Galileo orbit Determination for the Earth-2 Encounter

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Introduction

The Galileo spacecraft was launched on October 18, 1989 towards Jupiter using the Venus-Earth-Earth Gravity Assist (VEEGA) trajectory, On December 8, 1992, the spacecraft flew by the Earth at an altitude of 303 km on the final gravity assist which sent it on its way to Jupiter. To minimize the fuel required for propulsive maneuvers, the spacecraft had to be delivered accurately to the planned target point at Earth closest approach. To satisfy Earth avoidance constraints, three maneuvers were performed which moved the aim point successively closer to the final target. A fourth maneuver was also performed to clean up errors caused by the final aimpoint maneuver. This paper details the orbit determination strategy and results used to navigate Galileo from the first of these maneuvers through closest approach.

Orbit Determination Strategy

Due to the failure of the High Gain Antenna (HGA) to deploy, the spacecraft had to be navigated using one of the two Low Gain Antennas (LGA). The data from LGA-1 consisted of two-way Doppler and range points at S-band frequencies. In addition, an interferometric data type known as Delta difference one-way range (ADOR) was used during the latter portion of the approach. A combination of these three data types were employed to obtain the best solution for the orbit.

The accuracy of the orbit determination procedure is heavily dependent on the models used to propagate the spacecraft's orbit and the error sources affecting the data. The force models used to integrate the trajectory include the gravitational attractions of the sun, moon and the nine planets, solar radiation pressure, and spacecraft propulsive events. Error sources affecting the data include path length delays due to the troposphere and ionosphere and errors associated with DSN station locations. Orbit determination typically involves estimating, in addition to the spacecraft position and velocity at some epoch time, many of the force model and error source parameters. Or, if the data is not strong enough to estimate a particular parameter, it can be "considered", i.e. its contribution to the uncertainty in the estimate is quantified, but it is not solved for. For this portion of the mission, estimated parameters included the state, specular and diffuse values for solar radiation pressure, and three Cartesian velocity components of all propulsive events. The tropospheric and ionospheric path delays, and station location uncertainties were considered in the filter. Finally, two methods were tried to account for atmospheric drag caused by the low altitude fly-by, The first was an impulsive AV in three Cartesian components at the point of closest approach, and the second was to try and estimate drag directly.

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There were four major Trajectory Correction Manuevers (TCM's) which were used to target Galileo towards its final aim point from its post-Gaspra trajectory, These occurred on August 4, October 9, November 13, and November 28. In addition, many smaller propulsive events occurred which affected the trajectory. These included attitude update turns to keep the spacecraft pointed in a desired direction, line flushings of the retro-propulsion module (RPM), and turns used for HGA warming and cooling activities. Although these small thruster events were nominally performed in a balanced mode, small imbalances resulted in net AV'S which were explicitly solved for in the estimation procedure.

Navigation performance at planetary encounters are generally given in terms of "B-plane" parameters. The Earth B-plane is a plane through the center of the Earth and perpendicular to the incoming asymptote of the trajectory. The B vector points from the center of the Earth to the point at which the asymptote pierces the B-plane, and the projection of B onto axes parallel and perpendicular to the Earth Mean Ecliptic of 1950 are called B•T and B•R, respectively,

Results

The following table shows the final OD solution to support the TCM's and the selected aim point of the TCM based on the solution. The solution is shown in the Earth B-plane, along with the estimate for the Time of Closest Approach (TCA), given in UTC on December 8, 1992. The uncertainties for the solution and the delivery uncertainties for the aim point are also shown.

TCM	Data Arc	OD solution	Selected Aim Point
14	5/5/92 - 7/1 6/92	B•R = -12296.5± 435 km B•T = -83521.8±101 km TCA = 07:26:45±1 5 sec	BoR = 1725.4±802 km B•T = -16023.9±1 067 km TCA = 15:10:465376 sec
15	8/7/92 - 9/24/92	BoR = 361.2±131 km B•T = -15354.7±43 km TCA = 15:15:49±5 sec	BoR = 855.4±131 km B•T = -12,426.9±53 km TCA = 15:10:43*7 sec
16	8/8/92 - 11/2/92	B•R = 696.0±23 km B•T = -12,369.1±12 km TCA = 15:10:41±1 sec	B•R = 1099.4±25 km BoT = -10,531.1*24 km TCA = 15:09:27±2 sec
17	10/1 5/92 - 11/20/92	BoR = 1082.4±4. 1 km B•T = -10531 .7±2.5 km TCA = 1 5:09:27.8±0.1 sec	B•R = 1097.4*4.2 km B•T = -10,529.9±2.5 km TCA = 15:09:25.0±0.1 sec
Fly-by result	11/14/92 - 12/10/92	B•R = 1096.2±0.02 km B*T = -10,529.2±0.01 km TCA = 15:09:24.9±0.001 sec	

An initially disconcerting result of the analysis was the large discrepancy between the TCM- 14 target and where the spacecraft actually went as determined by the OD solution for TCM- 15. The miss was about 1520 km in the B-plane -- well above the l-sigma dispersion for the TCM- 14 delivery. Detailed analysis of the problem revealed the cause to be a combination of an anomalous overburn and a timing error which resulted in the thrusters firing slightly late. The timing error was present in all subsequent maneuvers, but due to their smaller magnitudes, its effect in the B-plane was not as large.

The OD solutions for TCM's 16 and 17 incorporated ADOR data, Because ADOR data is able to sense the motion of the spacecraft in the plane-of-the-sky directly, the solutions were more accurate in the declination component than with range and Doppler alone. Post-fit residuals of ADOR data showed the rms to be under 25 cm, which is its inherent noise level.

The impulsive AV computed at closest approach amounted to 5.8 9±0.08 mm/s along the velocity vector. The direct estimate of drag was very similiar. These compare favorably with predictions of 5 to 7 mm/s computed using various atmospheric models to calculate density. Due to the uncertainty in the knowledge of the atmosphere at 303 km altitude, the impulsive AV formulation was used operationally, and the more rigorous approach was primarily for comparison purposes.

The post fly-by reconstruction of the encounter showed a miss in the B-plane of only 1.4 km from the intended target. This accurate navigation of the encounter enabled the cancellation of TCM- 18, which was to take place 13 days later.