GALILEAN SATELLITES AND THE GALILEO SPACE MISSION

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Abstract. The Galileo spacecraft arrived at Jupiter in December 1995 to start its two-year mission of exploring the Jovian system. The spacecraft will complete eleven orbits around Jupiter and have ten more close encounters with the outer three Galilean satellites, after the initial close approach to Io on December 7, 1995. Since the Io encounter occurred closer to Io than originally designed, the spacecraft energy change was greater than nominally planned and resulted in an initial spacecraft orbital period about 7 days less than that designed in the nominal tour. A 100-km change in the Io-encounter distance results in an 8-day change in initial period of the spacecraft. Hence the first Ganymede encounter was moved forward one week, and the aim points for the first two Ganymede encounters were altered, but all other encounters would occur on their nominal dates and at the nominal altitudes. This was accomplished without expending spacecraft fuel and resulted in the first Ganymede flyby occurring on June 27, 1996 rather than the nominally scheduled July 4.

Earth- and spacecraft-based data were employed in developing ephemerides in support of the Galileo space mission. An analysis of CCD astrometric observations from 1992–1994, of photographic observations from 1967–1993, of mutual event astrometric data from 1973–1991, of Jovian eclipse timing data from 1652–1983, of Doppler data from 1987–1991, and of optical navigation data from the Voyager spacecraft encounter in 1979, produced the satellite ephemerides for the Galileo space mission.

1. Introduction

Jupiter's Galilean satellites have been of great scientific interest since their discovery in 1610. Because the periods of the inner three satellites are in the ratio of 1:2:4, the satellites obey the so-called Laplace libration which is of importance for the evolution of the Galilean system.

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Ole Roemer (1644–1710) employed eclipse timings in 1676 to investigate whether the speed of light was finite or infinite. The investigations by J.L. Lagrange (1736–1813) won the prize of the Royal Academy in 1766. P.S. Laplace (1749–1827) investigated the motion of the inner three satellites and discussed what we today call the Laplace libration, where the mean motions of the inner three satellites are locked together and follow the equation $n_1 - 3n_2 + 2n_3 = 0$.

One of the major efforts at international scientific cooperation in the 17th century involved the Galilean satellites and the attempt to determine terrestrial longitudes of observers by employing eclipses of the satellites. If an observer in Paris and an observer in Malacca, Malaysia, for example, observed the same satellite enter eclipse and recorded their local times of observation, then one could derive the longitude difference between Paris and Malacca from those eclipse timings. French Jesuits were active participants in these efforts, especially in the Orient, and some of the early maps of the world were drawn based upon Galilean satellite eclipse timings.

J-B. J. Delambre (1749–1822) collected more than 6000 eclipse observations prior to 1800 and his collection was considered the best in the world. It disappeared about the time of founding of the Bureau des Longitudes and was thought to be lost forever. Early in the 20^{th} century R.A. Sampson (1866–1939) found some reduced eclipse observations of Europa and Callisto from the Delambre collection at the Bureau des Longitudes. A-G. Pingre (1711–1796) had prepared a manuscript on 17^{th} century science (which contained a large collection of Galilean satellite eclipse observations because the satellites were employed for the determination of terrestrial longitudes, one of the most important problems in astronomy at the time) for publication at the end of the 18^{th} century, but it disappeared at the time of the French Revolution. C.G. Bigourdan (1851–1932) published Pingre's re-discovered manuscript in 1901. The extensive collection by J-N. Delisle (1688–1768) of observations of the Galilean satellites was re-discovered in 1980 and thus the lost Delambre collection has been recovered.

While eclipse observations are of interest in their historical setting, they are equally relevant in today's science. The observations by Roemer, for example, are being employed to guide the spacecraft Galileo in its forthcoming encounter with the Jovian system, since the Roemer data are included in the analysis which yielded the recent analytical ephemerides developed by Lieske and designated E5. Typical eclipse timing observations are accurate to about 800 km.

In 1979, S.J. Peale predicted volcanism on Io, before the Voyager spacecraft encountered Jupiter and dramatically photographed volcanic activity on Io.

TABLE 1. Close encounters during Galileo mission.

Encounter	Date	Satellite	Altitude [km]	Original plan
Io	7 Dec 95	Io	897	7 Dec, 1000 km
G1	27 Jun 96	Ganymede	844	4 July, 500 km
G2	6 Sep 96	Ganymede	255	6 Sep, 259 km
C3	4 Nov 96	Callisto	1 100	
E4	19 Dec 96	Europa	695	
E6	20 Feb 97	Europa	588	
G7	5 Apr 97	Ganymede	3 065	
G8	7 May 97	Ganymede	1 584	
C9	25 Jun 97	Callisto	416	
C10	17 Sep 97	Callisto	524	
E11	6 Nov 97	Europa	1 119	

2. The Galileo Mission

Launched in 1989, the Galileo spacecraft arrived at Jupiter in December 1995 and began its two-year exploration of the Jovian system which promises to return much new information. Although hampered by difficulties with the high-gain antenna, several innovative strategies have evolved so that most of the original scientific objectives can be accomplished by the Galileo space mission.

During the Galileo mission to Jupiter, there will be eleven close encounters with the Galilean satellites – one with Io on the inbound trajectory, 3 with Europa, 4 with Ganymede, and 3 with Callisto. The encounter dates and approach altitudes are given in Table 1. With the exception of the Io encounter, which occurred as the Galileo spacecraft was about to enter an orbit about Jupiter, all of the close encounters are denoted by the first initial of the satellite (*E*uropa, *G*anymede, *C*allisto) and then a number indicating on which orbital revolution of Jupiter the encounter occurs.

The spacecraft arrived at Jupiter on 7 December 1995 and entered Jupiter orbit. Originally the encounter distance with Io was planned to be 1000 km, which would assist in providing the first Ganymede encounter on 4 July 1996 at a distance of 500 km from the surface of Ganymede (D'Amario *et al.*, 1995). Pre-Io encounter tracking data indicated that an uncorrected spacecraft trajectory would approach to 900 km of the surface of Io on December 7, 1995.

3. The Io Encounter

Maneuver analysts at JPL (Byrnes, 1996) noted that if the Io flyby altitude were changed by 100 km from 1000 km to 900 km, then the subsequent Ganymede encounter would be changed by about 1 week, from July 4 to June 27, 1996. Because of the resonances of the Galilean system and the commensurability of their periods, Byrnes and colleagues noted that they could still accomplish the mission by moving the Ganymede encounter up by one week, without affecting any of the other planned encounters. By this on-the-fly mission re-design they thus were able to save precious fuel which would have been expended in getting the spacecraft "back on track" for the originally scheduled Ganymede encounter G1 on July 4. By accepting a slightly greater close approach to Ganymede and having the event occur on 27 June rather than 4 July, the JPL navigators were able to save fuel for the first Ganymede encounter and were able to keep the rest of the mission in unmodified form.

4. The Observations

The satellite ephemerides E5 were employed for the initial encounter with Jupiter. They were the product of an analysis of diverse Earth-based and Voyager-era spacecraft-based observations. The previously documented ephemerides E2 (Lieske, 1980) were developed prior to the Voyager mission and were based solely on an analysis of Earth-based observations.

The observational data which were employed in developing the ephemerides E5 consist of CCD observations made at the U.S. Naval Observatory Flagstaff Station, Voyager-era optical navigation images, astrometric observations of mutual events, photographic observations, Jovian eclipse timings, and CCD observations made at JPL's Table Mountain Facility. The Doppler observations of Ostro *et al.* (1992) were employed to assess the quality of that new data type. During the Galileo tour, the satellite ephemerides will be generated by numerical integration developed by R.A. Jacobson, with an analytical theory by Lieske (1977, 1995) as the back-up, because of the great magnification of errors from one encounter to the next and because of the km-level truncations in the analytic theory. Earth-based and spacecraft-based optical navigation data are not sensitive to the differences between numerical integration and theory, but it is expected that the close-encounter Doppler data may be sensitive in mapping errors from one close encounter to the next.

By intercomparing various data types one learns of the strengths and weaknesses of each individual type of data and discovers inconsistencies among the data types. The data are described in Table 2, which also gives the percentage change in weighted sum-of-squares for ephemeris E5 relative

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TABLE 2. Observational data employed for ephemeris E5.

Data span	observable type	observ.	% chg from E3
1992–1994	CCD data, Flagstaff ra & dec	870	−52.6
1979	Voyager opnav ra & dec	366	−19.0
1973–1991	mutual events ra & dec	860	−55.5
1967–1993	photographic ra & dec	8 462	−3.2
1652–1983	eclipse timings	15 711	+2.7
1994	CCD data, Table Mountain	72	+68.3
1987–1991	Doppler	50	−55.6

to ephemeris E3. A plus sign indicates an increase and a minus sign indicates a decrease in the weighted residuals.

4.1. CCD OBSERVATIONS

The new CCD observations were made at the U.S. Naval Observatory Flagstaff Station during the years 1992–1994, employing techniques developed by D. Monet and described in Monet and Monet (1992). The Flagstaff data consist of "normal-points", which are derived typically from 30–50 CCD "exposures." Some less-accurate CCD data from the JPL Table Mountain Facility (Owen, 1995) were also employed. After the development of E5, additional CCD data from Flagstaff for the years 1995 and 1996 were obtained. They serve as a good indicator of the stability of the E5 ephemerides.

The CCD data were processed using Lambert scattering to compute the offset between the center of light and center of figure (Lindegren, 1977) and it is believed that the dominant remaining unmodeled error source in these data is due to albedo variations across the disk of the satellites. Recent estimates of the albedo variations by several scientists (Goguen, 1994; Mallama, 1993; Riedel, 1994; Gaskell, 1995) are not entirely consistent and for the Galileo ephemerides it was decided to limit the processing to computation of the difference between center of light and center of figure due to Lambert scattering only.

4.2. VOYAGER OPTICAL NAVIGATION IMAGES

During the Voyager mission in 1979, some optical navigation images of the Jovian satellites were taken from the two Voyager spacecraft for use in navigating the spacecraft to the Jovian encounters (Synnott *et al.*, 1982). The optical navigation images are analogous to Earth-based astrometric observations of the satellites except that the "opnav" images are taken by an "observer" much closer to the Jovian system (typically 13–95 light seconds from the satellites). At $5 \cdot 10^6$ km from Jupiter, one arcsec corresponds approximately to 25 km.

4.3. ASTROMETRIC MUTUAL EVENT OBSERVATIONS

Astrometric observations from 1973–1991 of mutual events (where one satellite occults or eclipses another satellite) were employed. The mutual event "seasons" occur every six years. The 1973 and 1979 data of the Aksnes team (Aksnes and Franklin, 1976; Aksnes *et al.*, 1984) were affected by the phase offsets between eclipses and occultations which led Aksnes *et al.* (1986) to recommend that δt be added to the published observation times for the 1973 and 1979 data. That was implemented in the analysis of developing the ephemerides E5.

In the processing of mutual event observations by the Aksnes team in 1985 (Franklin *et al.*, 1991) and 1991 (Kaas *et al.*, 1996), it was intended that no value of δt would be required but that instead the authors would incorporate the phase effects into their published times and separations. However, the effects were added in the incorrect direction for the published data and hence it is recommended (Aksnes, 1993; Franklin, 1993; Lieske, 1995a) that the 1985 and 1991 data be employed by adding *twice* the published values of δt to the observation times. Essentially the first addition of δt removes the erroneous application of the phase effects with the wrong sign and the second application of δt corrects for the phase problem. That is the method being employed in developing future ephemerides using the mutual events of 1985 and 1991.

4.4. OTHER OBSERVATIONS

The long and valuable series of photographic observations made by D. Pascu of the U.S. Naval Observatory have been an essential ingredient of the Galilean satellite ephemerides since the first development of the Galsat software. In a remarkable series of observations 1967–1993, Pascu (1977, 1979, 1993, 1994) provided observations of the satellites. The typical photographic plate of Pascu contains about 4 exposures. A comparison of the root-mean-square residuals for the Pascu photographic data and the Monet CCD data tends to bear out the predictions of Lindegren (1980) concerning the atmospheric limitations of narrow-field optical astrometry. Lindegren indicated that the variance of the errors should be proportional to the square root of the separation and inversely proportional to the integration time. Since both the Pascu and Monet data by their very nature measure comparable separations of the satellites, the variance of the errors should follow something proportional to the inverse ratios of the integration times. For the Pascu data, one "normal point" of a photographic plate consists of four exposures of 20-sec duration and implies an integration time of 80 sec. A CCD normal point, on the other hand, consists of 30–50 "exposures" each of 10-sec duration and implies an integration time of about 400 sec. Hence the ratios of the errors should be about $\sigma_{photo}/\sigma_{CCD} = \sqrt{400/80} = 2.2$ which is rather close to the actual value.

The observations (Pickering, 1907; Pierce, 1974; Lieske, 1980, 1986) of eclipse times by Jupiter of its Galilean satellites from 1652–1983 were also employed. Such a long series is valuable for imposing realistic constraints on the satellite mean motions and is useful for investigating possible tidal accelerations.

5. Conclusions

The Galileo space mission is now in its tour phase of visiting the various Galilean satellites and sending back information and pictures to the Earth. Although hampered by a not fully deployed high-gain antenna, the spacecraft should complete most of its scientific objectives. An interesting application of on-the-fly mission re-design took advantage of the close approach to Io to modify the ensuing tour without expending spacecraft fuel to force the spacecraft back to its nominal trajectory. A variety of Earth-based and spacecraft-based observational data is employed to develop ephemerides of the Galilean satellites suitable for the Galileo space mission.

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