprocessing and recombining of tapes forwarded to JPL from the supporting sites.

Since the Callisto 9 orbit is three months long and its data return is scheduled to complete 14 September 1997, data collection is underway at this writing. If the current trends continue, and there is every reason to believe they will, Callisto 9 data acquisition and delivery arc estimated to be greater than 98% of the total transmitted by the spacecraft.

Phase 2 software operations with standalone 70 meter antenna and DGT support at each of the three DSN Complexes (California, Australia, anti Spain) started on 3 June 1996 and ended on 2 November 1996. The DSN provided 31,550 transfer frames of data to the Project in this mode. With the advent of the Array capability in November 1996, an additional 71,744 transfer frames have been delivered through mid-July 1997. The data performance increase is dramatically shown in the Data Return Performance chart, Figure 10. The month-to-month variation in data quantity is primarily duc to the variation in Earth Jupiter distance as Earth revolves around the Sun. It is seen that the arrayed performance of this year produced more than a two fold increase in data quantity over last year's non-arrayed performance comparing the years on a month for month basis. There arc two encounters (Callisto 10 and Europa 11) left in the primary Galileo mission. It is expected that the DSN data capture performance will remain above the 98% level for these two encounters. Thus far, 1.692 gigabits of data out of 1.737 gigabits transmitted from the

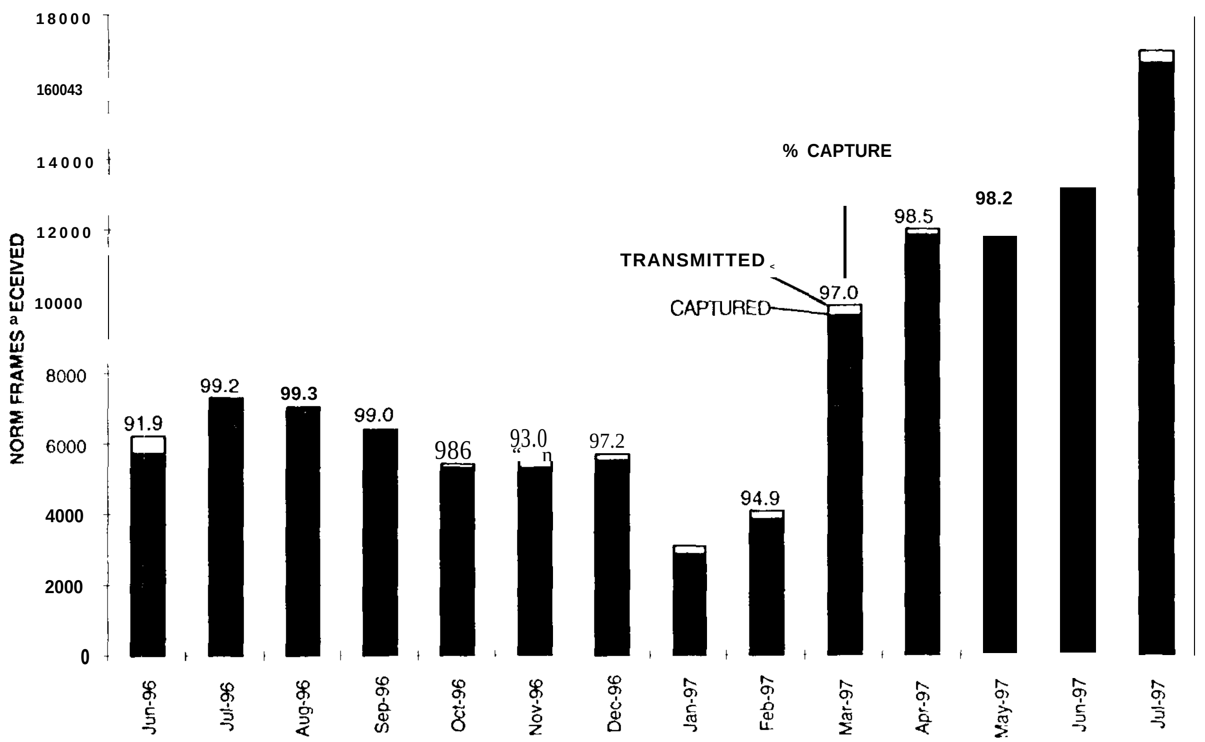


Figure 10. Data Return Performance

spacecraft have been acquired and delivered by the DSN. The DSN is doing an absolutely superb job for Project Galileo.

7. Realtime Operations

Monitoring spacecraft performance by analyzing the telemetry for both spacecraft safety and health and for science data delivery status, sending commands to effect desired spacecraft state changes including loading a new, large spacecraft sequence typically three times each orbit, and ensuring Deep Space Network (DSN) and Ground Data System (GDS) hardware and software subsystems proper operation are very complex but necessary tasks that Realtime Operations performs on a daily basis. Realtime Operations embraces the collective efforts of Flight Team, GDS, and DSN personnel who strive to deliver to the Project and the users every data bit transmitted by the spacecraft. This is the goal for operations and takes the form of a "whatever it takes to make it work" philosophy. Realtime Operations for Galileo is an extremely challenging function made even more so by the very weak downlink signal received by the DSN, which severely limits the transmission of data, and by the essential strategy of collecting data on the spacecraft tape recorder and playing it back over a sustained period of time. In one sense, because of the latter item, Realtime Operations is in a constant "encounter" posture as all data arc important and maximum data capture is the goal.

Realtime Operations is staffed by highly skilled, well-trained, and dedicated people who have an in-depth knowledge of the operation of the DSN, GDS, and spacecraft systems. Contingency plans and alternative approaches arc often used to solve problems and issues that arise. The problems and issues that surface range from requests from Project experimenters to locate one missing packet of data to requests from other projects for the use of a Galileo scheduled tracking antenna. An example of the latter problem surfaced on the 20th of July 1997 when the Mars Pathfinder Project lost contact with its spacecraft and requested the first four hours of the Canberra 70 meter support assigned to Galileo. Faced with the loss of Callisto 9 encounter playback data due to the interruption, Project opted to send realtime commands to pause the playback. After release from Mars Pathfinder support, the 70 meter antenna was returned to Galileo. The realtime commands already sent resumed the playback in accordance with the promised return time of the station. In supporting this request, operations modified the DSN configuration from listen-only to uplink for commanding in realtime. Modifying the ground configuration from the scheduled support introduces a risk that, in the rush to meet the challenge, the system is not properly established and a loss of data occurs that is greater than the one that would have been experienced if the system was not changed. Happily, as is usually the case, the reconfigurations were completely successful.

Commanding the spacecraft represents the single most critical activity of Realtime Operation.s. The sending of 'erroneous' commands (unauthorized valid commands) could catastrophically impact the Project. Special care is exercised at all times when commanding with Realtime Operations tightly controlling the application of command modulation on the uplink, turning it on oniy when ready to command and turning it oft immediately after transmissions arc completed. Without command modulation on the uplink, commands cannot be inadvertently radiated.

The Realtime Controller position, which is called the ACE, monitors the spacecraft and ground activities on a 24 hours/day, 7 days/week basis, providing a "first alert" notification of anomalous spacecraft or ground behavior. This permits the Project to marshal the "anomaly team" on an "as required" basis with maximum responsiveness. Project Galileo has five trained ACEs that typically work eight-hour weekday shifts and twelve-hour weekend shifts to achieve the continuous single ACE position coverage. Some of the problems controllers have discover-cd this past year include recognition of an AACS celestial reference problem less than one day before the Ganymede 7 closest approach, a Magnetometer instrument unplanned state change just two days before the Ganymede -8 closest approach and three DMS/ Tape Recorder problems: a limited search where the spacecraft onboard software corrected the problem, and no ground intervention was necessary; a limited search resulting in a infinite loop on 12 June 1997; and a tape recorder lockout on 16 December 1996. In these cases, the ACE requested modifications to the DSN support configuration in realtime so that the proper commanding to correct these situations could be performed.

Data processing, recovery, and delivery are the final steps in the Realtime Operations function. Once the data are safely received by the acquiring sites, it is processed and manipulated by many computers on its way to the Principal Investigators (PIs). Since the Callisto 3 encounter on 4 November 1996 up to mid August, 1997, 90,097 transfer frames (1.476 billion bits) of data have been received, processed into the form of Instrument Packet Files (IPFs) and delivered to the PIs. This represents 97.4% of ail data transmitted by the spacecraft during this period. Reprocessing of the ground data recordings has accounted for recovery of 508 transfer frames. This equates to 8.32 megabits of data that would have been lost if the reprocessing had not been performed.

Realtime Operations was particularly important to Galileo's highly productive past year with its severely constrained downlink via the Low-Gain spacecraft antenna.

8. Navigation Performance

Over the past year, the navigation performance continued to be superb. Despite the rather limited two-way, coherent S-Band doppler data over the spacecraft Low-Gain Antenna (LGA), and the reduced set of optical navigation frames relative to the original High-Gain Antenna (HGA) plans, the navigation accuracies have been excellent. The average orbit determination error (compared against post-encounter reconstruction) was 0.8 sigma in encounter time, and 1.0 sigma in altitude with the largest single error being 2.1 sigma in altitude.[7] Accurate delivery at each satellite encounter was critical to the navigation of the tour. Minimization of propellant usage has been one of the primary drivers in the navigation strategy, and has enabled the extension of the mission for another 2 years to further explore Europa and Io. The end of primary mission Propellant Margin is now predicted to be 37.4 kg (90% worst case) and there is an additional 20 kg of Project Manager's reserve propellant for a total of 57 kg. Table 1 shows the propellant utilization summary as of the post-Callisto 10 encounter Orbit Trim Maneuver (OTM)-33.

The navigation strategy includes typically three OTMS planned per orbit. The OTMS arc scheduled at apoapsis, approximately three days before the encounter and three days after the encounter. Most of the OTMS are statistical maneuvers which correct for the orbit determination and maneuver execution errors. There were several deterministic maneuvers at apoapsis, which were designed to change the orbit characteristics for special science opportunities, e.g., occultations with Io. After each flyby, the tour was reoptimized to minimize the remaining propellant usage by making small adjustments to the remaining encounter conditions in the tour. In addition, after each flyby, the orbit of the satellite encountered was redetermined, and the improved ephemeris was used in the tour reoptimization and targeting process.

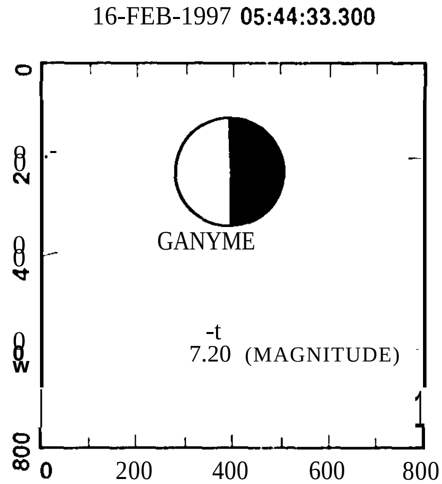
Optical navigation images were used for navigation for the first 6 encounters and were very successful. Depending on the relative direction, these images helped reduce out-of-plane and satellite down-track uncertainties. An optical navigation image consisted of shuttering one or two satellites against a background of 1 or 2 stars typically. To minimize downlink data requirements for navigation, on board autonomous editing algorithms were used to send down only packets with slices of the satellite's limb and terminator, and the stars. Figure 11 shows a typical optical navigation image design and Figure 12 shows the actual returned data. Figure 13 shows the relative line of sight of the spacecraft/satellite positions for the optical navigation images shuttered on approach to Europa 4.[7] Due to the scarcity of bright stars with Europa in the image, images of other satellites were also taken since the data was still useful for the encounter due to the satellites having highly correlated resonant orbits.

After six encounters, the satellite ephemerides were known to 10 km (1 sigma). After Navigation Team analysis, it was determined that the accuracy was good enough to navigate the rest of tbc prime mission without optical navigation images. Since designing and integrating optical images into the

Table 1. Galileo Propellant Utilization Summary
Epoch: Post-C10 (OTM-33, 9/20/97)

	ΔV (m/s)	ΔM (kg) Actual	Predicted[1]
Interplanetary ΔV	1320	127.7	
Interplanetary Attitude/Spin Control		30.0	
Interplanetary RPM Line Flushing		5,9	
HGA Anomaly Activities		51.3	
ODM	61.5	406	
JOI	645.2	379.8	
PJR	377.2	185.9	
Tour ΔV[2]	69.4	27.0	8.8
Tour Attitude/Spin Control		5.5	0.3
Tour RPM Line Flushing		1.6	02
Tour Science Turns[3]		7.8	22
Project Manager Reserves		200	
Propellant Margin[1]		37.4	
Total	128S.3	920.5	11.5
Total Usable Propellant (Actual + Predicted)=		932,0	

[1] Corresponds to 90% probability estimate
[2] Predicted ΔV includes 14.5 m/s (7.3 kg) deterministic at OTM 34 to connect GEM to baseline tour
[3] Corresponds to 17.2 kg of balanced turns
Note PM for GEM with Project Manager reserves . 0 (to 125) 19 kg (90% prob) or 28 kg (50% prob)



ID= 142, R= 2.357 Mkm, Cone= 79.251

Figure 11. Typical OPNAV Image Design

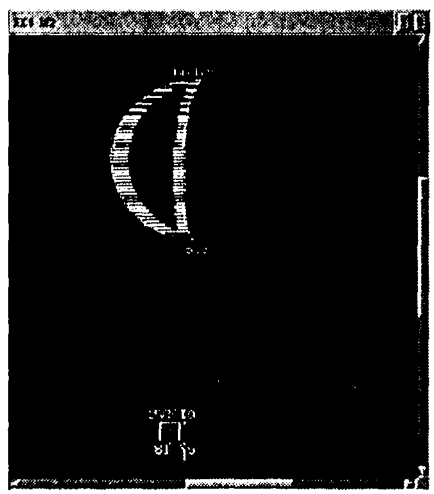


Figure 12. Actual Returned OPNAV Data

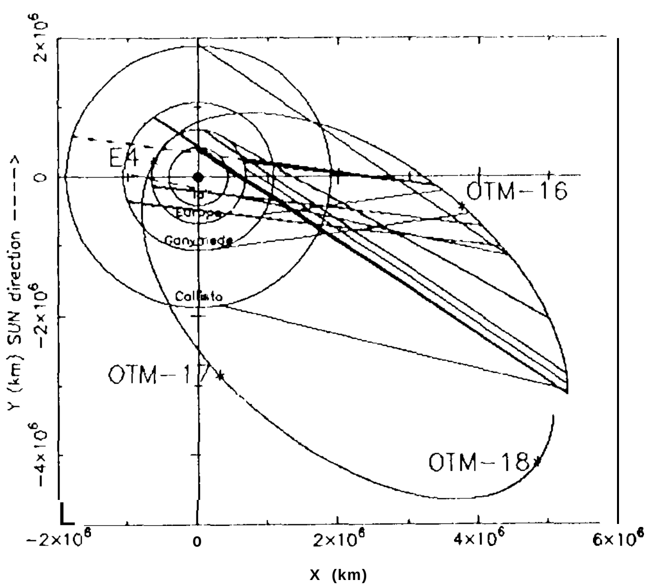


Figure l.?. Optical Navigation Imaging Times Geometry for E4

sequence plans was labor intensive, and the navigation value of the optical data was now marginal, the Project decided that optical images were not required after Ganymede 7. This decision helped to reduce operations costs, which is necessary for the small team in the GEM mission.

Following the successful Ganymede-2 encounter on September 6, 1996, navigation continued to be challenged with the first-ever targeted close encounters with Callisto (C3) and Europa (E4) on November 4 and December 19, 1996, respectively. Figure 14 shows the first Callisto encounter B-plane overview with various approach OD solutions with their associated 1 -sigma delivery dispersion, and the actual achieved flyby point.' OTM- 12 was the apoapsis maneuver which targeted to the C3 aimpoint. The approach OTM-13 was cancelled (not that we were superstitious), because the encounter conditions were close enough to the desired aimpoint, and the potential propellant cost delta was minimal. Figure 15 shows the first Europa encounter B-Plane overview.' OTM-15 was the apoapsis maneuver targeted to the E4 aimpoint. The approach OTM-16 was executed with the nominal design, and not the tweak design which used additional data closer to the encounter. This decision was made since the change in propel I ant cost between the designs was very small, and additional spacecraft commanding and associated risk for an onboard tweak could be avoided. For all the encounters to date, the maneuver and OD strategies worked very well. The excellent navigation performance enabled the cancellation of 5 of the 7 pre-encounter maneuvers this past year.

Table 2 summarizes the orbit determination (OD) errors at each of the encounters to date. The errors were smaller than expected duc to many factors including: the optical navigation process worked very well; the great performance of the DSN Block V receiver resulted in very clean doppler data; the modeling of non-gravitational accelerations on the spacecraft was better than expected; and the in-flight improvement of the ephemerides and masses of the satellites worked exceeding well. The OD error represents the overall navigation delivery performance, because the approach maneuver execution errors arc negligibly small. And in the five cases where the Project elected to cancel the approach maneuvers, it is indeed the

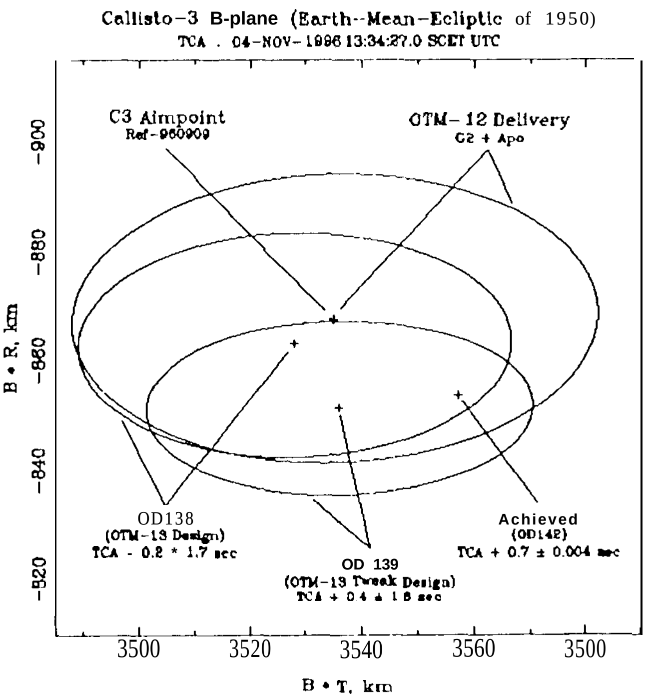


Figure 14. C3 Encounter B- Plane

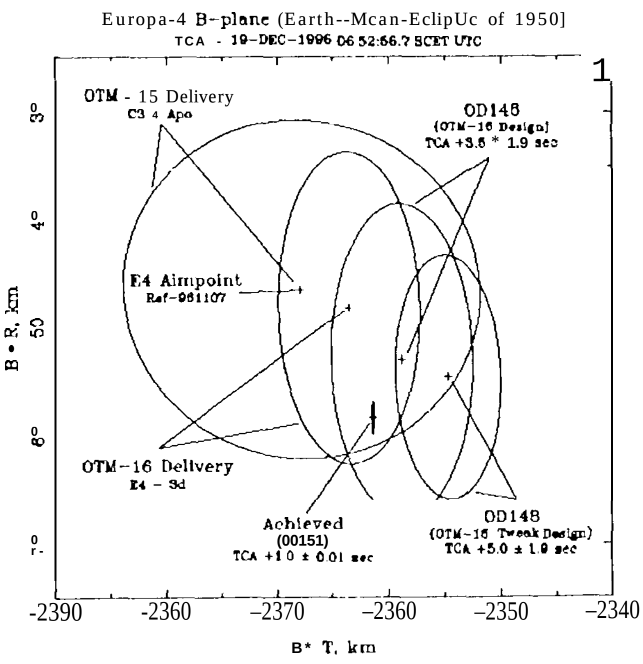


Figure 15. E4 Encounter B- Plane

Table 2. Navigation Performance Summary

ENCOUNTER	TARGET ALTITUDE	DELIVERY ERROR* ALTITUDE	TIME
GANYMEDE 1	844 Km	-9 Km	+27 sec
GANYMEDE 2	262	+1	-0.4
CALLISTO 3	1118	+21	+0.3
EUROPA 4	698	-2	-0.1
EUROPA 6	586	+6	+1.0
GANYMEDE 7	3095	+7	-02
GANYMEDE 8	1596	+4	0
CALLISTO 9	415	+1	+0.1
CALLISTO 10	534	-3	+0.3
EUROPA 11	2048		

* W'R'I PRE-ENC OTMOD IF OTM CANCELLED

Table 3. Gravity Assist

Encounter Name	Gravity Assist ΔV Components in Velocity Coordinates (m/sec)* Out-of-Plane	Along-Velocity	Normal-Velocity	Total Magnitude
Io	74	-198	-202	292
Ganymede 1	-310	.445	-489	730
Ganymede 2	-830	.127	-172	857
Callisto 3	.111	-401	-294	510
Europa 4	14	-223	443	491
Europa 6	152	211	449	519
Ganymede 7	-333	.181	143	405
Ganymede 8	-268	360	299	539
Callisto 9	-26	476	394	619
Callisto 10	-44	-469	-360	593
Europa 11	-130	-134	-243	307
				5867

* Velocity Coordinate System Definition:

Out-of-Plane Direction defined by Jupiter-centered position and velocity directions referenced to satellite closest approach epoch - 1 day (R X V)

Along-Velocity Direction de fined by Jupiter-centered satellite velocity at closest approach epoch plus inbound satellite—relative spacecraft V-infinity direction *prior to encounter* (Vsat + Vinf-in)

Normal Velocity Complete RHS (Along-Velocity X Out-o f-plane)

delivery accuracy that would have been achieved with the maneuver.

The gravity-assist delta-V produced at each of the targeted satellite encounters is presented in Table 3 resolved into the orthogonal components that produce: 1) plane change (''out-of-plane"), 2) orbital energy (period) change ("along velocity"), and 3) path angle change/in plane orbit rotation ("normal-velocity"). Note that the aggregate of the assists of 5,867 m/s is nearly five times the total spacecraft rocket propulsion delta-V capability (Table 1).

9. Orbiter Performance Overview

9.1 Attitude and Articulation Control Subsystem

The performance of the Attitude and Articulation Control Subsystem (A ACS) hardware and software for the past year has been excellent. Multiple science turns, attitude maintenance turns, Orbit Trim Maneuvers (OTMs), and spin and pointing corrections have been performed, all in accordance with the nominal mission plan. See Table 4 for summary information on the OTMs. All OTMS were performed vector mode. Wobble IDs, performed just prior to each encounter, show that the wobble continues to meet the stated functional accuracy requirements for the mission, 0.5 mradian. Consequently, no wobble compensation activities have been required during the past year. Analysis of gyro data shows that the gyro drift continues to meet mission requirements, 0.05 degrees/axis/hour. The Integer Cosine Transform (ICT) compression algorithm continues to performed as expected.

Table 4. Summary of Past Year's OTMs

OTM	Type: Pre-Encounter Post-Encounter Apojove	Maneuver Design*	Pointing Correct	Spin Correct
12	Apojove	2 POSZ, 1 LAT	N	Y, one after each POSZ segment
13	Pre-Encounter C3	Canceled		
14	Post-Encounter C3	2 LAT	N	Y
15	Apojove	1 PULZ, 1 LAT	N	N
16	Pre-Encounter E4	1 POSZ, 1 LAT	N	N
17	Post-Encounter E4	2 LAT	N	Y
18	Apojove (Post E4)	Canceled		
19	Apojove (Post J5)	1 POSZ, 1 LAT	Y, after LAT segment	N
20	Pre-Encounter E6	Canceled		
21	Post-Encounter E6	3 POSZ	N	Y, one after each segment
22	Apojove	1 PULZ, 6 LAT	N	Y, after each LAT segment
23	Pre-Encounter G7	1 PULZ, 1 LAT	N	Y, after LAT segment
24	Post-Encounter G7	1 PULZ	Y	Y
25	Apojove	1 POSZ, 1 LAT	Y, one after each segment	N
26	Pre Encounter G8	Canceled		
27	Post Encounter G8	3 POSZ	N	Y, after each segment
28	Apojove	1POSZ, 11 AT	N	N
29	Pre-Encounter C9	Canceled		
30	Post-Encounter C9	3 POSZ, 1 LAT	Y, after each POSZ segment	Y, after LAT segment
31	Apojove	1 PULZ, 1 LAT	Y, after LAT segment	N
32	Pre-Encounter	Canceled		
33	Post-Encounter	1 PULZ, 1 LAT	Y	Y

*POSZ: Along positive z-axis, PULZ: Along negative z-axis; LAT: perpendicular to z-axis.

9.2 Command and Data Subsystem

The Command and Data Subsystem (CDS) continues to show excellent health. To date, there has been only one RAM bit failure compared to a launch expectation of up to twenty during the mission.[2] The last transient bus reset occurred four years ago; "run-in" may have eliminated them. The only consumable currently of concern in the CDS is the despun CDS thermal cycles, which arc at 56% of mission lifetime allocation. The CDS hardware is in good shape.

The new CDS Phase 2A flight software has been successfully operating for over a year. The original CDS Phase 2 flight software design principally added packet telemetry and data compression. The Phase 2A software was a "last-minute" modification of the Phase 2 software which took into account the just then manifested tape recorder (DMS) operational faulting characteristics and constraints: its sticking behavior and potential end of tape problems. The modest number of inflight operational difficulties with the software has been worked around or corrected by uplinking patches to the flight software.

9.3 Tape Recorder Subsystem (DMS)

The Galileo tape recorder, in conjunction with the CDS flight software autonomous control algorithms and the operational constraints imposed since the DMS first clearly exhibited sticking behavior in October 1995, continues to operate satisfactorily. The heuristic mathematical tape stick prediction model described in last year's IAF paper[1] continues to be used to check planned sequences as a protection against sticking. In addition, standardized tape conditioning exercises are incorporated into each orbit's sequences, one near apoapsis and another just prior to encounter, the latter completing within a day or so of the start of the encounter recording sequence. The maximum time allowed between tape conditioning exercises continues to be 30 days.

Sever-al anomalies have occurred in the past year in which the DMS has been involved. These anomalies, referred to as DMS lockouts and DMS limited searches, have been determined to be independent of the DMS sticking problem experienced in the past, and indeed, do not reflect anomalous behavior on the part of the DMS, but rather reflect subtle idiosyncrasies in the interaction of the DMS hardware and the CDS software control algorithms. The anomalies arc discussed in Section 10.

9.4 **Power/Pvrolcchnic Subsystem**

The Power/Pyrotechnic Subsystem has performed well over the past year. The Radioisotope Thermoelectric Generator (RTG) power decay has been as predicted. The RTGs arc presently supplying 480 watts to the power bus. To date, adequate power has been available. Later in this and the extended Galileo Europa Mission proactive steps will be taken that make some compromises between engineering and instrument power usage requirements and thermal control requirements. These same changes must be reflected in the system fault protection algorithms which control post-fault power and thermal states.

The telemetry values for the AC and DC bus imbalances have remained stable. Sudden variations in these values have been the best inclination of an increased probability of the transient bus reset anomalies that have occurred in the past.

There were no pyrotechnic events in the last year, and none arc planned for the remainder of the spacecraft's operating life.

9.5 Rocket-Propulsion Module

The Rocket Propulsion Module (RPM) continued its excellent performance during the past year. A total of 16 OTMS were performed since the start of the Ganymede-2 cruise period, all well within specification. These 16 maneuvers were comprised of 41 firing segments, with the following distribution: 6 PULZ segments, 15 POSZ segments, and 20 LAT segments. Additionally, during the period, the RPM executed 18 thruster flushes, 8 balanced science turns, 7 balanced attitude turns, 10 unbalanced science turns, 25 spin corrections, and 39 pointing corrections. Each of these maneuvers occurred without anomaly. Data continues to show no variations in thruster performance for any 1O-N thruster, except possibly for the lateral thrusters. In particular, the L1B thruster[8, 9] shows variations between -4.9% to +1.4% compared to prelaunch performance during ground tests. In comparison, all other thrusters exhibit very stable performance and each is between 1% to 5% above ground test levels.

No known hardware failures of any RPM component occurred during the period. Helium budget analyses continue to show the RPM is leak tight.

During the period from Ganymede-2 cruise through Callisto 10 encounter, 27.2 kg of propellant was used. Since launch, 863 kg of propellant has been expended, over 92% of the usable propellant load. Notably, 7 kg of the reserved, residual propellant (unusable propellant due to assumed mixture ratio uncertainties) has been made available as usable propellant, following an analysis of the actual in flight mixture ratio and uncertainties. The prospects for completing the Galileo nominal mission and the Galileo Europa Mission remain excellent for the RPM.

9.6 Temperature Control Subsystem

The Temperature Control Subsystem has performed exceptionally well throughout the mission providing a very comfortable environment for the Galileo spacecraft for the hot extreme conditions of the Venus flyby (0.7 AU) to the cold environment that it experiences as it orbits Jupiter (5.2 AU). With some exceptions, all temperatures have been maintained within their respective allowable flight limits without any undue effort or at the expense of any other items of safety.

Onc subsystem continues to require special attention thermally. Bay A houses the despun portion of the CDS. CDS life expectancy is affected by the number and magnitude of temperatures cycles it experiences. Bay A has essentially constant power dissipation, but Bays B, C, and D which are closely thermally coupled to Bay A may have significant power variations. Power variations of Bays B, C, and D have been controlled to minimize the temperature cycles and depth of temperature changes of Bay A.

Some components have experienced temperatures that arc close to their lower allowable limit. The allowable limit in most cases is the Flight Acceptance temperature, but some have been waived in orbital operations to allow operations as low as Protoflight or even the more extreme Qualification Acceptance (QA) levels. There has been no performance degradation in any of these cases. Two items that now consistently operate at their QA level are the Inboard and Outboard MAG sensors. Their design incorporated Radioisotope Heater Units (RH LJs) and they do not have any electrical heaters so they arc solely dependent on the heat from the RHUs to maintain their temperature. As the mission has continued the RHU output has decayed as expected and eventually will not provide enough heat to keep the MAG sensors above their QA limit.

All other elements of the spacecraft have experienced benign temperatures either duc to ground sequencing of heaters, passive temperature control, or because they are thermostatically controlled.

9.7 Telecommunications Subsystem

The Telecommunications Subsystem continues to operate on the original redundant elements selected before launch. The subsystem has operated in the S-band TWTA high power mode and on the Low Gain Antenna (1 .GA) throughout the past year. As constrained by downlink performance, the subsystem was sequenced to transmit the available rates between 8 and 160 bps. Normal down link modulation was suppressed carrier (90 degree phase modulation index). As planned, during solar conjunction, the downlink was operated in the residual carrier mode at modulation indices between 51 and 60 degrees. To support some radio science activities, telemetry modulation was turned OFF for brief periods.

The last planned Radio Frequency Subsystem Automatic Gain Control test was in May 1997. It confirmed the receiver drop-lock threshold was -151.5 dBm, unchanged since launch. The last planned CDU Signal to Noise Ratio and Command Threshold tests were also done in May 1997. Due to a ground procedural problem during that station pass, no useful telemetry data was produced,

Only three kinds of performance variation from design normal occurred this year. All three had previously been seen and are discussed below.

- Unexpected CDU/CDS lock changes. Since September 1996, [here have been seven instances of unexpected Command Detector Unit (CDU)/CDS lock count changes. This rate is approximately the same as has occurred starting about one year after launch. These extra lock counts are an idiosyncrasy and do not hinder commendability. The receiver and CDU remain healthy.
- LGA Drive decrease. Telemetry values for the LGA Drive have shown decreases of 1 data number (about - 0.03 dB) in September 1996 and May 1997, continuing the pattern of decreases since launch. If real, the total decrease in RF output of the TWTA would be -0.9 dB since launch. Link residuals and other TWTA telemetry do not support this apparent decrease as real, thus suggesting a telemetry measurement problem. The S-band exciter and S-band TWTA remain healthy.
- USO trends. The Ultra Stable Oscillator (USO) frequency, as deduced from 1-way Doppler measurements, steadily changes with time, due to aging of the crystal. The steady change stops, and may reverse temporaril y, at each Jupiter encounter. A week or two later, the rate returns to approximately its pre-encounter value. This behavior is thought to be due to Jupiter's radiation effects on the oscillator; i.e., crystal and circuitry. These changes occurred at Jupiter arrival and at each encounter since then.

10. Anomalies

10.1 Transient CDS Bus Resets

As presented in previous papers[3-6], the transient CDS bus reset anomalies were found to be most likely caused by conductive slip ring brush debris in the spin hearing assembly forming unwanted circuit paths that produced spurious transient fault signals between the Command and Data Subsystem (CDS) spun and despun electronics when both brushes on a signal ring lifted (opened) simultaneously for as short as 10μsec. The spurious signals caused one of the redundant CDS strings to go down which automatically results in safing the spacecraft. There has been no occurrence of a transient bus reset since the ninth such event in September 1993.

10.2 Voltage Controlled Oscillator (VCO) Problem

On September 9, 1996, three days after the Ganymede 2 encounter anti less than an hour after the completion of the post-encounter Orbit Trim Maneuver- 11, data channels that measure the status of the spacecraft's S-Band Receiver showed anomalous readings indicating that the VCO had started moving erratically from its normal rest frequency. Other performance channels of the Radio Frequency Subsystem (RFS) were reviewed and no problems with them were noted. It was believed at the time that the VCO problems could possibly be 'data errors' and when the channels received updated telemetry inputs the anomalous readings would disappear but this turned out not to be the case. The DSN tracking support for the spacecraft during this period was in the 'listen only' mode which did not exercise this particular spacecraft hardware. To exercise the hardware, an uplink needs to be present. (When the Galileo spacecraft's S-Band receiver is phase-locked to the DSN uplink in coherent mode, the downlink reference frequency source is the VCO.) A problem with [he VCO manifests itself as a missed uplink acquisition as the spacecraft does not perform the coherent two-way transition that is the normal state in the presence of an uplink signal. That is, the DSN uplink fails to 'lock' onto the spacecraft receiver.

It was at the next uplink pass some 10 hours later at Madrid, Spain when an attempt was made to 'lock' the spacecraft receiver. A standard ±100 Hertz tuning sweep was performed, but the spacecraft did not respond and the acquisition was aborted. Ground controllers immediately implemented contingency plans and increased the tuning sweep to ±250 Hertz. This resulted in acquiring the spacecraft in the phase-locked loop mode. After this uplink pass was completed, analysis of the data received over the next twenty-four hours in downlink only mode showed that the VCO was not remaining at its rest frequency but had commenced an upward 'wandering' trend in frequency. Just prior to the Madrid uplink pass the following day, it was decided that ground controllers would not sweep the standard ± 100 Hertz but would attempt ±300 Hertz to acquire the spacecraft. This resulted in another missed acquisition. Scrambling to achieve acquisition, the controllers immediately implemented a ±750 Hertz tuning sweep and were successful in capturing the spacecraft receiver. A set of Radio Frequency Subsystem Tracking Loop Capacitor (RFSTLC) tests were planned to check the state of the Radio Frequency Subsystem and verify its subsystem operation. The first of these tests, conducted on September I 1, 1996 showed that the RFS VCO was not yet operating nominally. A second RFSTLC test, two days later, however showed the VCO was operating properly as it had before the anomaly. Post anomaly investigation did not identity the exact cause of the anomaly. However it was speculated that radiation received by the spacecraft Phase Lock Loop chip was the cause.

10.3 DMS Lockout

On *15* December 1996, when the tape recorder (DMS) was in the process of positioning the tape from the beginning of track to Tape Increment Count (TINC) 1750 on track 1, the CDS/DMS fault protection tripped and the tape stopped at TINC 252 in a DMS lockout mode. This mode is one in which the CDS will not issue any more commands to the DMS until the mode is cleared from the ground. Subsequent analysis indicated the tape recorder lockout occurred because the Beginning of Track (BOTR) marker on track 1 extends very slightly beyond the BOTR marker on track 3. A tape conditioning activity had completed properly on 13 December with the track 2 to track 3 turnaround stopping the tape at ready mode on track 3, just off the marker. The subsequent positioning slew command on 15 December properly switched the recorder from track 3 to track 1 for a slew to TINC 1750 for the start of recording in the Europa 4 encounter sequence. Immediately, the slew read the "extended" marker on track 1, the CDS interpreted it as the track 1 End-of-Track marker, and the fault protection properly stopped and locked out the recorder 50 TINCs later. Ironically, this fault had not occurred previously, because the automatic "forward pull" unsticks serendipitously moved the tape off the track 1 marker; these had just been removed from the forward tracks 1 and 3, because it was determined they were unnecessary and undesirable on forward tracks.

Real-time commands were sent to perform Memory Readouts (MROs) of CDS memory addresses. The MROs confirmed that the tape recorder was in lockout and had not seen any synchronization errors. Commands were then sent to clear the tape recorder lockout condition, go to ready mode on track 4, and clear the fault indicators. The command to clear the tape lockout condition was sent again when it was discovered that the fault indicators had to be cleared before removing the lockout condition would take effect. Additionally, the commands to go to ready mode on track 4, do a track 4 to track 1 turnaround, slew to TINC 1750, and go to ready mode on track 4 were not issued by CDS the first time, because the tape recorder was in the lockout condition. Following retransmission, these commands were executed nominally on the spacecraft. At the end of this activity, the tape was at the proper location for the start of data recording in support of the encounter just onc hour before the first record.

10.4 DMS Limited Searches

Limited Search Anomaly. On 17 March 1997, telemetry from the spacecraft indicated that the tape recorder had ceased playing back data and was in a "limited search". Indications included tape position beyond the bounds of predicts and playback packets replaced by fi ll packets.

Limited search mode occurs when the playback process is searching for recorded data as defined by an entry in the playback table, specifically a record frame time tag, and has passed the tape location at which the recorded data can be found. In the nominal case, the playback process continues to search for the appropriate time tag to the end of the current track, reverses onto the next higher number track, searches that track to its end, reverses back onto the next lower (original) track, continues to search until a time greater than the time being searched for is encountered, and then proceeds to the next entry in the playback table.

This problem occurred, because the PPR burst-to-tape records an unpredictable number of records and the playback table requested PPR data from a time interval that PPR had not been recorded.

Unlimited "Limited Search" Anomaly. On 12 June 1997, telemetry indicated that the tape recorder was again in limited search mode. At the time of the anomaly, the playback table was requesting playback of data on track 2 at TINC 850 (currently, the valid TINC range is 200 to 6025).

After the initial analyses indicated the limited search mode, memory readout of software parameters was commanded, Marginal link performance, duc to a station hardware problem (prime maser gain out of specification), resulted in loss of a portion of the readout. A second memory readout was commanded, and poor link performance resulted in total loss of that readout. The partial readout did, however, indicate that the time that was being searched for was a "bad" invalid restart time, captured during an autonomous pause, and would not be found. The partial readout also indicated that the values for program control flow flags were unchanged, so they would not produce the nominal end to the search and that the search would continue indefinitely. At no time was there an indication that the CDS or the DMS hardware was in immediate danger. All power and thermal telemetry was consistent with the operation of the DMS as observed.

Meanwhile, the poor link performance was mitigated by actions taken at DSS63 (Madrid). Maintenance personnel arrived on site to adjust the maser gain. This corrected the link performance that had caused loss of memory readout data. Telemetry then indicated that indeed a continuous (unlimited) search was in process and ground action would be required. Recovery was implemented in two stages. First, playback was terminated, the DMS was commanded to slew to an appropriate position (in this case on track 2 at TINC 848), and memory readouts were repeated for the third time. The memory readouts confirmed successful termination of the search, the position of the tape, and the state of the CDS and DMS. Second, the CDS and DMS process flags were cleared in preparation for reinitializing playback, a revised playback table was loaded, PWS realtime was deselected (this is one of the processes that could adversely interact with the playback process, and although very low probability, it was disabled to remove one uncertainty), playb back was reinitiated, and finally, after playback had resumed, PWS realtime was reselected. The process of terminating and then initiating play back caused the program control flags that were maintaining the search (i.e., looking for the re-start time) to be reinitialized to a state that looked for the "next" data specified in the new playback table, which placed the start of the new playback past the point at which it could capture the invalid header from the tape as a restart time.

After the recovery commanding, telemetry indicated that appropriate playback packets were being received and all indications were consistent with correct operation of the playback process.

Analysis of all of the data collected for this problem indicates that the problem was caused by the reading of "bad" record frame header data from the tape during the autonomous pause process. An autonomous pause is a normal process caused by several circumstances, such as the need for the PWS realtime process to use the compression resource which it shares with the SS1 playback process. The bad header data collected during the autonomous pause contained a time that did not actually exist on the tape and therefore could not be found. During the pause process the time from the last record frame header played back prior to the pause request is saved as the resume restart time and the tape is backed up 2-3 TlNCs. When playback is resumed the tape is searched for the restart time prior to the collection of data from the tape for processing into packets. This prevents the collection of duplicate data from the (ape. If the time is not found on the tape, then the search for the restart time continues until playback is terminated and restarted.

A record frame header consists of a 4 byte sync code, followed by a 2 byte record ID, followed by a 6 byte time tag. Because of the limited availability of onboard computing resources, the playback process accepts any record frame header with a valid sync code as valid. The playback process dots not check the more varied record ID or time fields for validity so a record frame header with a valid sync code and an invalid time can be accepted as valid for the purpose of saving a restart time. Since the time, even if invalid, would be read again during the resume process, the lack of this check dots not normally cause a problem. Additionally, there is no correlation between the time a header is placed onto the tape during record and the time a pause occurs during playback; the congruence of these two events is a very rare occurrence.

However, there arc two conditions in which the data read from the tape the first time may not match the data read from the tape at a subsequent time at exactly the same position. In one condition, the record frame header played back just prior to the pause must have been recorded during the hardware process of stopping the recording of the recorder. Since the record head is slightly physically separated (downstream) from the erase head, a small gap of erased but unrecorded noise on the tape is created each time the record process is stopped. The results of reading the tape at one of these "noise gaps" is a return of indeterminate data, that is, data that can differ each time that it is read, because noise is being read. If the last record frame header read prior to a pause has a correctly recorded sync code followed by one of these noise gaps, then when the header is read again during the resume, the time read will be different from that collected and wiii cause the playback process to enter the search mode observed during this instance.

This problem of having the record frame header time recorded over a gap and being unreadable was actually detected during Phase 2A system testing on the Galileo TestBed. Because the problem of saving a restart time recorded across a gap involves low probability interactions among multiple nondeterministic and asynchronous processes, the possibility of encountering the problem was deemed to be an acceptable risk when compared to the resources nccdcd to protect against it. That assessment has not changed.

In the other condition, the header must have been recorded over a severe tape ding. Severe tape dings can be caused when the tape is stopped after a relatively long high-speed movement of the tape results in a tape stick. During the autonomous unsticking of the tape, either some of the tape oxide material is removed or some foreign material is deposited. Each action causes a ding and leaves a small gap which will not accept valid recording.

10.5 RRCC Anomaly

During the second Record-IJLIring-cruise (RDC) activity on Juiy 14, 1997, the Multi-Use Buffer (MUB) was placed in an anomalous state by the Record-Rate-Change-Coverage (RRCC) CDS routine. RRCC is the capability of avoiding data loss for the Fields & Particles instruments during periods when their data is supposed to be continuously recorded and the tape recorder is changing between different record rates for other observations (e.g., imaging). When RRCC is enabled, raw Fields & Particles data is placed into the MUB whiie the tape recorder is running down from the previous record event and then running up to the next record event. Thus, no Fields and Particles data are iost in the transition between record rates.

Prior to the start of RRCC execution on July i4, the MUB contained 3 partial Virtual Channel Data Units (VCDUs). These VCDUs cannot be downlinked until completed by additional processed data; either playback data, real- time science data, or RRCC data. During the execution of RRCC, raw data was placed in the MUB at 22 separate times during the record during-cruise activity on Juiy 14. Each time RRCC data was placed in the MUB, 7 VCDUs of raw data were accumulated. This totals i 54 VCDUs of raw data. At the completion of RRCC execution, the MUB contained 157 VCDUs with no downlinkable (completed) VCDUs.

The CDS routine that processes raw data from the MUB requires 10 VCDUs of empty MUB space to safely process all types of data under all conditions. Thus, this routine waits for the MUB level to fall below 155 VCDUs before processing raw data (the MUB capacity is 165 VCDUs). Due to a programming bug, the RRCC routine was allowed to write raw data above the 155 VCDU limit (all other routines cannot). On **July, 14,** the MUB level was high enough to prevent the CDS from processing data. In addition, the MUD level could not decrease since no completed VCDUs were available for downlink. Thus the science data processing and downlinking halted.

Real-time commands were sent to disable the 155 VCDU check done by the CDS before processing data. After normal operations resumed, the 155 VCDU check was reenabled. A long term solution was put in place with aonc-byte code patch preventing RRCC from writing raw data when the MUB level is at or over 1S4 VCDUs.

10.6 RPM Issues

The serious concerns and mitigation efforts for the possibility of oxidizer and fuel mingling on the pressurization side of the RPM prompted by telemetry indications of checkvalve leaking are described in Rcf 1. RPM performance has been flawless throughout this past year. All indications since the third and final burn of the 400N main engine for the Perijove Raise Maneuver (PJR) and pyro isolation of the He pressurant supply in March 1996 are that the system is tight and, in particular, the ox pressurant checkvalve is holding the substantial (0.7 bar) ox/fu pressure differential.

10.7 G7 Star Loss

On April 4, 1997, about one day before Ganymede closest approach in the G7 sequence, the spacecraft lost its star-based attitude reference. and went to using gyros only for attitude reference, i.e., star data was no longer available to correct for the drift in the gyro based attitude estimate. The sequence was designed to use stars 2 and 61 for attitude reference. (Stars arc numbered from tbe brightest, with increasing numbers representing dimmer stars; star number 2 is Canopus.) In order to protect the star scanner from sources of bright light as it rotates around the spin axis, onc or more vectors, with angular ranges, can be specified at various times in the orbit when a bright body comes into view. Over the specified portion of the arc, the scanner is disabled so the bright light source has no effect. At the time of this problem, a bright body vector had been specified to protect the scanner from Europa. Star 61 was known to be close to the protected region, but ground based simulations indicated that it would work satisfactorily. However, in flight, star 6 I was cutoff by the bright body protection, because tbc margin allowed for flight software timing uncertainties was in.sufficient.

The problem was resolved by replacing star 61 with star 148, at which time the star based attitude reference function resumed proper operation. Star 148 was not used originally, because star 61, believed to be useable at the time, was significantly brighter and less likely to be obscured by radiation hits in the near-Jupiter environment. However, since the G7 encounter occurred after perijove, and the spacecraft bad already passed through the worst of the radiation environment by the time of the anomaly, there was high confidence at this point that star 148 would work well for the remainder of the sequence, which it did. During the approximately 17 hours that the spacecraft was using gyros only for attitude reference, gyro drift caused some degradation in the observations. Celestial reference was re-established about 4 hours prior to Ganymede closest approach, and the bulk of the Ganymede observations were made with no effects from tbe anomaly. This particular problem is not expected to occur again, since in the star selection process, greater margins are being implemented to insure adequate spacing between the star locations and the regions protected by the bright body algorithm.

11. Flight Software

11.1 Command and Data Subsystem Flight Software Patches

A series of patches to the Command and Data Subsystem (CDS) flight software have been transmitted to the spacecraft during the last year. Some were corrections to the flight software that were identified during testing but were deemed deferrable. Others corrected problems identified in the early Ganymede orbits, including some fine tuning of the autonomous tape recorder control algorithms. Still others corrected problems as they *were* identified through continued usc of the very complex Phase 2A orbital software. Each patch is routinely verified with a memory readout (MRO) or checksum.

On 25 September 1996, flight software patches associated with Optical Navigation (OPNAV) and playback service routines in the CD Low Level Modules (LLMs) were uplinked to the spacecraft and temporaril y located in available buffer space.

On 27 September 1996, a flight software patch associated with the playback manager was uplinked to the spacecraft and verified via MRO. Additionally, the flight software patches associated with OPNAV and playback service routines in the CDS LLMs were transferred to the appropriate memory locations. The playback was paused via real time command during the flight software patch command activity and was resumed after the activity was completed.

On 4 December 1996, flight software patches included changing the tape recorder control subroutine to remove the unstick process on tracks 1 and 3 and changing the playback editor routine in a CDS LLM used with the PWS high rate edit process were uplinked to the spacecraft, Again, playback was paused during the operation,

During the 4-6 January 1997 time period, two flight software patches were upl inked to the spacecraft. These patches corrected errors involving timing and buffer overrun problems which could cause loss of Attitude and Articulation

Control Subsystem (AACS) and UVS real time data, and a problem in the CDS B string Buffer Manager Bus Transaction crossover support software.

On 5 February 1997, a real time command was sent to restore the write protect for the CDS High Level Module. This command completed the restoring of write protects for the CDS.

On 9 August 1997, a patch was uplinked that fixed a problem in the Record Rate Change Coverage (RRCC) Data Storer routine that resulted in locking the Multi Use Buffer (MUB) in a deadly embrace, unable to convert the raw RRCC data into RRCC packets. This problem required ground intervention to release the MUB from that state. The fix increases the amount of free VCDU's[4] that must be left available by the RRCC Data Storer routine. Since this was a single byte patch, it was not necessary to pause playback during the operation.

11.2 System Fault Protection (SFP) Flight Software Patches

During the past year a series of changes to the System Fault Protection (SFP) flight software, which is located within the CDS hardware, have been necessitated by changing circumstances as the orbital tour has proceeded.

On 12 March 1997, a flight software patch was uplinked to the. spacecraft which disabled the EPD Science Alarm Monitor on the CDS B string. Instrument engineers wished to keep the instrument powered on, its preferred post fault state, in the event that the CDS A string went down. Before the patch, in that circumstance, the status word that is only produced by the A string disappears, the B string which is controlling the spacecraft assumes an EPD problem, and the EPD gets turned off.

On 19 April 1997, a patch that modified the Thermal Safing routine of SFP to leave the NIMS Shield Flash Heater permanently off was uplinked to the spacecraft. Instrument engineers wished to avoid thermal cycling of the instrument by SFP routines.

On 25-26 August 1997, a series of patches was uplinked to the spacecraft that modified the post-fault heater configurations of multiple SFP routines to eliminate the turn-on or off of Bay B, C, and D heaters by SFP. As noted earlier, it is necessary to minimize the temperature cycles and depth of temperature changes of the adjacent Bay A. AACS flight software was modified to give AACS exclusive autonomous control of these heaters.

11.3 Attitude and Articulation Control Subsystem Flight Software Patches

On 5 June 1997, a patch to the AACS flight software modified its scan type 3 mode to utilize the actual measured spin rate rather than a nominal canned value when controlling scan platform clock angle without the gyros. The resulting patch reduced the stator drift from as much as 1.0 mrad/sec down to roughly 0.01 mrad/sec without the loss of CPU timing margin. The change utilizes less computational resource and allows ICT compression with gyros on and sampled, but not in control loop, i.e., cruise mode. This patch was originally developed in conjunction with the Phase 3 DMS Loss Contingency Flight Software discussed below. Its benefits also apply to Phase 2A and it was decided to employ them immediately.

On 25-26 August 1997, the AACS patches related to the SFP post fault heater configuration described above were uplinked to the spacecraft. The patches modified power codes to place all control of the Bay B, C, and D heaters in the AACS.

11.4 DMS Loss Contingency Flight Software

At the onset of the observed tape recorder (DMS) sticking behavior in October 1995, the largest set of possible causes that might have explained the DMS anomaly was made up of items which could mean total loss of the recorder. A design team quickly developed a design fora spacecraft software set, called Phase 3, which would enable imaging without the tape recorder. This design preserved the enhanced downlink capabilities of the Phase 2 software set and provided for storing a few (-5) SS1 compressed images in the CDS buffer and a real-time capability for the PPR, which lacks that capability in Phase 2.

After the tape recorder recovery, it was decided to develop Phase 3 as a background task during the orbital tour, as a contingency. The development was split into two portions, identified as Phase 3A and Phase 3B, with development proceeding serially such that a minimum Phase 3A capability could be made available as soon as possible.

Three Phase 3A subsystem flight software deliveries were made, on 17 January 1997 for the AACS portion, on 11 April 1997 for the CDS portion, and on9 May 1997 for the SSI portion. System integration and testing, including testing of the in flight loading procedure, was completed on 4 June 1997 and the Phase 3A software set was archived as a replacement, in the three subsystems, for the Phase 2A software set currently performing in the orbital tour.

Two Phase 3B subsystem flight software deliveries were made in September 1997, for the CDS and SS1 portions. System integration and testing, also including testing of the in flight loading procedure, are expected to be completed and archived in October 1997. The Phase 3B CDS and SS1 portions, along with the Phase 3A AACS portion, is also a replacement, in the three subsystems, for the current Phase 2A.

<u>CDS Phase 3A Functionality</u>. The Phase 3A functionality within the CDS retains all of the basic redundant spacecraft command anti health/safety functions anti many of the nonredundant telemetry and science processing functions of Phase 2A. Changes include; i) the deletion of ail code associated with recording, playback, and DMS tape recorder control and DMS fault protection (about 42 Kbytes), 2) the deletion of all inactive sequence memory (32 Kbytes) but the

expansion of the CDS A string active sequence memory (from 8 Kbytes to 12 Kbytes), 3) the addition of the memory space freed up by the above code and sequence deletions to the Phase 2A 90 Kbytes MUB, increasing its capacity to about 160 Kbytes, 4) the addition of a capability to process SS1 images in real time, i.e., passing the small blocks (8x8) of image pixels from the instrument CCD directly through the Integer Cosine Transform (ICT) compressor within the AACS and then into the CDS MUD, and 5) the addition of a real-time PPR capability based upon the code used by the Phase 2A PPR Burst to Tape capability but producing slightly more data volume than that burst capability.

AACS Phase 3A Functionality. The Phase 3A design of the AACS included a modification to its scan type 3 mode to utilize the actual spin rate rather than a canned value when controlling de-spun clock (azimuth) angle. This would have freed up computational resources and allowed ICT compression while in cruise mode with gyros on. Recently, it was decided to incorporate this same modification in the current Phase 2A, therefore there is no “added” Phase 3A functionality.

SSI Phase 3A Functionality. The SS1 Phase 3A functionality adds the ability to provide single line readouts from the SS1 CCD to the CDS, both as contiguous sets of lines or as single lines with skipped lines between them.

At the time of the Phase 3A delivery cutoff, the functionality of one of the instrument imaging modes, the compressed IM-4 mode, was not performing correctly and it was decided to defer the necessary changes to the Phase 3B delivery.

CDS Phase 3B Functionality. The Phase 3A CDS functionality was enhanced in Phase 3B by the addition of a capability to rapidly transfer raw SS1 CCD image readout directly to the MUB, before processing it with the ICT algorithm. This capability is critically important since radiation hits to the SS1 images during the long dwell time on the SS1 CCD during the many minutes long readout during the ICT processing through the AACS would severely limit the size of the images that could be returned near Europa (and lo). This capability was not included in Phase 3A because the development team was not sure at that time that it was even feasible and it was decided not to jeopardize the timely availability of the Phase 3A capability.

SSI Phase 3B Functionality. The SSI phase 3B functionality consists of corrections to the rmc imaging mode capability (IM4) that was not achieved in the Phase 3A delivery.

Planned CDS InFlight Load Procedure for Phase 3. The plan for the complete InFlight Load (IFL) of the CDS flight software (and partial reload of the SSI flight software) is based on the successful techniques used for the complete reload of the CDS with the current Phase 2A software set, which included the CDS, AACS, and 8 of 1 I instruments. The current AACS flight software already incorporates the Phase 3 functionality changes and further changes will not be necessary. The IFL process consists of a large number of command packages generated and uplinked to the spacecraft as a real time process.

A generic CDS Phase 3 IFL timeline is illustrated in Figure 16. It is hoped, of course, that the need for Phase 3 will never be realized. Timing specifics would be determined by the particular time period in which the IFL is executed, the tracking coverage, and the state of the subsystems of the spacecraft. The entire CDS flight software set has to be loaded from scratch. The core engineering functions of the CDS arc located primarily in the high level module memory of the CDS and these functions were not changed appreciably in Phase 3, although they were relocated in the process of recompiling the Phase 3 software. Large portions of the CDS memory are not involved in the engineering operation of the spacecraft, in particular, the BUMS and DBUMs, which are used for the MUB, and portions of the HLMs. In addition, since the spacecraft would not be controlled by a stored science sequence during the IFL process, other science processing buffers would be available to be loaded directly without interfering with [he operation of the spacecraft.

The availability of these blocks of memory allow the

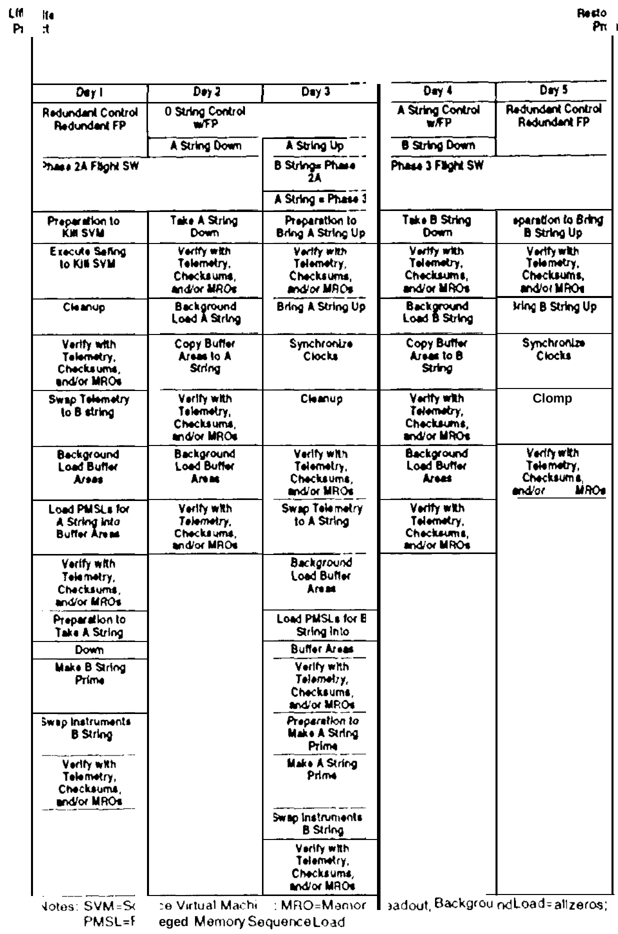


Figure 16. CDS InFlight Load Timeline

buffering or temporary staging of the Phase 3 software prior to its transfer to an area of memory that was in use controlling the spacecraft earlier in the process. This loading of flight software installments first into unused memory and later transferring to the ultimate memory locations will speed up the 1 FL process and allow for the greater use of onboard conditionals, i.e., checking progress by the flight computer without reliance upon analysts on the ground. During the Phase 1 IFL more than 27 "GO's" were required. Each involved analysts evaluating the state of the spacecraft and progress with the IFL. For the Phase 2A IFL, only 17 GO'S were required even though Phase 2A CDS load required nearly 10 times the command volume of the Phase 1. It is anticipated that the Phase 3 IFL would require approximately 20 GO's.

The IFL starts with both CDS strings redundantly controlling the spacecraft operating with Phase 2A software. CDS mernory write protects are lifted. It has been decided that the best way to terminate the Science Virtual Machine (SVM) is to force the execution of spacecraft safing, which *'kills" the SVM and leaves the spacecraft in a safe and well-defined state. After commanding the spacecraft from the safe state to the preferred IFL state, that state is verified by a combination of onboard conditionals, telemetry data, memory readouts (MROs), and/or checksums. This method of verification is applied at each major step of the IFL process.

The Phase 3 String A memory is loaded (uplinked) into the available buffer areas after backgrounding those areas with zeroes. After some preparation commanding, control is transferred to the B String and the A String is taken down. At that time, the B String hardware is controlling the spacecraft still using the Phase 2A software. The Phase 3 software is copied and transferred from the staging buffers or loaded via uplink commands into the A String memories, also after backgrounding the A string memories with zeroes. The A String is brought up, the A and B String clocks are synchronized, and as a partial Phase 3 software test, telemetry is returned to the ground using the A String and the newly loaded Phase 3 software while operational control is being exercised by the B String and the Phase 2A software.

The Phase 3 String B memory is loaded via uplink into the avail able buffer areas, again after backgrounding those areas with zeroes. After some preparation commanding, control is transferred to the A String and the B String is taken down. At that time, the A String hardware is controlling the spacecraft for the first time using the Phase 3 software. The Phase 3 software is copied and transferred from the staging buffers or loaded via uplink commands into the B String memories, once again after backgrounding the B String memories with zeroes. The B String is brought up and the A and B String clocks are synchronized. The spacecraft is then operating with both CDS strings redundantly controlling the spacecraft operating with Phase 3 software. The spacecraft is final ly commanded to the preferred state for initializing the SVM.

The Phase 2A CDS IFL took about 6.5 days and it is anticipated that the Phase3 CDS IFL will take somewhat less, about 5 day s.

Planned SSI InFlight Load Procedure for Phase 3. The plan for the IFL of the SS1 Phase 3 flight software, when compared with the CDS IFL processes, is quite different. Since the SS1 software load is controlled by a sequence, the SVM must first be initialized and checked out. Then a tailored sequence that conducts the SS1 IFL, and other instrument commanding, must be uplinked to the spacecraft and executed. The SS1 IFL sequence loads the SS1 memory via the CDS, verifies the memory load with checksums, and runs the instrument through a standard checkout routine.

After the SSI is loaded, other instruments are commanded from their preferred IFL state to their normal data taking states. The last step will be to uplink a science sequence that continues with the mission.

Summary. The Phase 3, like its Phase 2A predecessor, will be more than the load of new flight software. It will involve some new ground based software, revised flight rules, and new or modified ground processes. It is anticipated that Phase 3, should it ever be necessary, will meet its objectives just as successfully as Phase 2A has.

12. Galileo Europa Mission (GEM)

12.1 Introduction

The follow-on mission for Galileo known as the Galileo Europa Mission, has been approved and funded by NASA. GEM is a highly focused follow-on to Galileo's current Jupiter system exploration and a precursor for future missions to Europa and Io. GEM will conduct a detailed study of Europa over 14 months, then plunge repeatedly through the Io Plasma Torus to reach volcanic Io. The GEM timeline is provided in Figure 17.

12.2 Background

The first budget estimate for a follow-on mission for Galileo was provided to NASA in early 1995, not long before the early budget scoping began for FY98. This early estimate was for a two year, $45M continuation of mission operations. Although substantially cheaper than the primary mission, this prospect did not generate much interest, possibly due to the fact that Galileo had not yet gotten into orbit nor demonstrated its capability to operate with its new flight software, the lack of a science focus for the continuation, the perception in some circles that Galileo was old technology anti best retired, and perhaps most important of all, large potential budget cuts in NASA's Office of Space Science, Development of a specific proposal was deferred until Jupiter Arrival.

With the successful arrival of Galileo at Jupiter, a small design study was initiated to look at possible follow-on missions. Many possible mission concepts were examined, including an intensive study oftlurop.tie, an Io/Jupiter remote

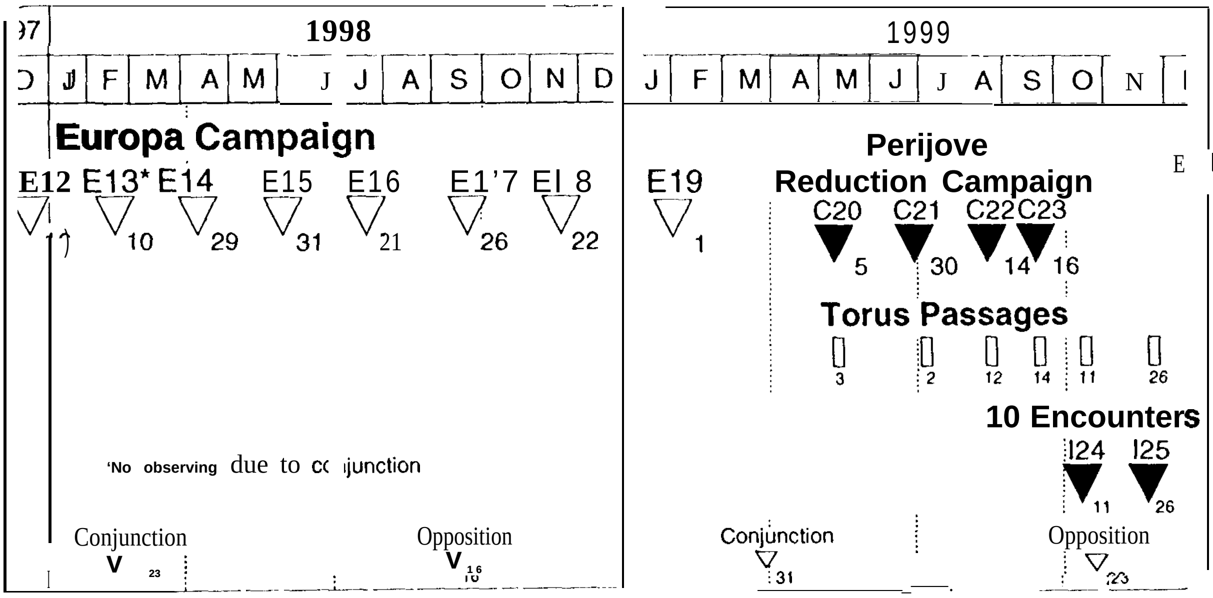


Figure 17. Galileo Europa Mission Timeline

sensing monitoring mission, a high inclination/dusk side magnetospheric survey, an outer satellite flyby, Galileo as a communications !) relay satellite for an early 2000's Europa lander mission, and even a possible trojan asteroid flyby mission. Out of this set, the Europa/Io intensive study concept, later called GEM, was found to have the broadest appeal to the science community and had the tight science focus and associated requisite streamlined cost and operations approach.

12.3 Overview

Figure 18 shows the Galilean satellite orbits and the chosen GEM trajectory as viewed from Jupiter's north pole in a Sun-Jupiter-fixed reference system. The start and end of the GEM are 7 December 1997, and 31 December 1999, respectively [10]; 7 December 1997 is the end of the Galileo prime mission.

The primary science objectives of the GEM arc to better understand:

- Internal structure, surface morphology, atmosphere, and possible subsurface ocean of Europa
- Structure and composition of the Io Torus
- Surface morphology, volcanism, internal structure, atmosphere, and possible intrinsic magnetic field of Io

GEM is to accomplish these objectives through a coordinated series of remote sensing and fields and particles observations and radio tracking of the spacecraft during its eight close flybys of Europa, the four Io torus passes associated with its flybys of Callisto, and two Io flybys. As explained below, only gravity data will be taken during the E13 encounter.

The operations concept involves collecting real-time and recorded data during each approximately two day encounter period (as opposed to the one-week encounter periods of the primary mission), and dedicating the rest of each approximately 8 week duration orbit to playback of the recorded data. This appoach represents a significant reduction in the complexity of sequence development as compared to the primary mission where orbit cruise real-time science data collection had (o be interleaved with the playback process.

The cappted cost of the GEM is $30M for the entire two year mission which is 20-25% of the prime mission budget for

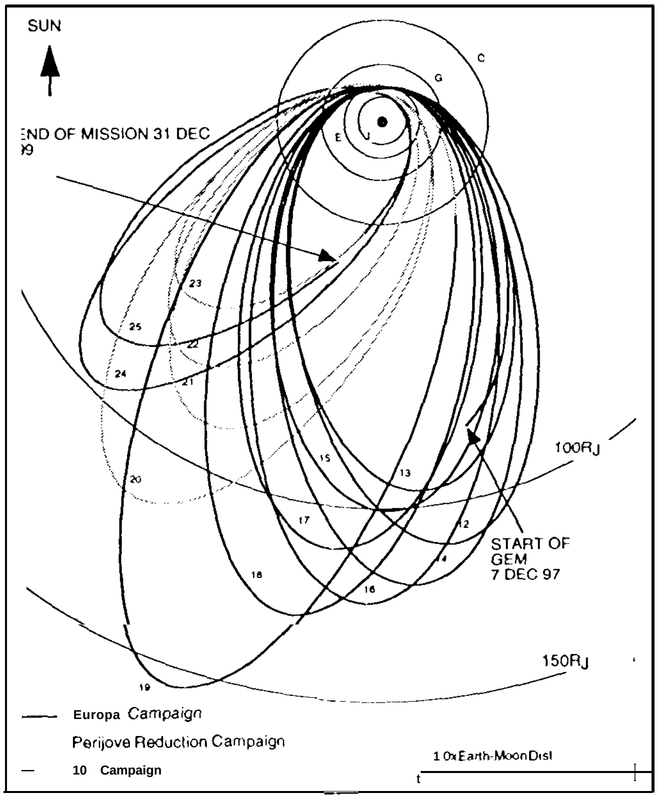


Figure 18. Galileo Europa Mission Tour

an equivalent period of time. Roughly a third of that amount is earmarked for the science data analysis activities, while the rest provides for the spacecraft operation, data processing, and science and sequence planning activities.

12.4 Tour Design

Table 5 describes the key characteristics of the GEM encounters. This series of encounters is the result of many tradeoffs and the accommodation of several key guidelines and constraints, including that a) the (first) Io encounter occur at near minimum Earth-Jupiter range in late 1999, b) the tour include at least 6 but no more than 10 Europa encounters, c) the post-(first) Io encounter orbital period be 50 days or more to provide enough time to playback data prior to returning to the high radiation environment, d) no encounters occur near conjunction, e) the primary mission's E 11 encounter could be substantial ly altered as necessary for GEM although the encounter date was to remain the same, f) the nominal C 10 aimpoint could be shifted only inside of the navigation reoptimization "box," g) the C 10 apojove maneuver could be redesigned to provide the attachment of the GEM trajectory to the primary mission tour trajectory, h) latitude and longitude diversity of the Europa flybys be maximized, and i) the radiation exposure of the spaceacraft be minimized. Very early in the tour design process it became clear that some compromise would have to be accepted in the post-Io period and the longitude diversity guidelines. Figure 19 shows the resulting closest approach subspacecraft points for the Europa Campaign, which display a bimodal distribution in longitude but rather good latitude diversity, allowing viewing into Europa's polar regions and providing an excellent gravity experiment. The F.12 encounter will be the closest approach of any encounter that Galileo will *ever* have—a breathtaking 200 km above Europa's surface!

Because E13 occurs only a few days before the conjunction moratorium (the period of time during which Galileo is unable to reliably communicate with the Earth) and because of the limited uplink planning resources available to GEM, it was

Table 5. GEM Tour Encounter Data Summary

Orbit	Target	DATE - TIME [1] (yymmdd - hhmm)	Flyby Altitude (km)	Flyby Latitude (deg)	Perijove (Rj)	Orbital Period (days)
E12	Europa	971216-1206	200	-7.9	8.8	56,6
E13	Europa[2]	980210-1758	3562	-86	8.9	46.3
E14	Europa	980329-1324	16-49	119	8.8	63.7
E15	Europa	980531-2113	252 l	14.9	8.8	49.9
E16	Europa	980721-0508	1837	-25.6	8.8	67.2
E17	Europa	980926-0351	3598	.425	8.9	56,9
E18	Europa	981122-1148	2281	41.8	8.9	70.8
E19	Europa	990201-0211	1 49s	31.1	9.1	91.4
C20	Callisto	990S05 -1407	1311	2.5	9.4	59.5
C21	Callisto	990630-0747	1050	-0.8	7.3	41.3
C22	Callisto	990814-0840	2288	.3.2	7.3	33.4
C23	Callisto	990916-1736	1053	-0.6	6.5	26 2
124	Io	9910[1 -0437	500	-17.4	5.5	46.0
I25	Io	991126-0401	300	-80.5	5.7	39.0

1. UTC
2 Radio science only.

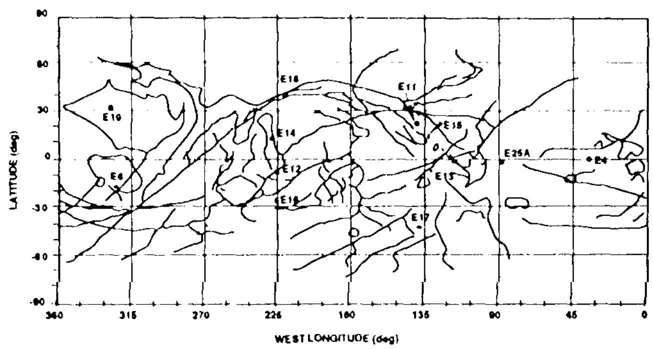


Figure 19. Map of Europa Flybys: GEM 96-04

decided that the small remaining E13 playback downlink resources could be more effectively allocated to E12 playback. This plan would allow the elimination of an entire encounter sequence development effort, another significant step in reducing the cost of the GEM.

After the Europa campaign, the spacecraft enters a phase known as the perijove reduction campaign. During this six month period, four Callisto encounters are used to reduce perijove to the orbit of Io; Callisto was chosen for this campaign as it is the best perijove reducer of the three outer Galilean satellites. It is during this time that the spacecraft experiences a sharply increasing radiation dose. Science opportunities during this phase include the opportunity to dissect the Io Torus a little more on each subsequent orbit as the perijove is reduced from the orbit of Europa to that of Io.

The final phase of the mission is the Io Campaign. The pair of Jo encounters are particularly high risk. Risk increases throughout the course of GEM as the spacecraft accumulates radiation dose at every perijove pass. Galileo will have exceeded its radiation design specification sometime during the early-middle of the Europa campaign. However, there has been only one known memory cell failure compared to the pre-launch expectation of about twenty in the prime mission and no other radiation problems seen i n engineering subsystems, so the prospects for completing the Io encounters are quite good. Rich encounters are planned to take best advantage of whatever spacecraft capabilities do exist in late 1999 as the spacecraft will swoop to within 500 and 300 km, respectively. The 124 encounter has been designed to pass directly over the known active regions of Pele, Marduk and Reiden Patera, allowing Galileo to "look right down the throat of an Ionian volcano. " The 125 flyby latitude was designed to be nearly polar to help answer the question of whether Io has an intrinsic magnetic field, a question raised due to the interesting magnetic interaction that Galileo detected during its flyby of Io on 7 December 1995.

12.5 Telecom/DSN strategy

An additional cost-saving and complexity reduction measure was to reduce the tracking coverage. During the primary mission, Galileo had essentially continuous coverage from arrival through end-of-mission on the 70m subnet, with the addition of two to three 34m stations and the Parkes Radio Telescope for arrayed operations at Canberra (the Australian DSN tracking complex) for roughly the last year of the primary mission. The GEM profile calls for seven tracks per week from the Canberra 70111,6 hours every other day from the Goldstone 70m, and three tracks per week from the Madrid 70m station. No 34m or Parkes coverage is required. Without including the Parkes tracking contribution, the GEM profile represents a three-fold reduction in the total nurnbcroftracking hours as compared to the primary mission.

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Spacecraft health is excellent, with no indication of radiation induced degradation in any of the engineering subsystems aside from the single CDS memory cell failure. As indicatcdin the instrument status, several of the instruments have been showing signs of radiation induced anomalies; this trend is expected to accelerate during GEM although there is no way to fully predict either the instruments' or the spacecraft's future performance.

Propellant remaining after GEM is predicted to be 19 kg (90%). There is ample power to continue operating Galileo in essentially the same operating modes as it uses in the prime mission. There is ample reserve in all consumables except in the tape recorder, where the stop-start cycle allocation will be exceeded early in GEM. No attempt will be made to conserve this resource as the limit on its use is considered a soft constraint, and it would be a poor trade to restrict science data acquisition early in GEM when the probability of successful spacecraft operation is much higher than it will be later.

13. Summary

With only one orbit and satellite encounter remaining in its eleven-orbit, ten satellite encounter primary orbital mission, the Galileo Orbiter now joins the Galileo Atmospheric Entry Probe. as an outstanding success. Recall that the Orbiter superbly delivered the Probe to Jupiter and received the Probe data in 1995 and later relayed the Probe data to Earth. But upon completion of the Probe relay in Spring 1996, the entire orbital mission still lay ahead. The success of the orbital mission is particularly stunning considering that it was achieved by one of the most remarkable inflight failure workarottnds ever. Following extraordinary, but unsuccessful efforts to deploy the High-Gain Antenna (HGA), the Project extensively reprogrammed the spacecraft computers to provide onboard compression, editing, and improved coding while the DSN built new ground receivers and arraying capability. These integrated efforts produced an effective downlink information rate of one kbps *over* the Orbiter's Low-Gain Antenna. This has been achieved with a received power density at Earth 40 db (10,000 times) less than the HGA was to have provided!

Galileo has provided a tremendous bounty of science. Although not all of the original objectives could be rnct with the severely reduced bit rate, the great majority of the original objectives and many new objectives have been achieved. It is arguable that the scientific bounty from Galileo with its many discoveries to date and undoubtedly many more in the continuing data analysis wiii easily exceed the original expectations. For example, there were no Europa or 10 encounters in the original objectives!

The Galileo Orbiter is performing superbly as it now approaches the threshold of its two year mission extension (GEM) with the prospect that its operations will continue even beyond that on a very reduced basis into the early years of the next century.

14. Acknowledgment

Project Galileo represents the work of thousands of people. They all deserve acknowledgment for the tremendous success of Galileo at Jupiter.

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