Galileo Orbit Determination for the Ida Encounter

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Abstract

This paper summarizes Galileo's orbit determination activities leading Up to its encounter with asteroid 243-Ida on August 28, 1993. In addition to the nominal 2-way S-band range and Doppler radio metric data obtained from the Deep Space Network (DSN), several navigational aids were brought together to make this encounter successful. These include a comprehensive ground-based observation campaign of the asteroid during rhe four years prior to the flyby to improve Ida's ephemeris significantly, and the Optical Navigation picture campaign which helped to decrease considerably the uncertainties of Galileo's position relative to Ida. Details in the modeling of Galileo's orbit and in the navigational tools described above will be explained, and the results of several key orbit solutions will be given. After the encounter, reconstructions of Galileo's orbit with respect to Ida were performed using several SS1 science images of the asteroid that were returned to Earth from September 1993 through late April 1994. The final determination resulted in knowledge of the flyby within ± 2 km in Ida's B-plane B*R and B•T directions and within ±0.4 seconds in time of closest approach.

Introduction

En route to Jupiter, the Galileo spacecraft successfully encountered asteroid 243-Ida on August 28, 1993, at 16:52:04 UTC, marking another historic milestone for the Galileo project. Ida now has become the second asteroid to be visited by a spacecraft. (Galileo's pioneering encounter with 951 -Gaspra on October 29, 1991 was the first asteroid encounter.) Discovered in 1884 by J. Palisa in Vienna, the asteroid 243-lda is believed to be a member of the Koronis family of asteroids in the middle of the main asteroid belt. Based on Earth and IRAS-based observations, Ida has been thought [o be a relatively young S-Type asteroid with triaxial ellipsoid dimensions of 53 km by 23 km by 18 km. Three weeks after the encounter, Galileo returned a high resolution picture of Ida that indicated Ida to be slightly larger arsd much older than previously believed. Several months after the encounter, in late March 1994, two images (one Solid State Imaging (SS1) and one Near Infrared Mapping Spectrometer (NIMS)) revealed a small 1 km diameter moon orbiting Ida, The moon was also found in subsequently returned images. With this new discovery, scientists require the best possible reconstruction of Galileo's orbit with respect to Ida in order to compute the moon's orbit about Ma.

Galileo is nominally tracked by 2-way S-band Doppler and range radio metric data obtained by the 70 m Deep

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that $T = N \times R$ (roughly alongtrack). The B-plane coordinate system shown in Figure 1 is defined by a frame centered at the target body with axes S, T, and R, such that the unit vector, S, is defined parallel to the spacecraft approach asymptote, the unit vector, T, is normal to S and parallel to the Earth mean ecliptic of 1950 (EMO- 1950), and the unit vector, R, is orthogonal to both S and T such that R = S x 1'. The B-plane is then defined by the R-T plane. The B-vector points from the origin of the coordinate system to the point where the incoming asymptote intercepts the R-T plane. Results of spacecraft encounters are typically expressed by the components of the B-vector in this plane, B •R, B •T and the linearized time of flight (TOF) determined (for a body of negligible mass) by the spacecraft-target distance along the *S* direction divided by the relative approach velocity, V_∞.

The dates listed in Table 1 represent successive Ida ephemeris deliveries and error analyses [1,3-7]. The final ephemeris determination, delivered in April 1993, reduced the 1-sigma uncertain y error ellipsoid of Ida's position at encounter on August 28, 1993 by approximately 50% of the January 92 delivery and by nearly 75% of the original delivery. The errors for the last delivery (designated IN3) were 108 km in the B •T component, 81 km in the B •R component and 5.5 sec in the TOF. Since movement of the asteroid in the B •T and B • R directions represent plane of the sky motion as viewed from the spacecraft, observations of Ida relative to Galileo using the OPNAV pictures help reduce these uncertainties significantly. The error in the TOF is not reduced, however, through OPNAV until very close to closest approach. Travelling at 12.4 km/s relative to Ma, the distance equivalent of this error normal to the B-plane is 68 km. Table 2 lists the changes in Ida's orbit position with successive Ida ephemeris deliveries, IN1, IN2, and IN3 in both Earth-mean-equator of 1950 cartesian (EME- 1950) and B-plane coordinates. The orbit elements of the final ground-based Ida delivery, IN3, are listed in Table 3 [1].

Table 1: Ida l-sigma uncertainties as observing program progressed

Date	No. of Observations Actual	Simulated§	*R* (km)	*T* (km)	*N* (km)	B • T (km)	B • R (km)	S (km)	TOF (See)
October 88	105	12	162	440	317	NJA	N/A	N/A	N/A
January 92	218	26	86	245	161	224	161	131	10.6
October 92	268	20	45	156	91	145	91	73	6.0
April 93	405	10	44	120	81	108	81	68	5.5

† Assuming ground-based observing program for Ida through July 93

§ Simulated observations through July 28, 1993 were used to account for data not yet acquired.

Space Network (DSN) antennae in California, Spain, and Australia. It wits known that the accurate navigation of Galileo to its target aimpoint, 2400 km from Ida, could not have been performed using only radio metric data; therefore two kcy elements were employed to reduce the relative spacecraft-asteroid uncertainties significantly. These include an extensive ground-based astrometric observation of Ida to enhance substantially the knowledge of Ida's ephemeris, and onboard optical navigation (OPNAV) data of Ida against a background of known stars to improve the relative spacecraft-asteroid orbit knowledge significantly. Many nongravitational forces influenced Galileo's trajectory on its way to Ma; these include solar pressure, unbalanced attitude turns, Retro-Propulsion Module (RPM) thruster line clearing flushes, and a practice atmospheric probe delivery spin-up/spin-down. Three trajectory correction maneuvers (TCM 's) were planned after the second Earth flyby; however, only two maneuvers were actually needed to achieve the desired target at Ida precisely. The process of determining Galileo's orbit involved fitting a mathematical representation of Galileo's orbit to observed position and velocity information from the tracking data through a least squares method. Parameters such as the spacecraft's initial state, sofar radiation pressure and AV impulses of each thrusting event are adjusted to minimize residuals between the observed and computed orbits using the Orbit Determination Program (ODP), which uses a batch-sequential square root filtering algorithm. Analysis of the post-encounter flyby reconstruction revealed that Galileo's final flyby position with respect to Ida had been within the accuracy predicted by a covariance analysis performed for the S-band Low Gain Antenna (LGA).

The Ground-Based Ida Observation Program

Precise knowledge of Ida's orbit was essential to Galileo's successful navigation to its target aimpoint at Ida. After Ida had been chosen as the second asteroid flyby for Galileo, a select group of experienced astronomers made accurate observations of the asteroid using the latest astrometric equipment and techniques. Therefore, in addition to several decades of observations of Ida, special state-of-the-art CCD detectors, automatic measuring engines and sophisticated data reduction techniques along with special Lick Observatory reference star catalogs were incorporated to determine Ma's ephemeris with high precision. Astrometric observations of Ida were made with accuracies of better than 0.2 arc seconds during the 1992-93 period [1]. The final observations included in this data set were reduced using two stars observed from the Hipparcos spacecraft, resulting in orbit residuals of 0.06 arc seconds [1].

As the high precision observing program that began in 1988 progressed, Ma's l-sigma uncertainty ellipsoid reduced significantly. Table 1 illustrates the advancements made in Ida's orbit determination as additional observations were accumulated. Here the l-sigma uncertainty error ellipsoid of Ida's position at encounter on August 28, 1993 is expressed both in the heliocentric orbit-fixed Radial-Transverse-Normal (RTN) and in the Galileo spacecraft B-plane coordinate frames. In the RTN coordinate system, R represents the Sun-asteroid unit vector, N is the unit vector normal to orbit plane (crosstrack), and T is orthogonal m both R and N such

Table 2: Orbit differences between ephemeris deliveries in EME- 1950 Cartesian coordinates and Ida B-plane

Ephemeris ID	Dare	Difference	X (km)	Y (km)	Z (km)	Magnitude (km)	B• T (km)	B• R (km)	TOF (we)
IN1	October 92	IN 1-IN0*	-433	-88.3	339	556	N/A	N/A	N/A
IN2	April 93	IN2-IN1	-260	197	187	376	306	-90.9	-16
rN3	July 93	IN3-IN2	25.0	-54.0	97.6	114	58.2	97.7	-0.90

*INO was prelaunch ephemeris.

Table 3: Orbital elements of Ida based on final Ida ephemeris delivery (IN3) in EMO- 1950

Epoch	t	1993 November 9.0 TDB§
Time of Periapsis Passage	t_p	1991 November 20.633822 TDB§
Periapse Radius	q	2.73880979 AU
Eccentricity	e	0.04340313
Argument of periapsis	ω	113.210864 deg
Longitude of Ascending Node	Ω	323,662512 deg
Inclination	i	1.131261 deg

§ TDB = barycentric dynamical time

The Optical Navigation Strategy

Due to the failure to deploy the High Gain Antenna in April 1991, OPNAV images obtained during the Gaspra and Ida encounters had to be recorded on the onboard tape recorder; then the recorded data was transferred to the Command and Data Subsystem (CDS) where it was subsequently read into the downlink telemetry stream and transmitted back to Earth at 40 bits per second. This technique is referred to as Data Memory Subsystem Memory Readout (DMSMRO). To replay the information for one OPNAV image and receive it on Earth, Galileo must perform seven DMSMRO commands. During the intervening time between Gaspra and Ida, engineers were able to reconfigure the DMS MRO in order to double the speed with which the data is read into the telemetry stream. This faster DMSMRO allowed the crucial OPNAV pictures to be shuttered closer to Ida than Gaspra and returned in less time thereby decreasing the uncertainties of Galileo's flyby position relative to Ida. This decreased the time to receive one OPNAV image from over 70 hours for the Gaspra encounter down to approximately 35 hours using the new DMS MRO.

OPNAV for the Ida encounter used the Single-Frame Mosaic (SFM) technique that was originally designed for the Gaspra encounter. This technique involved leaving the camera shutter open for approximately 25 seconds while performing several small scan platform slews to capture multiple sets of asteroid and star images in one picture frame [8]. One SFM image is essentially equivalent to 4 or more pictures. The Gaspra SFM OPNAV experience resulted in much better quality data, higher signal strength of dim objects, lower data noise, and more stars and data points than expected. During the Gaspra encounter, SFM center-finding algorithms proved to be more accurate than predicted [8]. Also dim objects (stars and asteroid) appeared brighter than expected due to a bias in favor of detecting dim star magnitudes and better-than-expected spacecraft wobble control [8]. At least five images per SFM were obtained due to good camera pointing *control* and spacecraft motions. For the above reasons, many dim stars were obtained resulting in excellent camera pointing solutions [8]. More images per OPNAV allowed a better assessment of the optical data accuracy. With these assessments, the Ida OPNAV campaign was designed with more confidence in obtaining higher accuracy; therefore, the science observations were designed to take advantage of the lower B-plane uncertainties. Please refer to [8] for a complete explanation of extracting the data from an OPNAV image.

Similar to the Gaspra encounter OPNAV schedule [8], the Ida OPNAV picture schedule was primarily determined by the amount of 70 m antenna coverage the Galileo Project could obtain from the DSN. With this amount of available antenna coverage, it was concluded that five OPNAV images could be returned. The placement of the 5 OPNAV images were scheduled to support the design of two Trajectory Correction Maneuvers (TCM's) designated TCM-20 and TCM-21, which were to be performed to deliver Galileo to the desired Ida flyby aimpoint. TCM-20 and TCM-21 were respectively planned to be performed on August 13, 1993 (15 days before Closest Approach (C/A)) and August 26, 1993 (2 days before C/A). In the case of the Gaspra encounter, the Frost targeting maneuver was based on one OPNAV which was subsequently found to have a systematic bias[8]. Therefore, it was then desired to use at least two OPNAV images to design each maneuver, thereby reducing any effects of possible systematic biases. Therefore two OPNAV'S (OPNAV 1 and 0PNAV2) were planned to be included in the OD solution for the design of TCM-20, which began 29 days before C/A (July 30). TCM-21 was to be designed in two steps. The nominal design was to begin on August 16 (C/A -12 days) with an OD solution that was to incorporate 0PNAV3. The updated design ofTCM-21 was to begin on August 23 (C/A -5 days), and it was to be based on an OD solution which was to include the remaining OPNAV'S 4 and 5. Therefore, the planned Ida OPNAV campaign using the LGA consisted of shuttering five pictures at 47, 36, 17, 11, and 7 days before C/A and were to be returned at 42, 33, 13, 8, and 5 days, respectively, before C/A. These images were sequentially named OPNAV'S 1, 2, 3,4, and 5.

Radio Metric And Optical Tracking Data

From the period after the second Earth flyby through the Ida approach, Galileo was primarily tracked by 2-way S-band Doppler and range radio metric data obtained by the 70 m DSN antennae in California, Spain, and

Australia, A few Delta-Differenced One-way Range (ADOR) tracking measurements were also employed to measure plane-of-the-sky position of the spacecraft relative to nearby quasars. This data type is desired primarily to provide out-of-plane position determination during periods of low declination. As the spacecraft became sufficiently close to the asteroid (at C/A-47 days), the onboard optical navigation was to become the primary tracking source.

Sources of error affecting the S-band signal include the Earth's ionosphere and troposphere. In general, the ionosphere and troposphere slow the propagation of the electromagnetic signal, so the data must be corrected for these delays. Daily day and night ionospheric calibrations are provided by the Tracking Systems Analysis and Calibrations group who model the zenith path length delay through a network of the GPS satellite system and GPS *receivers.* A Chao model is provided to calibrate the wet and dry components of the troposphere. When the DSN antennae track the spacecraft at low elevations, these conditions have a more pronounced effect on the signal; thus, to avoid larger errors in the orbit determination process, all data is deleted below elevations of 15 degrees or less.

Doppler

The Doppler data type measures line-of-sight velocity of the spacecraft relative to Earth through frequency shifts in the radio signal. In addition to the nominal Doppler shift, the spacecraft's S-band transmissions are circularly polarized and hence are affected by the spacecraft's nominal spin rate of 3.15 rpm. The spin impresses a constant bias of 109.5 mHz onto the Doppler signal (offset of 7.3 mm/s) [91. The nominal spin rate implies that the spacecraft is in a dual-spin mode whereby one section that contains the scan platform and other instruments is inertially fixed (called the despun section) and the remaining section which contains the HGA and LGA antennae is spun. Occasionally the spacecraft is configured into the all-spin mode where the entire spacecraft spins at 2.89 rpm. The reduction to the Doppler bias as a result of this spin rate change must afso be accounted for [9]. As Galileo approached Ida, the Earth-equator-spacecraft geometry resulted in the acquiring of the 2-way Doppler signal at low geocentric declinations (6 to -8 degrees). The result of this unfortunate geometry was to limit the knowledge of out-of-ecliptic-plane motion; therefore, the uncertainties in this direction could not be reduced significantly through the Doppler data type.

Range

Relative Earth-spacecraft distance is determined by the range data type that is acquired by way of the DSN's Sequential Ranging Assembly (SRA). The SRA measures the round trip light-time of the uplink carrier signal modulated with a known digitrd code from the tracking station to the spacecraft and back to the station. As of the first week of June 1993 (-3 months prior to C/A) the spacecraft-Earth distance became too large to obtain an adequate signal-to-noise ratio for the SRA ranging reduction over the LGA. Subsequent attempts to improve the ranging signal measurement were unsuccessful and resulted in unusable data. Range data obtained prior to (his time, however, were used.

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ADOR

To help ascertain the plane-of-sky position of the spacecraft, a relatively new interferometric data type, S-band Delta-Differenced One-way Range (ADOR) was employed. ADOR uses the near simultaneous one-way range observations of Galileo from two DSN tracking stations separated by an intercontinental baseline. Similar observations are performed on a quasar that is angularly in close proximity to the spacecraft and this data is difference with the spacecraft observations to measure accurately the spacecraft-quasar angular separation. This differencing effectively reduces the effects of atmospheric and station location errors. Measurements taken from both the Goldstone-Canberra (North-South) and Goldstone-Madrid (East-West) baselines provide near orthogonal angular plane-of-the-sky information. Two orthogonal ADOR pairs were planned on April 23, 24 and June 7, 8. Operationally, the ADOR measurement requires extensive use of resources to obtain a successful measurement. As such, problems sometimes occur resulting in the loss of the measurement as was in the case of the April 23 point, For orbit reconstruction purposes, East-West ADOR points obtained on October 1, December 18, and 28, 1993 and two North-South points, December 19,28 were also used,

Science **Images**

Science SS1 images taken of Ida during the flyby provided valuable post-encounter information of Galileo's relative orbit to Ma. The post-encounter reconstructions of the flyby were to be performed using the high resolution SS1 mosaic shuttered from -5.5 to -1.3 minutes before C/A, and the close encounter mosaic shuttered from -1 minute to +1 minute before and after C/A provided that the asteroid was captured in one of the frames. From the determination of the geometric center of Ida within the mosaics and the telemetered camera pointing, a relative type of 'OPNAV' could be formed.

Orbit Determination Strategy

Data Weights

One important aspect of orbit determination is the amount of confidence placed on each of the four types of tracking data, Since it was known that the OPNAV data would become the primary data type once the first image was received, it was important to weight the OPNAV accordingly. Inconsistencies between data types could result in differing solutions depending on the data weighting schemes. Therefore, it was important to balance correctly the data weights given to the radio metric and OPNAV data types. At the beginning of Galileo's Earth to Ida trajectory, Galileo was close enough to Earth to acquire very good tracking data with uncertainties less than 100 m for range and 0.2 mm/s for the Doppler. As the spacecraft- Earth distance grew, the

Doppler and range data became nosier. The Doppler signal was weighted at 15 mHz 1-sigma uncertainty from the Earth flyby on December 8, 1992 through mid-April for a 60 second count time. Then from mid-April through encounter on August 28, the Doppler signal was weighted at 60 mHz (60 second count time). This corresponds to 4 mm/s uncertainty in the velocity measurement. Likewise, the range data was deweighted in mid-April from 100 m to 1 kilometer (l-sigma). When the ADOR data was introduced into the orbit solutions, the uncertainty applied to the signal delay was 3.33 nanosec or equivalently 1 m in one way path *length*. Finally, when OPNAV was added to the OD, each data point was weighted at 0.35 pixel. A SFM OPNAV image was expected to contain 5 to 8 points; therefore, (he resultant weight applied to the entire image ranged from 0.157 to 0.124 pixel. For the post-encounter reconstruction, higher weights were applied to the science images. Since there were large uncertainties associated with determining the center of the asteroid in the high resolution and encounter images, these science images were weighted from 50 to 100 pixels.

Estimated and Considered Parameters

In order to determine Galileo's orbit, several standard parameters such as the initial state of the spacecraft, the diffuse and specular reflectivities of a flat plate solar pressure model, and the change in velocity (ΔV) resulting from all thruster activities within the data arc must be estimated. In addition to actual targeting maneuvers (TCM-19 and TCM-20) thruster activities include unbalanced attitude updates to re-point the spacecraft's LGA, and RPM thruster flushing events to clear old propellant oxidizer out of the RPM passages. Figure 2 lists chronologically the sequence of events leading up to encounter. RPM flushing events typically occur every 23 days; their resultant AV contributions are predictable and usually average at 18 mm/s along the spacecraft's minus Z-axis. However, when a new program sequence to perform the flushes was executed on February 8, March 1, and March 24, anomalous unbalanced S-thruster firings occurred thereby applying AV in the spacecraft's X-Y plane direction. By the time of the next RPM flushing in April, the problem had been rectified. In another thruster event to practice for the atmospheric probe release later in July 1995, the S-thrusters were fired to spin the spacecraft up to 10 rpm, and then back down to the nominal all-spin rotation speed of 2.89 rpm. This resulted in large unpredictable Z-axis velocity changes. Shortly after Galileo flew by Earth in December 1992, five HGA cooling turns were executed; each turn involved both an attitude turn to position the HGA away from the sun, and a sun acquisition turn to return to near-sun pointing. Finally, several tests were performed in mid March and late June to test the HGA's ability to receive and to transmit the X-band signal. These tests involved very small maneuvers to turn the spacecraft's -Z-axis at consecutive angles off-Earth-line to determine the antenna's radiation patterns. These small turns generally contributed approximately 1 mm/s change in velocity to the spacecraft. All thruster events were estimated using a impulsive AV model with the execution times situated at the center of the event.

When the OPNAV images were incorporated into the orbit solutions, Ida's ephemeris as determined by the

Brouwer and Clemence 'Set 111' coordinates was estimated. Also, the SS1 camera pointing in right ascension, declination and twist were treated as stochastic variables, so their values were estimated for each individual data point within each OPNAV image. It was important to batch each data point separately so that their individual pointing solutions could be estimated and to ensure that their solutions were uncorrelated in time. For solutions involving the ADOR data, locations of quasars 'P 1055+01', '3C 273', 'DW 1335-12', and 'P 1504-167' in right ascension and declination were also estimated with *a priori* uncertainties of 150 nanoradians. *A priori* uncertainties for each estimated parameter are listed in Table 4.

Table 4: *A priori* uncertainties in the estimated and considered orbit solution parameters

Estimated Parameter	A Priori Uncertainty (1-sigma)
Spacecraft position	10^8 km
Spacecraft velocity	10^8 km/s
Specular reflectivity coefficient	10% Or nominal value
Diffuse reflectivity coefficient	10% of nominal value
TCM-19,TCM-20	10% of nominal ΔV impulse
Attitude turn maneuvers	2 mm/s, spherical
RPM thruster flushes	1 rends ● long axial (spacecraft Z) direction, 0.5 mm/s in orthogonal directions (spacecraft X-Y plane), ellipsoidal
10 rpm Spin-up/Spin-down	2 mm/s, spherical
Anomalous S-Thrusting events	1 mm/s along ● xial (spacecraft Z) direction, 20 mm/s in orthogonal directions (spacecraft X-Y plane), ellipsoidal
HGA attitude turns	2 mm/s, spherical
Ida ephemeris	see Table 1
Quasar position	150 nanoradians in RA, Dec
SSI Camera pointing	0.10° in RA, Dec, and 2" in Twist
SS1 Scan Platform cone, cross-cone	6.8 mrad in line, 2 mrad in pixel
Considered Parameters	
Troposphere	4.0 cm wet, 1.0 cm dry
Ionosphere	75 cm day, 15 cm night
Station location coordinates	SO cm m spin radius, 6 m m z-height, 70 m in longitude
Ida ephemeris	see Table 1

Up until the first OPNAV image was shuttered, the errors associated with Ida's orbit were considered in the orbit solution. Considered parameters are not adjusted in the fit, but the effects of their *a priori* uncertainties are included in the post covariance of the estimated parameters. Uncertainties that account for errors in the cylindrical coordinates of the three DSN 70m antennae, and errors in the media calibrations of wet and dry troposphere and day and night ionosphere path length delays over each DSN *station were* typically considered in Galileo's orbit determination. *A priori* uncertainties for each considered parameter are listed in Table 4.

Maneuvers

As Galileo approached Earth for the second and last time, a series of maneuvers were executed to achieve the optimum Earth flyby aimpoint that would minimize the propellant expenditure *to* encounter Ida while en route to Jupiter. After this Earth flyby, three statistical trajectory correction maneuvers (TCM-19, TCM-20, TCM-21) were planned to retarget Galileo to the desired Ida flyby aimpoint. A complete explanation of the 10 N thrusters used to maneuver the spacecraft are described in [10]. The start of the design of TCM-19 took place on February 23, 1993 and TCM-19 was subsequently executed on March 9, 1993. Table 5 lists the axial, lateral, unbalanced turn and resultant AV'S for TCM-19 and TCM-20. Also included in Table 5 are the designed AV segments for TCM-21.

Table 5: Axial and lateral segments for Ida targeting maneuvers.

Maneuver	Date Designed	Execution Date	Axial AV (m/s)	Turn AV (m/s)	Lateral AV (m/s)	Resultant AV (m/s)	Earth Look Angle* (deg)
TCM-19	2/23/93	3/9/'93	1.92	0.20	N/A	2.12	8.9
TCM-20	7/30/93	8/13/93	0.073	N/A	0.615	0.618	87.1
TCM-21**	8/20/93	8/26/93	0.050	N/A	0.060	0.077	51.0

*Earth Look Angle is angle between AV vector and spacecraft-Earth direction vector.
**Not executed.

Data Arcs

The data arc for the design of TCM-19 consisted of two-way Doppler and range from December 11, 1992 (three days following the Earth-2 encounter) to February 22, 1993. For the design of TCM-20, a new epoch was established on April 1, 1993 so that all the various thrusting events which occurred in March could be avoided; the data arc then spanned from April 1 through July 301993 for the Doppler and from April 26 through June 5, 1993 for range. The final design of TCM-21 (not executed) included additional Doppler data up to August 18, 1993. For post-encounter reconstructions, the data arc extended from April 1, 1993 up to January 30, 1994.

Predicting Orbit Determination Performance Before Encounter

Several covariance analyses of the encounter were performed many months in advance to predict the encounter B-plane 1-sigma uncertainties [11]. These covariance analyses provided a framework for the mission design and science teams to design their observational programs. To insure capturing the asteroid in their instruments, a mosaic of observations was taken to cover an error ellipsoid projected into the camera plane which gives a 95% (±2.448 sigma) probability of encompassing the asteroid. Table 6 lists the predicted statistics of the l-sigma error ellipsoid in Ida's B-plane coordinate frame for the designed OPNAV/TCM schedule using the recommended optical data weight of 0.125 pixel. Uncertainties are presented in B •R, B •T, and Linearized Time of Flight (TOF) for the design of TCM-20, the initial TCM-21, and updated TCM-21 design.

Table 6: Predicted Ida l-sigma B-plane encounter uncertainties

Maneuver Design	σB • R	σB • T	σTOF	Includes
TCM-20	55.7 km	39.8 km	4.3 sec	OPNAVS 1, 2
TCM-21 Initial	27.3 km	21.0 km	4.1 sec	OPNAVS 1,2, 3
TCM-21 Final	11.1 km	8.2 km	4.1 Sec	OPNAVS 1, 2, 3,4, 5

Results

Results of the encounter are presented in Earth-mean-ecliptic of 1950, Ida centered B-plane. The details of Galileo's navigation up to encounter are cited in the context of consecutively numbered orbit determination (OD) solutions, OD #68-OD #75. Post-encounter orbit reconstruction solutions, OD #77, OD #80, and OD #82 are also discussed.

Preliminary Ida Navigation

As Galileo approached Earth for its last gravity assist (Earth-2), a final Earth flyby targeting maneuver, TCM-17, was performed on November 28, 1992 to achieve an optimum trajectory to Jupiter while also targeting to Ida. TCM-17 was designed to achieve a 304 km Earth flyby altitude over the South Atlantic at precisely 8 December 1992, 15:09:25 UTC while also obtaining a preliminary Ida B-plane target of -296 km in the B • R component, 3186 km in the B • T component with an unconstrained time of encounter. Figure 3 shows Ida's B-plane diagram for the TCM-17 target aimpoint with its l-sigma ellipsoid dispersion that accounts for execution errors and orbit determination uncertainties. After passing by Earth, orbit determination solution number *68* (OD *#68)* was the first orbit solution to map Galileo's trajectory to Ida's B-plane (Figure 3). The primary purpose of OD #68, however, was to reconstruct the Earth-2 flyby trajectory. Details of the Earth-2 encounter are presented in [12]. The tracking data consisted of optimal (i.e. low noise) 2-way Doppler, and range from November 29 through December 10, 1992. Because of its primary purpose, Ida's ephemeris errors were not considered, and therefore, Ida's B-plane dispersions do not include these errors. The resultant Ida B-plane components and their corresponding uncertainties are listed in Table 7. Figure 4 shows a close-up view of OD #68 in Ida's B-plane. Since TCM-17 achieved its aimpoint at Earth with a high level of accuracy, the follow-up maneuver, TCM-18, scheduled to clean-up the errors of TCM-17 was canceled.

Shortly after the Earth-2 flyby, the decision was made to change the Ida flyby target to 2400 km distance, 75 S ecliptic latitude (darkside) on August 28, 1993, 16:51:00 (UTC-spacecraft event time). This new aimpoint with B-plane components of -621.2 km in B • R and 2318.2 in B • T is represented in Figure 3. The next maneuver, TCM- 19, would then be designed to achieve this aimpoint.

Design of the First Ida Targeting Maneuver, TCM-19

The OD #69 solution delivered on February 8 was a preliminary estimate for the design of TCM-19. To enable the OD process to take advantage of the strong radio metric signals close to Earth, the Doppler and range data included in this orbit solution spanned from December 11, 1992 through February 6, 1993. From the end of December 1992 through January 1993, five HGA warming/cooling turns were performed to allow for the HGA hammering activities which attempted to open the HGA (High Gain Antenna).[1] These turns involved either a balanced attitude turn to position the HGA away from the sun and a turn to return the HGA to the sun-pointing direction (sun acquisition). Also during this data span, three RPM thruster flushes occurred. The nominal AV'S imparted by each of these turns and RPM's were included in the trajectory and their values were estimated in the orbit solution. Ida's ephemeris errors were considered in this solution. Figure 4 shows the mapped Ida B-plane solution for OD #69.

The next solution, OD #70, was delivered February 22 for the design of the first Ida targeting maneuver, TCM-19. OD #70 incorporated the same epoch and trajectory as OD #69, but included 2-way Doppler and range data through February 22, 1993. Also during this data span an additional RPM thruster flush occurred on February 8 which displayed an anomalous S-thruster imbalance. This S-thruster anomaly was estimated to impart approximately 22 ± 3 mm/s to the spacecraft's motion. Figure 4 displays the mapped Ida B-plane results of OD #70 compared to OD'S #68 and #69. The change in the B-plane from OD #69 to OD #70 is primarily a result of this S-thruster anomaly as well as two anticipated additional unbalanced turns on July 7 and August 13. It was planned to take at least two months for the spacecraft engineering team to correct the S-thruster RPM program sequence; therefore, the errors associated with the next two S-thruster flushes were considered in the orbit solution. For this reason, the B-plane dispersion for OD #70 is larger than the previous solution. Table 7 lists the B-plane position and the corresponding dispersion.

Based on OD #70, TCM-19 was executed on March 9, 1993 with a AV of 2.12 m/s to make a change in Ida's B-plane of 19,642 km and to change time of C/A by 39 min. 46 sec. This correction to the trajectory is displayed in Figure 3 as the path of TCM- 19. An unbalanced turn was performed to bring the spacecraft to the bum attitude; then TCM- 19 was executed using the axial -Z thrusters. The TCM- 19 target and I-sigma delivery dispersion resulting from OD and execution errors are shown in Figure 5.

After TCM- 19, a new epoch was initialized on Feb 10, 1993 to avoid modeling all the various thruster activities from December through February 8. Two-way Doppler and range from Feb 10, 1993 through April 27, 1993

[1] The HGA hammering activities involved repeatedly turning on and off the HGA ball screw motor used to open the antenna while the HGA was at its coldest equilibrium temperature.

were incorporated to estimate Galileo's orbit for the OD #71 solution, delivered on April 28. In addition, one North-South (California-Australia baseline) ADOR point (weighted at 1 m) was used in this solution. To practice for the atmospheric probe delivery to Jupiter on Marc}h 10, the spacecraft's spin rate was changed from the nominal dual spin rate of 3.15 rpm to the all-spin rate of 10 rpm and then it was reduced back to the nominal dual spin rate on March 12. In addition, since each spin-up and spin-down event imparts a AV to the spacecraft, these AV'S were estimated. OD #71 also incorporated a new improved Ida ephemeris, IN2, into the orbit solution; it displaced Galileo's relative distance to Ida 320 km from its original position within the B-plane (see Table 2). Furthermore, IN2 indicated that the time of encounter was to occur 16 seconds later. Figure 5 shows the mapped Ida B-plane solution for OD #71 with its l-sigma uncertainty dispersion in relationship to the TCM-19 target. From OD #71's estimation of the AV imparted by TCM-19, it was shown that TCM-19 resulted in a *0.22%* underburn.

The Galileo Project decided in May, to delay the time of encounter by 60 2/3 seconds in order to reduce propellant expenditure during the next targeting maneuver. In addition, at the beginning of July a leap second was **added** to UTC. A decision was made to fix the target time in Ephemeris Time (ET = UTC + 60.2 sw). Therefore, the new time of encounter then became 16:51 :59.7 UTC on August 28. The final Ida ephemeris, IN3, was provided just prior to the delivery of OD #72 (July 22). OD #72 began with an epoch on April 28. The initial conditions and a constrained state covariance were derived from OD #71. This constrained state covariance was effectively equivalent to the data prior to April 28. The 2-way Doppler and range data spanned from this epoch **through** July 19, 1993. Two ADOR points, taken in the beginning of June, were evaluated in this solution. This ADOR pair consisted of an East-West (Califomia-Spain baseline) and a North-South point. The final Ida delivery, IN3, again changed the spacecraft-Ida relative position in the B-plane by nearly 1-sigma of the asteroid position uncertainty. This delivery indicated the spacecraft to be closer to the aimpoint in the **B•R direction** yet further in the **B•T** direction and time of C/A was to happen nearly one second sooner (see Table 2). The mapped B-plane results of OD #72 is shown in Figure 5. For comparison, Figure 5 demonstrates the migration of Galileo's relative flyby position to Ida using OD #71 with consecutive Ida ephemeris deliveries, IN1, IN2, and IN3.

Design of the Second Ida Targeting Maneuver, TCM-20

Just before the five picture OPNAV campaign was to begin (C/A-47 days), the spacecraft experienced a safing event caused by a Command and Data Subsystem (CDS) A-string Bus Reset. This had the effect of halting the onboard sequence, and since this event happened just prior to the shattering of OPNAV 1, the picture was lost. Subsequently, the remaining spacecraft program sequence for the Ida approach, including the remaining OPNAV images, had to be quickly regenerated, validated and uplinked to Galileo. On July 22, 1993, the second scheduled picture, 0PNAV2, shown in Figure 6, was successfully taken and eventually returned to Earth four days later.

The loss of OPNAV 1 was not detrimental to navigation, although it could have hindered the design of TCM-20, if 0PNAV2 had a systematic bias.

In order to process the [da relative information from OPNAV2, the current best solution, OD #72, was used to generate a new trajectory and partials file, then the residuals of the computed minus the observed Ida/star line and pixel values were generated by the Optical Navigation group. This optical regres file was combined with the radio metric regres file and the orbit was then estimated, The next Ida targeting maneuver, TCM-20, was then based on the orbit solution OD #73, which incorporated OPNAV2. The epoch for this arc began on April 1. The OPNAV2 image resulted in a set of eight data points which, when combined, produced an effective uncertainty of approximately 1/8 pixel (Table 8). In addition, the April North-South (California-Australia baseline) ADOR point was used in this solution. The quasar's Right Ascension (RA) and Declination (Dee) were estimated in this process with *a priori* uncertainties of 150 nanoradians. The two ADOR points obtained in June appeared to be slightly biased when they were evaluated in a prior orbit determination solution, so they were not included in OD #73. Figure 5 shows the mapped Ida B-plane solution for OD #73 compared to previous solutions OD #71 and #72. With the inclusion of 0PNAV2 into the orbit solution, Ida's ephemeris could now be estimated and therefore, the relative spacecraft-asteroid uncertainties could be reduced. This OPNAV provided enough information to lower Galileo's orbit uncertainties relative to Ma by nearly one half of the previous radio metric/ΔDOR solution (OD #72). With this additional observation of the asteroid , the results from OD #73 were used to generate an improved Ida ephemeris, 14N. The solution for Ida's position moved it 27 km from the ephemeris prediction. The change in Ida's orbit in the RTN orbit-fixed frame is listed in Table 9.

At just 17 days before encounter the spacecraft experienced another CDS A-string Bus Reset; thus, Galileo again went into safing mode. This safing event occurred just before an attitude turn to position the spacecraft for execution of TCM-20. Again a new sequence was reprogrammed, validated, and uplinked to the spacecraft. There was no time, however, to reschedule 0PNAV3 (which was lost); and the attitude turn had to be moved just prior to the execution of TCM-20. Fortunately, the attitude turn and TCM-20 maneuvers executed flawlessly 15 days before encounter. To place Galileo back on target, TCM-20 required a AV of 0.618 m/s for a change in Ida's B-plane of 785 km and change in time of C/A of 1.42 seconds. The overall TCM-20 reconstruction based on a later solution, OD #75, indicated that there was a 0.5% overburn.

At 11 days before encounter, 0PNAV4 was shuttered and returned 8 days before encounter (see Figure 6). At this point there appeared to be some inconsistencies between the OPNAV dominated solution and the solution that incorporated the three ADOR points. When the additional June orthogonal ADOR pair was added to the orbit determination process with 0PNAV2, the orbit solutions moved 80 km upwards in the B-plane from previous solutions. The residuals of the 0PNAV2 line elements were biased off substantially from zero mean.

Furthermore, when the ADOR data points were deleted in the solution, the bias in the OPNAV residuals **vanished.** This inconsistency in the data became more apparent when OPNAV4 was included in the orbit determination. A brief study was performed at this time to determine what solution was giving us the correct answer. One analysis involved incorporating three ADOR points, but relaxing the Ida a *priori* ephemeris covariance significantly, thus allowing its state to move freely. The ADOR residuals were reduced significantly with no apparent bias. The position of Ida was shown to move approximately 226 km, which was nearly 2 sigma outside its original prediction and the OPNAV residuals were biased significantly. Since [here had been such a thorough observation program performed for Ida, we believed the original Ida position to be favorable, and thus we suspected that the June ADOR points were in error. Therefore, it was decided to delete the ADOR data and rely on the spacecraft-Ida relative information given by the OPNAVS. With [his assessment (OD #74), Galileo's mapped orbit was determined to be only 20 km from the target flyby position, well within the expected l-sigma error of 84 km. Complete details of the ADOR/OPNAV discrepancy are discussed in [13].

Delivered on August 20, OD #74 solution was based on OPNAV'S #2 and #4. Six data points were extracted from 0PNAV4 effectively reducing the OPNAV data weight to 0.143 pixel (Table 8). No ADOR data were used in this solution. The solution for Ida's ephemeris, 15N, also placed it 27 km from the ephemeris prediction. The RTN changes from the last ground-based ephemeris (IN3) and their l-sigma uncertainties are listed in Table 9. The mapped B-plane position and I-sigma dispersion of Galileo's orbit determined by OD #74 is shown in Figure 7 and listed in Table 7.

Later, after careful analysis of 0PNAV4, the third data point appeared to be out of normal distribution with the other points. When this point was deleted, the orbit solution moved nearly 12 km up in the B •R direction and 4 km away from Ida in the B •T direction. The resulting B-plane was 2325.4 ± 29.2 in B •R and -624.9 km in the B •T direction with time of C/A at 16:51:59.2 UTC ± 3.95 seconds. It will be shown in the next solution with OPNAV5 that this solution is closer than OD #74 was to the actual flyby conditions.

Cancellation of the Last Ida Targeting Maneuver, TCM-21

0PNAV5 was shuttered on August 20, 8 days before encounter. As the image was being received by the DSN 70 m network, Mars Observer (MO) was preparing for orbit insertion around Mars. Then suddenly flight controllers lost contact with MO. In a desperate effort to communicate with MO, they commandeered the 70 m DSN network after only 1/4 of 0PNAV5 was received. Fortunately, five data points were extracted from the partial OPNAV 5 image (Figure 6). Orbit solution, OD #75, which included OPNAV images, #2, #4 and #5, and no ADOR data, indicated that Galileo's orbit was 10.5 km and 0.67 seconds off the target aimpoint. It should be noted that the third data point in 0PNAV4 was deleted in this solution. This solution placed Galileo's encounter at 2328.6 km in B•R, -621.8 km in B•T with time of encounter at 16:51:59.0 UTC. The solution for Ida's position placed it 32 km from the ephemeris prediction of IN3 (Table 9). The additional information gleaned from 0PNAV5 increased confidence of the decision to remove the ADOR data in the orbit determination. Figure 8 displays both the range and Doppler residuals for OD #75. Range residuals are within ± 250 m with a rms of 63 m. Doppler residuals arc within ± 18 mHz (or ± 1.2 mm/s) with a rms of 2.9 mHz (0.2 mm/s). The residuals for the camera frame line (abscissa axis) and pixel (ordinate axis) elements of the Ida OPNAV'S are also presented in Figure 8. The line and pixel residuals for Ida have near zero mean with a rms of 0.07 pixel in the pixel direction and 0.08 pixel in the line direction. The desired Ida flyby aimpoint was well inside the B-plane dispersion of 24.4 km in **B.R** and 13,9 km in the **B .T** direction (Figure 7). Galileo was headed so close to its targeted aimpoint that performing TCM-21 would not have significantly improved the encounter accuracy. Therefore, the execution ofTCM-21 was canceled. Furthermore, the Project decided to reduce any more risks by canceling the backup scan platform pointing correction, which was intended as a measure only in case TCM-21 failed to execute. Figure 7 shows the Ida B-plane results for the OD #75 solution along with the targeted aimpoint.

Close science observations of Ida began 6 hours before *C/A* with the *shattering* of rotation movies of Ida in visible and near infrared wavelengths. Within four hours before closest approach Galileo experienced a gyro rate anomaly. The effect of the gyro anomaly was to change how the scan platform positioned each Solid State Imaging (SS1) camera frame; originally, attitude information from the gyros was to be used to point each frame precisely, but without the gyro information the SS1 camera was pointed by small slews/scans referenced from its initial position. It was not known how this would affect the Ida observations, specifically the high resolution and close encounter SS1 mosaics shuttered respectively from -5.5 min to -1.3 min and from -1 min to + 1 min before closest approach. As the encounter took place, all of the Ida data was captured on the spacecraft's tape recorder. A few days later, a quick search of the information received on the tape recorder through a method known as the jailbar search revealed that the entire asteroid had been captured in 5 frames of the 30 frame high resolution mosaic (see Figure 9). Then the frames containing portions of Ida were *returned* one by one until the entire image displayed in Figure 10 was received three weeks later.

Table 7: Orbit solutions from post-Earth-2 through post-Ida (with I-sigma uncertainties)

Solution	B • R (km)	B • T (km)	TOF (Aug 28, 1993, UTC)	Comments
TARGET	**2318.2**	-621.2	**16:51:59.7**	
OD #68	**4522.4 ± 82.0**	19113.7 ± 137.6	**16:09:53.1 ± 9.91**	First OD [0 target to Ida
OD #69	**4360.8 ± 108.5**	18779.3 ± 146.3	**16:10:06.7 ± 7.78**	Preliminary OD for TCM- 19
OD #70	**4511.6 ± 393.4**	18898.0 ± 345.0	**16:11:12.8 ± 21.7**	For design of TCM-19
OD#71	**2814.7 ± 157.6**	-964.0 ± 148.4	**16:51:59.5 ± 6.14**	
OD #72	**2682.2 ± 119.6**	-1029.0 ± 108.5	**16:51:56.2 ± 5.50**	
OD #73	**2956.9 ± 83.1**	-1073.0 ± 53.4	**16:51:58.2 ± 4.32**	For design of TCM-20
OD #74	**2337.1 ± 27.0**	-619.8 ± 19.5	**16:51:59.0 ± 3.95**	
OD #75	**2328.6 ± 24.4**	-621.8 ± 13.9	**16:51:59.0 ± 3.91**	For initial design of TCM-21
OD #77	**2314.7 ± 19.5**	-624.9 ± 10.2	**16:52:04.1 ± 2.36**	Post- Encounter Reconstruction
OD #80	**2314.7 ± 17.9**	-616.6 ± 6.9	**16:52:05.0 ± 1.90**	Intermediate Reconstruction
OD #82	**2311.7 ± 1.8**	-611.45 ± 1.6	**16:52:04.6 ± 0.38**	Final Reconstruction

Post-Encounter Orbit Reconstructions

Preliminary Reconstruction: OD #77

To plan for the 1994 Ma data playback, a trajectory from a preliminary post-encounter orbit solution, OD #77 was delivered on October 5. The OD #77 solution was obtained by fitting all the OPNAV data, plus one data point (representing the center of the asteroid) taken from the high resolution image of Ida shuttered at Aug 28, 16:48:25 UTC (-3 minutes 35 seconds before the planned C/A). Additional post-encounter two-way Doppler data through September 10, 1993 was included in the data arc. Stochastic platform pointing in cone and cross-cone directions were estimated. *A priori* uncertainties for these parameters were 6 mrad in cone and 2 mrad in cross-cone. The high resolution image (Hi-Res1) was weighted at 100 pixels and all other parameters were the same as OD #75. Again the Ma ephemeris was estimated, When this additional image was included in this post-encounter reconstruction solution, it was found that the time of closest approach was 4.4 seconds later than planned. This was *greater* than the l-sigma uncertainty. Except for this time of flight error, OD #77 placed Galileo's flyby B-plane position less than *6* km from the aimpoint. Table 7 lists the OD #77 B-plane results. Figure 11 displays OD #77 solution in the Ida B-plane compared to OD #75. Ida's position, I7N, was estimated to have shifted 56 km in the radial direction and -75 km in the transverse direction. The end result of these changes was to delay the time of closest approach. Figure 12 compares the displacement and l-sigma dispersion of Ida's position as determined through OD #75 (I6N) and OD #77 (I7N) in a trajectory pole view from the final ground-based ephemeris, IN3. The pre-fit residuals of the Hi-Res1 image was -500 pixels in the pixel direction and *+300* pixels in the line direction. The post-fit residuals were 11 pixels in the pixel direction, and -10 pixels in the line direction.

Table 8: The number of data points and effective weights for each OPNAV image

OPNAV	Date Shuttered	Date Received	Data points Obtained	Effective Weight (pixels)	Comments
1	7/1 2/93	—	—	—	Lost as a result of 1st "safing"
2	7/'22/93	7/26/93	8	0.124	
3	8/12/93	—	—	—	Lost as a result of 2nd "sating"
4	8/17/93	8/20/93	6	0.143	As used for OD #74
4	8/1 7/93	8/20/93	5	0.156	Delete bad point
5	8/20/93	8/22/93	5	0.156	1/4 of image returned
Hi-Res1	8/28/93	9/30/93	1	100	High Res. Mosaic
Rot-Movie	8/28/93	5J94	1	10 Ida/ 0.25 star	
Hi-Res2	8/28/93	5/94	1	*50*	New Ma center
Enc	8/28/93	5/94	1	50	

Intermediate Reconstruction: OD #80

In an effort to utilize the additional Doppler and ADOR data obtained after the Ida encounter, another reconstruction of the flyby was computed. The primary purpose of OD #80, however, was for the design of the Jupiter targeting clean-up maneuver, TCM-22A. The data arc spanned from April 1, 1993 through January 30, 1994. In addition to the aforementioned estimated parameters, the 40 segment Jupiter targeting maneuver, TCM-22 (executed October 4- 8) was estimated as AV impulses in 5 portions. Six ADOR points were included in the data arc (four East-West points, June 7, Ott 1, Dec 18,28, and two North-South points, Dec 19, 28), The Hi-Resl Image was weighted at 100 pixels to account for center finding error. The camera pointing parameter a *priori* values were 0.1 deg. in right ascension and declination, and 2.0 degree in twist. OD #80 indicated that the time of C/A was nearly one second later than OD #77 (5.3 seconds later than planned). While the B •R component remained the same as OD #77, the B •T component moved 6 km towards the asteroid, but the B-plane position, like OD #77, was still less than 6 km from the aimpoint. Ida's position moved 76 km in the radial, -44.2 km in the transverse and 45 km in the crosstrack directions relative to IN3 (see Table 9). The post-fit residuals of the Hi-Res1 image was 35 pixels in the pixel direction, 2 pixels in line directions. The post-fit ADOR residuals showed a mean of -0.589 nanoseconds (-18 cm) and a RSS of 0.630 nanoseconds (19 cm). Figure 11 shows Galileo's Ida B-plane position and l-sigma dispersion as determined by OD #80. These numbers are also tabulated along with the time of C/A in Table 7.

Final Orbit Reconstruction: OD #82

In March 1994, the Ida science data continued to be returned to Earth. An unexpected discovery of a small satellite orbiting Ida was found in a few of these images. This discovery won't help in our determination of Galileo's orbit relative to Ida, but the determination of this moon's orbit relies on this final orbit reconstruction. A jailbar search of the close encounter mosaic (shuttered from approximately 1 minute before to 1 minute after C/A) revealed that the bright limb of the a-steroid had been captured in one of the 16 frames as shown in Figure 13. In the middle of April, we finally received the close encounter image (Eric). *In* addition, one of a series of science images that were taken earlier to record the rotation of the asteroid revealed a known bright 3.4 visual magnitude star in the constellation of Virgo. This rotation movie image (Rot-Movie), shuttered approximately –22 minutes before C/A, was equivalent to a powerful single frame, one star OPNAV image. Even if this image was weighted loosely (approximately 10 pixels), it alone would lower the Ida B • R and B • T uncertainties by nearly one magnitude. With a camera angular resolution of 10.158 microradians/pixel, and an approximate distance of 16,505 km, the weighting of the rotation image at 10 pixels constrained the l-sigma B-plane ellipsoid to 1.7 km in the B • R and B • T directions. Because of its geometry, the close encounter image captured the asteroid directly along the time of flight axis. Therefore, with the determination of the center of Ida in the encounter mosaic, the time of C/A could be estimated more accurately.

In addition to these images, the center of the asteroid had been better determined in the high resolution image (now referred to as Hi-Res2); this changed the center approximately 40 pixels from Hi-Res1 in OD'S #77 and #80. Table 11 lists the camera shutter times in UTC and the *a priori* line and pixel coordinates of Ida's center of figure for the three science images (and the star in the Rot-Movie image). The *a priori* camera pointing directions in RA, Dee, Twist are presented in Table 12. For OD #82, the orbit solution of OD #80 was used as the nominal orbit. Therefore, the optical regress file was generated using this updated trajectory. The data arc began April 1, 1993 as before. However, to include the October 1st E-W ADOR point, but avoid the TCM-22 maneuver estimation, the data arc ended October 2, 199300:00 UTC. For the rotation image, Ida was weighted at 10 pixels and the star was weighted at 0.25 pixels. The high resolution and close encounter images were both weighted at 50 pixels. *A priori* camera pointing uncertainties were 2 mrad in both cone, and crosscone, and 0.5 deg. in twist. The solution moved Galileo's encounter in Ida's B-plane approximately 6 km closer to the asteroid than indicated in OD #80; *this* resulted in the final Ida B-plane position that was I I.7 km from the aimpoint (Figure 11). The time of encounter was slightly sooner (0.4 sec) than OD #80 which ended up being 4.9 seconds later than planned. The changes to the nominal camera pointing parameters in both the right ascension, declination and cone and crosscone coordinates are listed in Table 12. Also listed in Table 12 arc the final camera pointing solutions in RA, Dec and Twist with their corresponding l-sigma uncertainties. For this RA, Dec solution, the camera pointing *a priori* uncertainties were scaled by the inverse of the cosine of the camera declination of each science image to get the proper *a priori* value in RA. The pre-fit residuals for the Rot-Movie, Hi-Res2, and Enc images were approximately -70, 110, and -120 pixels in the pixel direction, and 5,30 and 230 pixels in the line direction, respectively. The post-fit residuals shown in Figure 14 were 2.5, 0.9 and -2.5 pixels in the pixel direction, and -0.6, -1.4 and -2.8 pixels in the line direction for the Rot-Movie, Hi-Res2, and Enc images. The two ADOR residuals were biased at -1.0 nanoseconds. The combination of the rotation movie and the two encounter images reduced the l-sigma uncertainties to 1.8 km in B •R, 1.6 km in B •T directions and 0.38 seconds in time of C/A. Figure 12 compares the displacement and l-sigma dispersion of Ida's position as determined through OD #80 (I8N) and OD #82 (I9N) in a trajectory pole view from the final ground-bawl ephemeris, IN3.

The mapped B-plane coordinates for all the orbit determination solutions, OD #68 through OD #82 are included in Table 7. The number of data points extracted from each OPNAV image and the equivalent data weights of each OPNAV and science image are tabulated in Table 8. Table 9 lists the changes in Ida's estimated orbit position from the last ground-based ephemeris delivery, IN3, in the RTN frame for each OPNAV-based orbit solution, OD #73-OD #82.

Table 9: Further improvements in Ida's ephemeris through optical navigation

		Change from Last Ground-based ephemeris, IN3		
OD Solution	Delivery	*R*, Radial (km)	*T*, Alongtrack (km)	N, Crosstrack (km)
OD #73	I4N	2.43 ± 43.5	-26.9 ± 65.8	3.22 ± 78.0
OD #74	I5N	2.63 ± 42.9	-27.9 ± 51.0	-0.21 ± 78.3
OD #75	I6N	2.96 ± 42.9	-31.4 ± 49.7	0.17 ± 78.1
OD #77	I7N	55.95 ± 26.7	-75.17 ± 43.1	13.5 ± 77.3
OD #80	18N	76.02 ± 20.8	-44.24 ± 58.5*	45.18 ± 74.6
OD #82	19N	74.72 ± 9.8	-34.64 ± 36.1	66.98 ± 72.7

*The Earth ephemeris errors were considered in OD #80 which resulted in a higher transverse uncertainty

Achieved B-plane Dispersions

Table 10 exhibits the achieved l-sigma B-plane uncertainties. Because of the loss of OPNAV 1, 0PNAV3 and

3/4 of 0PNAV5, the data used to compute the actual B-plane dispersions for the design of TCM-20 and TCM-21 is different than that used in the covariance studies discussed earlier. Despite this loss of data, the actual B-plane dispersions did compare within acceptable boundaries to that of the predicted values in Table 6. The improvement in the Time of Flight (TOF) uncertainty for the design ofTCM-21 from the predicted to the actual is mainly due to the improved Ida ephemeris covariance delivered in April of 1993 (see Table 1); the results in Table 6 were based on a previously delivered Ida covariance. When OPNAV3 was canceled, it was decided to delay the data cut-off for the initial design of TCM-21 until after the reception of 0PNAV4; thus it is this reason that these uncertainties compare very well to the predicted values in Table 6. As the spacecraft approached sufficiently close to the asteroid, Galileo could measure Ida's position along the TOF axis of Ida's l-sigma error ellipsoid. Because of the spacecraft-asteroid geometry at the time the High Resolution Image was shuttered (3^m35^s before encounter), this additional 'OPNAV' had better visibility in determining the time of encounter and therefore reduced the TOF uncertainty. Shuttered at approximately 49 seconds post encounter, the close encounter image had even greater visibility into determining the time of encounter. The fortuitous rotation movie image with the star constrained the B-plane uncertainties to within ± 2 km as mentioned above.

Table 10: Achieved Ida l-sigma B-plane encounter uncertainties

Maneuver Design	σB · R	σB · T	σTOF	OPNAVs
TCM-20	83.1	53.4	4.32	2
TCM-21 Initial	27.0	19.5	3.95	2, 4
TCM-21 Final	24.4	13.9	3.91	2, 4, 5
Post-encounter Reconstructions				
Preliminary (OD #77)	19.5	10.2	2.36	all, Hi-Res1
Intermediate (OD #80)	17.9	6.9	1.90	all, Hi-Res1
Final (OD #82)	1.8	1.6	0.38	all, Rot-Movie, Hi-Res2, Enc

Table 11: *A priori* Ida center of figure, star coordinates for the encounter images

	Shuttered (UTC)	Ida Pixel	Ida Line	Star Pixel	Star Line
Rotation Movie Image	16:29:48.4	203.300	273.300	225.819	147.004
High Resolution Image	16:48:24.8	641.000	578.300	—	·
Close Encounter Image	16:52:53.4	1318.000	525.000	—	—

Table 12: Estimated camera coordinates for the Ma encounter images used in OD #82

	RA (deg)	Dec (deg)	Twist (deg)	Δcone (mrad)	Δxcone(mrad)
Rotation Movie Image*					
A priori	*193.350*	*3.810*	*75.500*		
A	0.053	-0.026	0.018	1.00 ± 0,024	-0.21 ± 0.007
Estimate	193.403 ± 0.001	3.784 ± 0.001	75.518 ± 0.50		
High Resolution Image					
A priori	*198.507*	*36.447*	37.120		
A	0.020	0.021	0.001	-0.13 ± 0,77	0.45 ± 0.79
Estimate	198.53 ± 0.05	36.47 ± 0.05	37.121 ± 0.50		
Close Encounter Image					
A priori	*336.000*	*77.300*	*250.100*		
A	-0.120	-.005	0.003	0.41 ± 1.63	0.23 ± 1.20
Estimate	335.88 ± 0.35	77.30 ± 0.09	250.103 ± 0.50		

● Science image with bright known star enabled better estimate accuracy.

Conclusions

Both the extensive ground-based and the onboard optical observation campaigns of Ida were fundamental to Galileo's successful encounter with Ida. The ground-based observation program significantly improved the knowledge of Ida's orbit prior to encounter, while Galileo's onboard optical navigation further refined Ma's orbit with respect to the spacecraft. These navigational aids provided the improvements in the relative spacecraft-asteroid uncertainties that were essential to Galileo's close observation of Ida.

With all the obstacles presented to Galileo, such as the unexpected safing events and loss of OPNAV'S during the months prior to encounter, the navigation of Galileo through encounter with Ida was fortunate. The decision to remove the June ADOR data in OD #73 was essential to the successful design of the Ida targeting maneuver, TCM-20, which executed flawlessly. And despite the loss of 3/4 of 0PNAV5, the additional information obtained from the partial 0PNAV5 image was sufficient to confirm that Galileo's flyby position with Ida was very close to the desired aimpoint. This aimpoint error predicted by OD #75 was so small that the Galileo Project canceled the final Ida targeting maneuver, TCM-21, and the nominal "no camera pointing update" plan prevailed.

Through a preliminary post-encounter reconstruction solution, OD #77, which used the high resolution image as an additional OPNAV, Galileo was determined to have actually flown even closer to the desired Ida B-plane aimpoint. The actual time of encounter, however, was more than I-sigma later than predicted. Two more science images that were received in April provided the final information to nail down the Galileo's orbit with respect to Ida. These images included the close encounter image shuttered at approximately 49 seconds after encounter and a rotation movie image taken approximately 22 minutes before encounter which had the fortuitous result of capturing a bright known star within the image. By incorporating these science images, the final orbit reconstruction (OD #82) determined that the actual flyby position was less than 12 km away from the target aimpoint, and the time of C/A was 4.9 seconds later than planned. The rotation movie image constrained the determination of the B-plane coordinate within ± 2 km and the close encounter image constrained the time of C/A within ± 0.40 seconds.

Acknowledgments

The navigation of Galileo through encounter with 243-Ida was a success because of the exceptional contributions and consultation from the Optical Navigation and Solar System Dynamics Groups. Specifically, the authors wish to thank Don Yeomans and Paul Chodas for the determination and error analysis of Ida's ephemeris through ground-based observations, Ed Riedel for his expert interpretation and analysis of the OPNAV and science images, and Bill Owen for planning the astrometric asteroid and star observations.

REFERENCES

[1] YEOMANS, D. K., CHODAS, P. W., KEESEY, M. S., and WIMBERLY, R. N., "Asteroid 243-Ida: Delivery of Final Pre-encounter Ephemeris and Partial Derivatives Files," JPL Internal Document IOM 314.10-49, July 21, 1993.

[2] OWEN, W. M., JR., and YEOMANS, D. K., "The Overlapping Plates Method Applied to CCD Observations of 243 Ma," *Astronomical Journal,* Vol. 107, No. 6, , June 1994, pp. 2295-2298.

[3] YEOMANS, D. K., CHODAS, P. W., and KEESEY,M.S., "Orbit partial derivatives and uncertainty analysis for Asteroid 243 Ida," JPL Internal Document IOM 314.6-1005, October 25, 1988.

[4] YEOMANS, D. K., "Updated Uncertainty Analysis for Asteroid 243-Ida," JPL Internal Document IOM 314.6-1466, October 9, 1992.

[51 YEOMANS, D. K., CHODAS, P. W., KEESEY, M. S., and WIMBERLY, R. N., "Orbit Update and Partial Derivatives for Asteroid 243-Ida," JPL Internal Document IOM 3 14. 10-003, October 30, 1992.

[6] YEOMANS, D. K., "Updated Uncertainty Analysis for Asteroid 243-Ida," JPL Internal Document IOM 314.6-1389, January 3, 1992.

[7] YEOMANS, D. K., CHODAS, P.W., KEESEY, M. S., and WIMBERLY, R. N., "Asteroid 243-Ida: Updates for Orbit, Partial Derivatives and Error Analysis," JPL Internal Document IOM 314.10-32, April 23, 1993.

[8] NICHOLSON, F.T, HAW, R. J., KALLEMEYN, P. H., POLLMEIER, V. M., REIDEL, J. E., and VAUGHAN, R. M., "Report on Galileo Orbit Determination for the Gaspra Encounter," JPL Internal Document IOM GLL-NAV-92-87, May 11, 1992.

[9] KALLEMEYN, P.H., HAW, R.J., NICHOLSON, F. T., MURROW, D. W., POLLMEIER, V. M., "Galileo Orbit Determination for the Venus and Earth- 1 Flybys," Paper AAS-91 -470, AAS/AIAA Astrodynarnics Conference, Durango, Colorado, August 19-22, 1991.

[10] PO'ITS, C. L., WILSON, M.G., "Maneuver Design for the Galileo VEEGA Trajectory," Paper AAS-93-566, AAS/AIAA Astrodynamics Specialist Conference, Victoria, B. C., Canada, August 16-19, 1993.

[11] ANTREASIAN, P. "Reevaluation of the Ida Encounter Uncertainties Based upon the Latest EJ-2 Time-line," JPL Internal Document IOM GLL-NAV-93-043, March 19, 1993.

[12] BHASKARAN, S., NICHOLSON, F.T, KALLEMEYN, P. H., HAW, R.J., ANTREASIAN, P. G., and GARNER, G. J., "Galileo Orbit Determination for the Earth-2 Encounter," Paper AAS-93-607, AAS/AIAA Astrodynamics Specialist Conference, Victoria, B.C., Canada August 16-19, 1993.

[13] MASE, R. A., " Examination of the Conflict Between Optical and ADOR Data at Ida Encounter," JPL Internal Document IOM GLL-NAV-93-160, December 13, 1993.

Figure Captions

Figure 1: Definition of the B-plane coordinate system

Figure 2: Sequence of spacecraft activities

Figure 3: Ida-centered B-plane for Post-TCM- 17 orbit solutions

Figure 4: Ida-centered B-plane solutions leading up to the design of TCM-19

Figure 5: Ida-centered B-plane solutions leading up to the design of TCM-2O

Figure 6: Ida optical navigation images: 0PNAV2, 0PNAV4, and OPNAV5

Figure 7: Final pre-encounter Ida-centered B-plane solutions

Figure 8: OD #75 residuals of (a) Range, (b) Doppler, (c) Ida pixel elements, and (d) Ida line elements

Figure 9: The capturing of Ida in the SS1 high resolution mosaic

Figure 10: The five frame high resolution mosaic of 243 Ida

Figure 11: Comparing post-encounter orbit reconstruction solutions

Figure 12: Trajectory view of Ida ephemeris displacements from last ground-based ephemeris

Figure 13: The capturing of Ida in the close encounter mosaic

Figure 14: OD #82 science image residuals in (a) pixel and (b) line elements

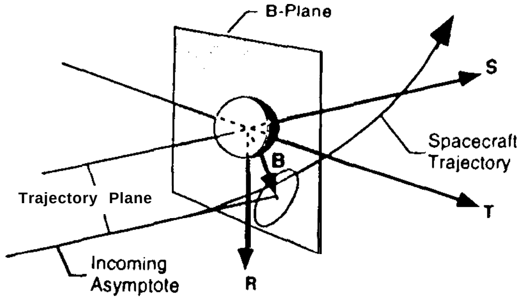


Figure 1: Definition of the B-plane coordinate system

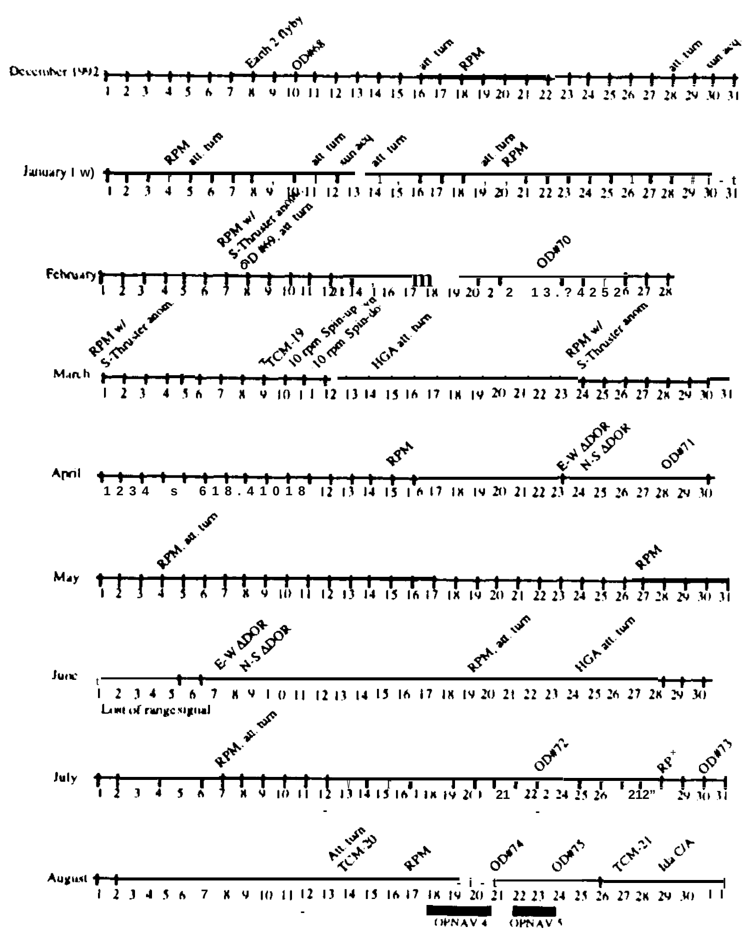


Figure 2: Sequence of spacecraft activities

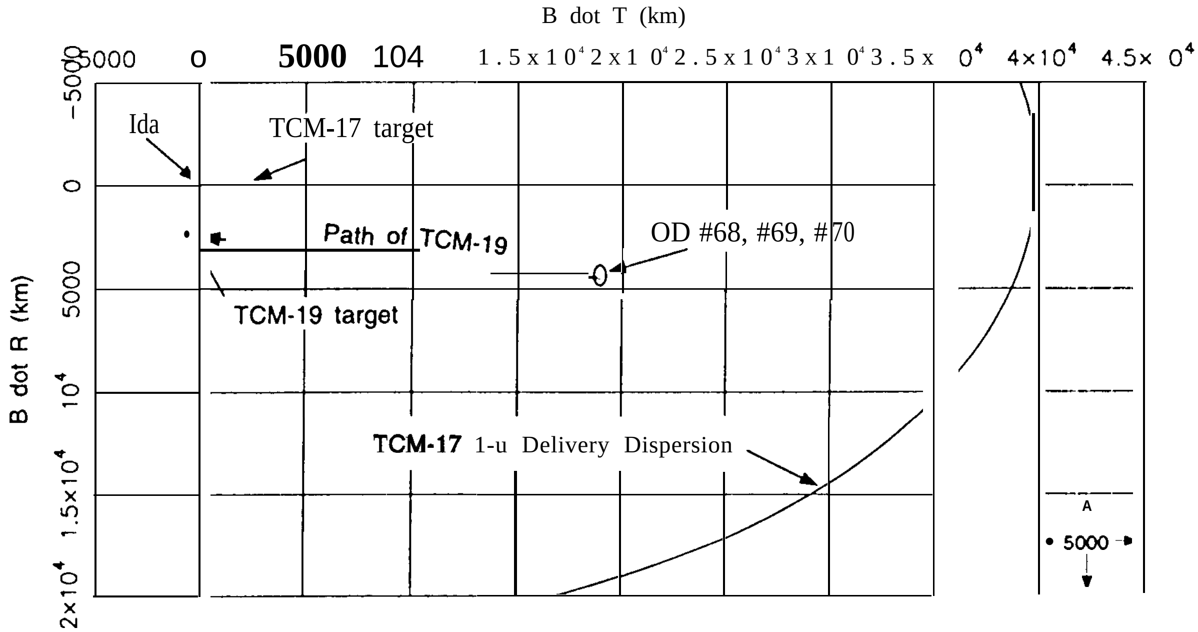


Figure 3 Ida-centered B-plane for Post-TCM- 17 orbit solutions

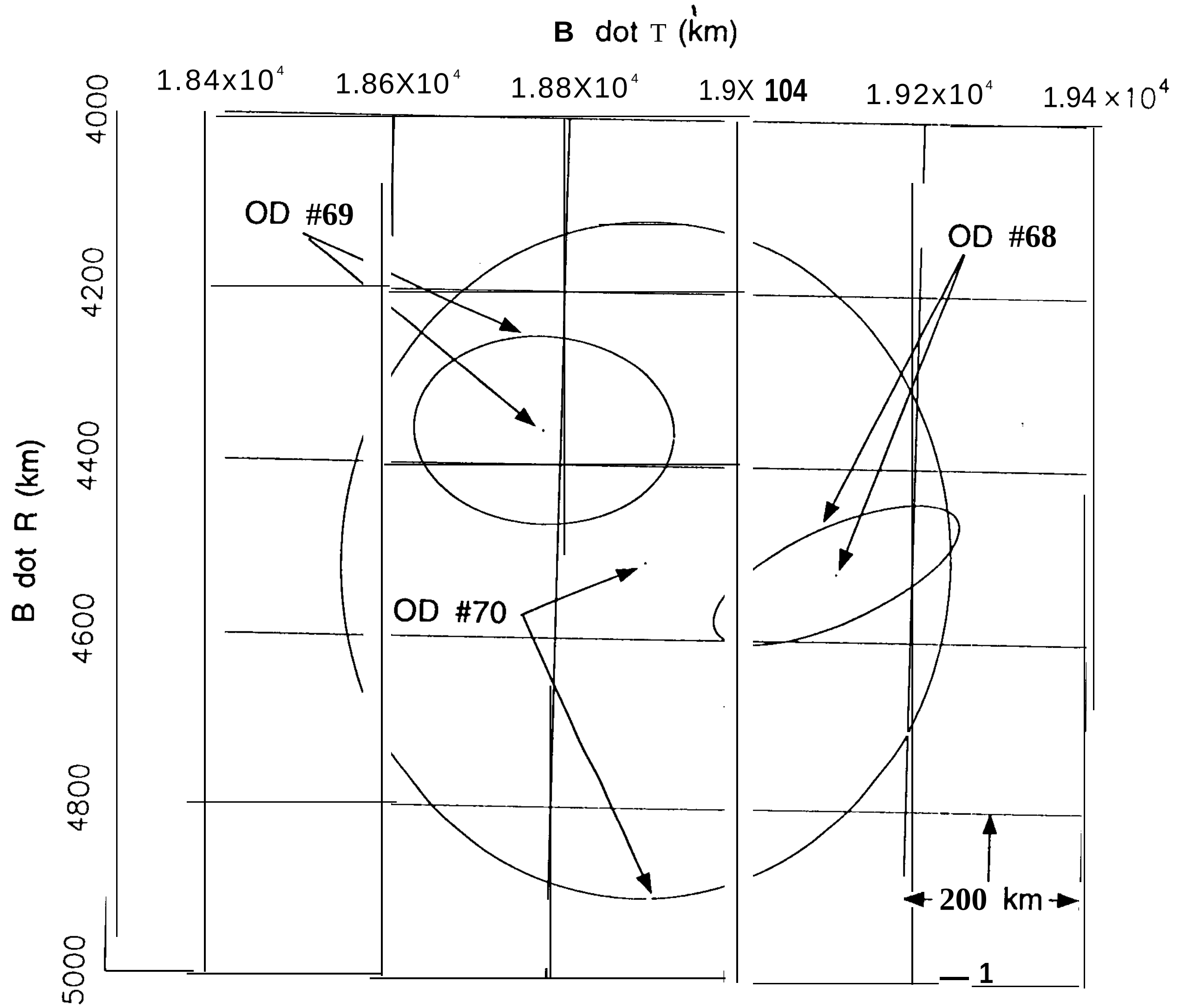


Figure 4: Ida-centered B-plane solutions leading **up to the design of** TCM-19

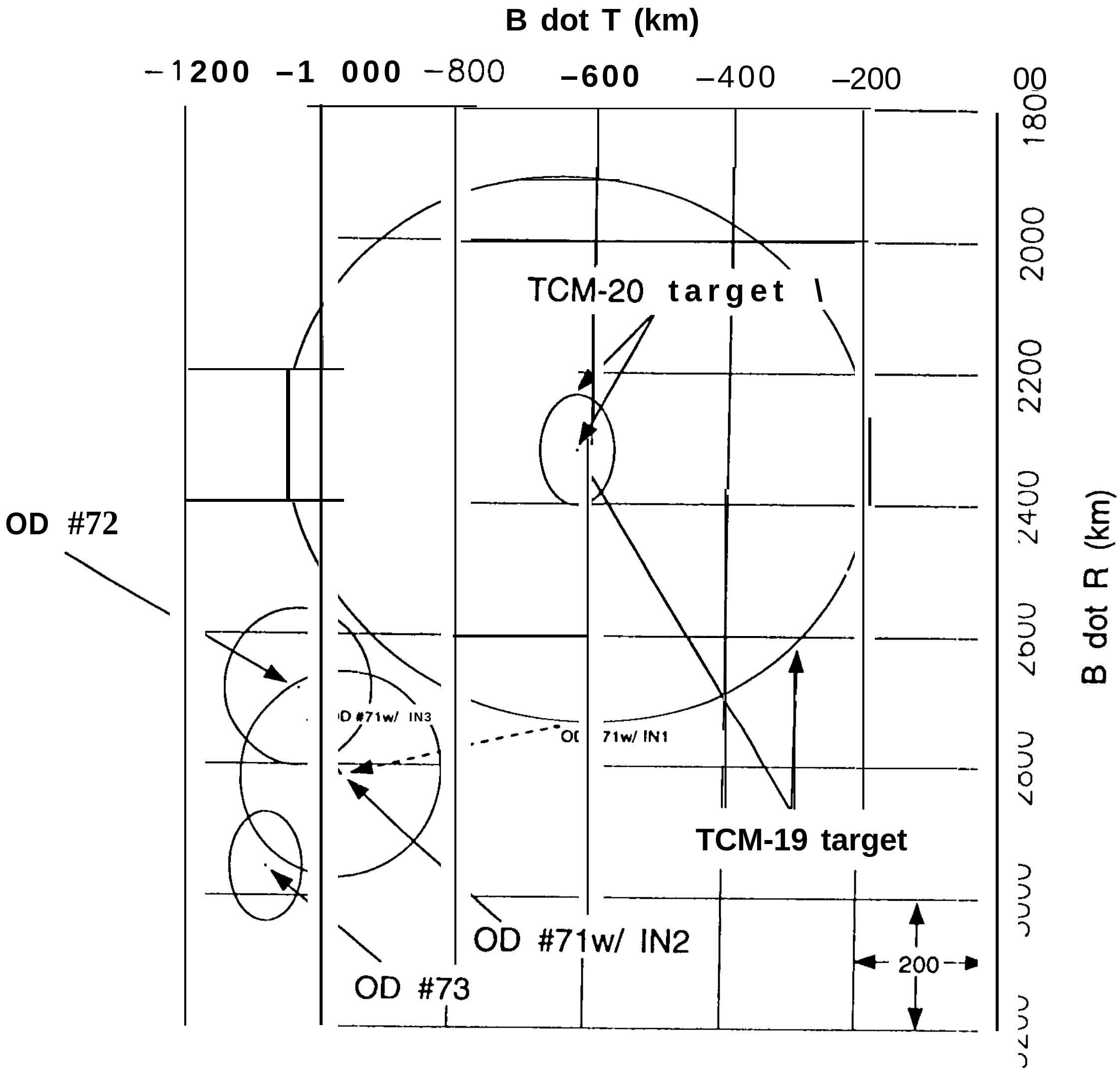


Figure 5: Ida B-plane solutions leading up to the design of TCM-20.

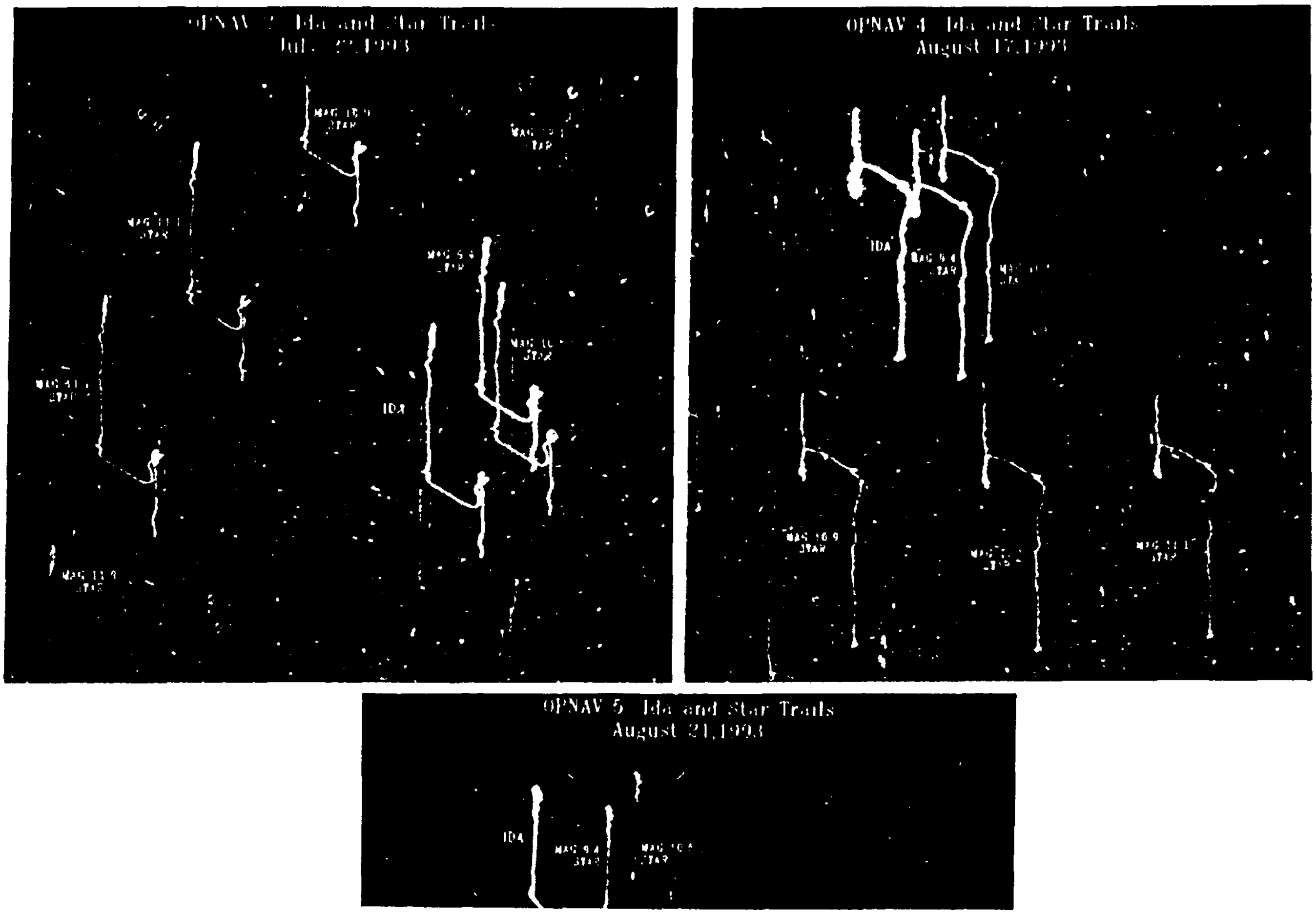


Figure 6: Ida optical navigation images: OPNAV2, 0PNAV4, and OPNAV5

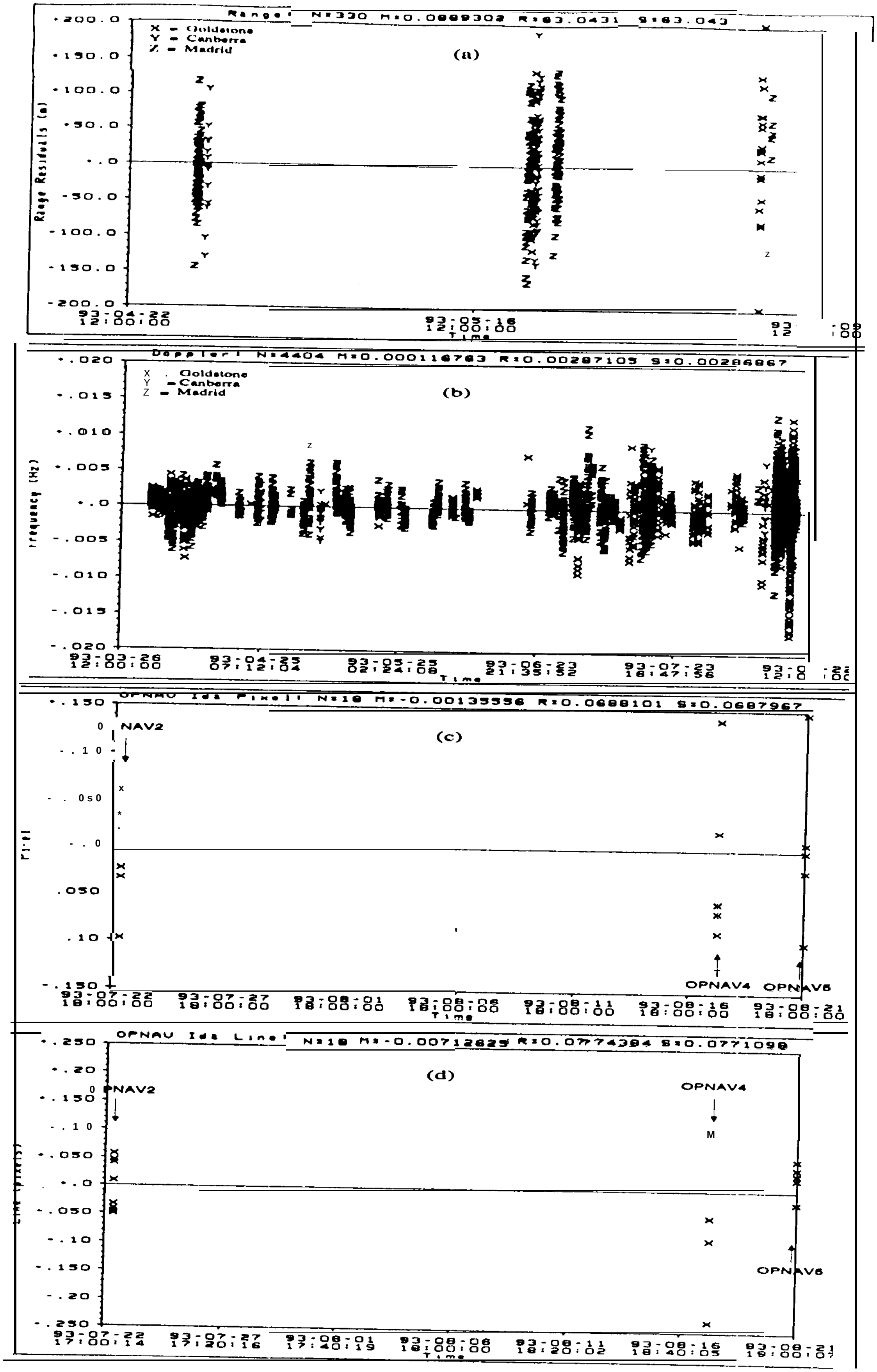


Figure 8: OD ##75 residuals of (a) Range, (b) Doppler, (c) Ida pixel elements, and (d) Ida line elements

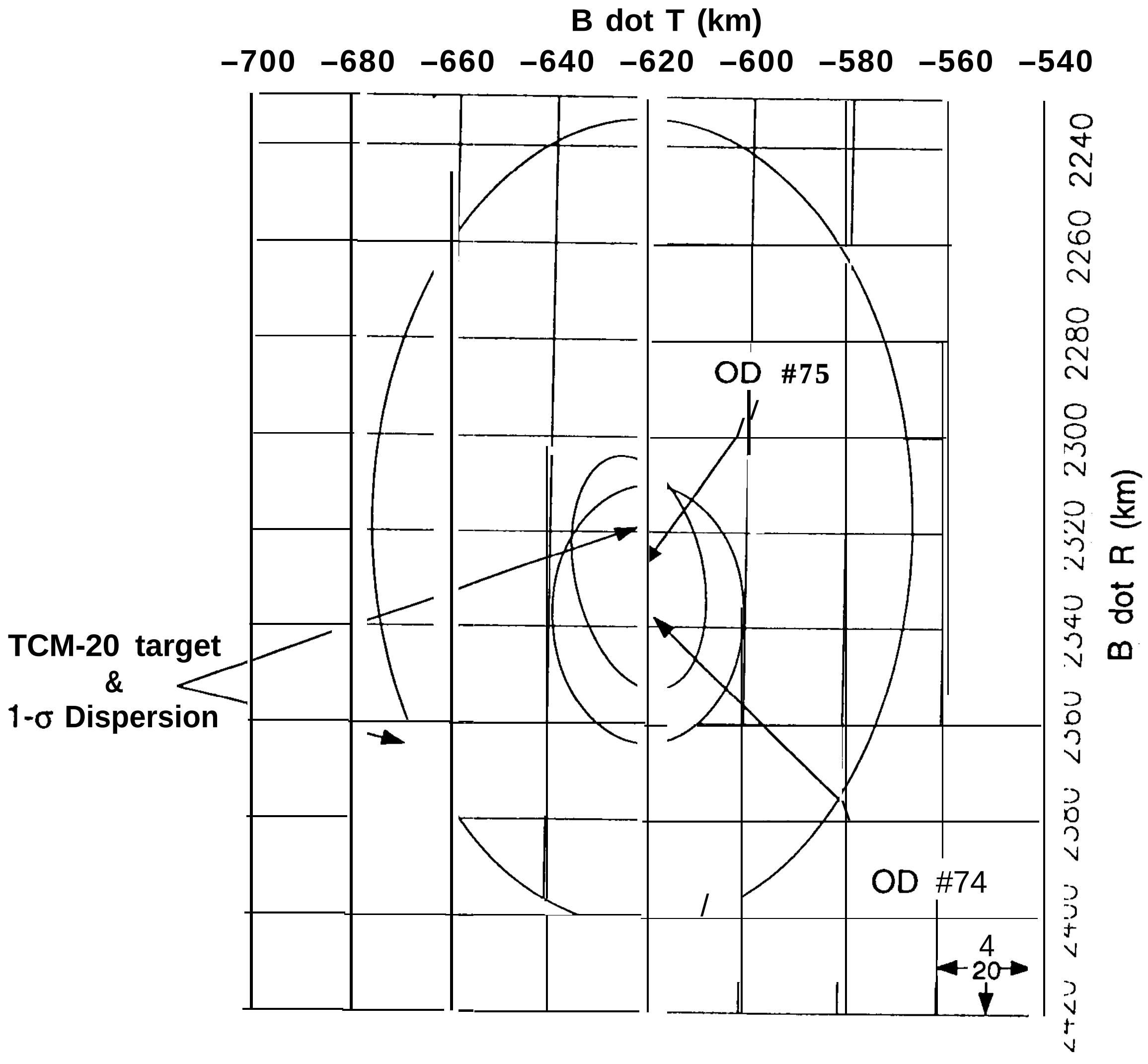


Figure 7: Final pre-encounter Ida-centered B-plane solutions

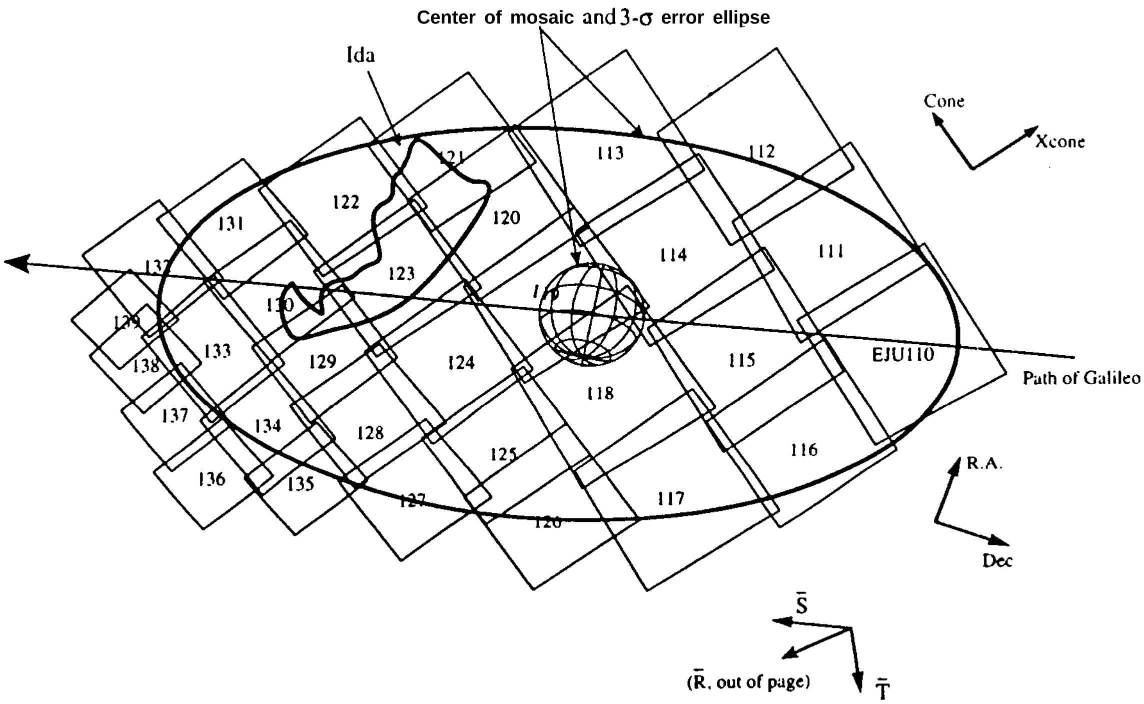


Figure 9: The capturing of Ida in the SS1 high resolution Image (30 frames)

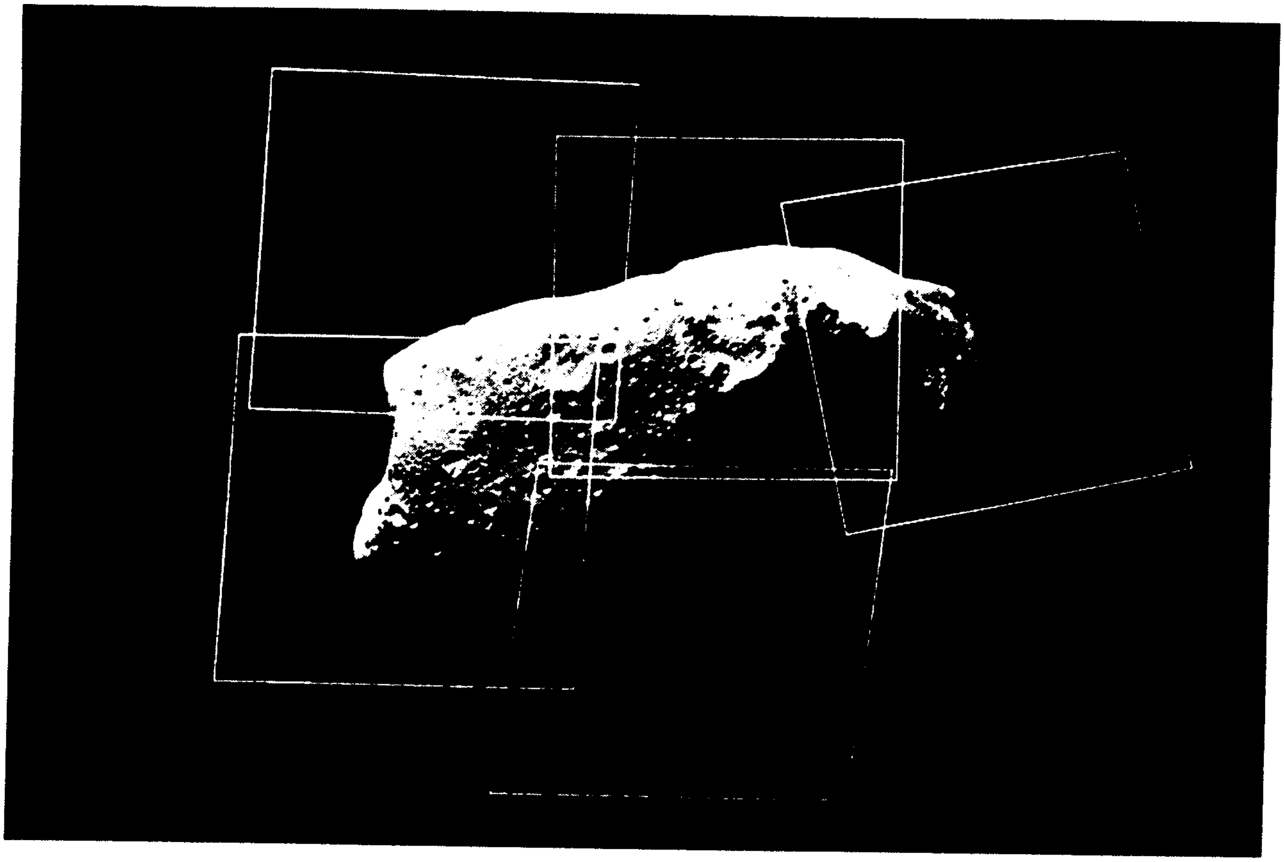


Figure 10: The five frame high resolution mosaic of 243 Ida

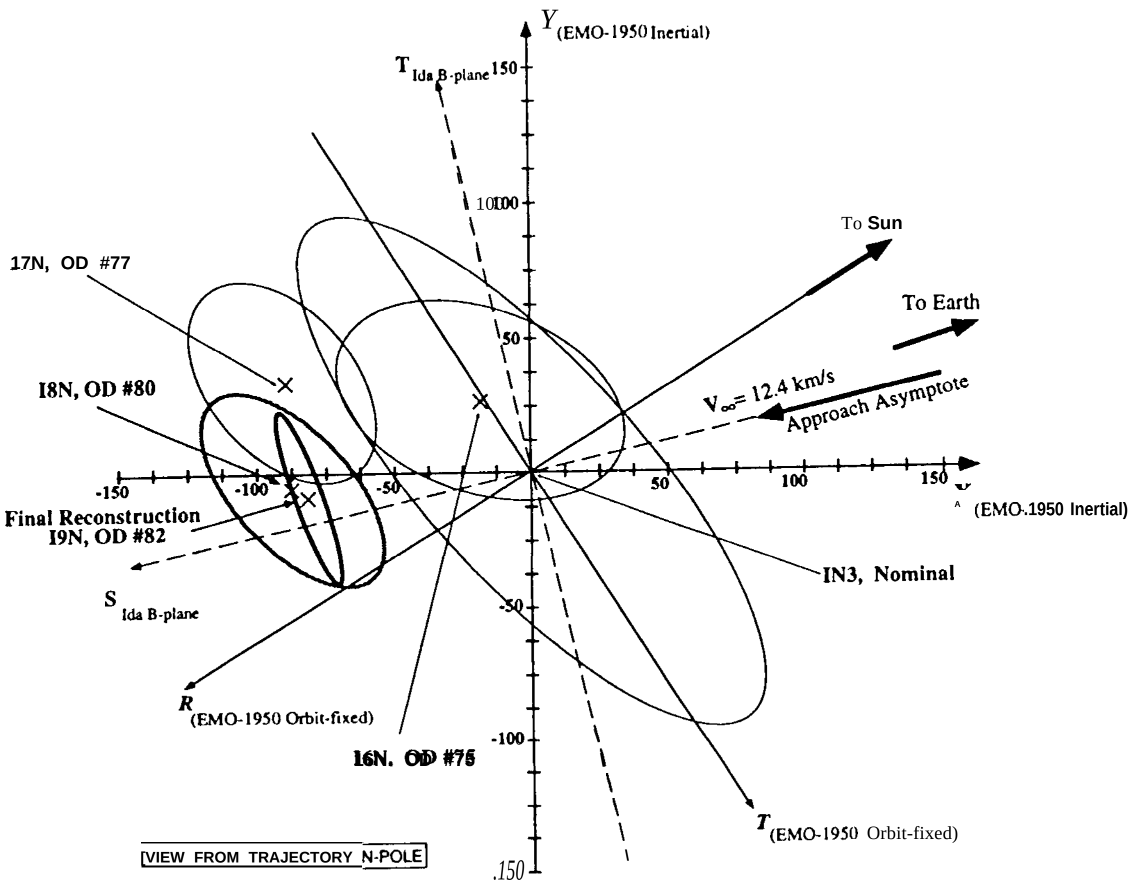


Figure 12: Trajectory view of Ida ephemeris displacements from last ground-based ephemeris

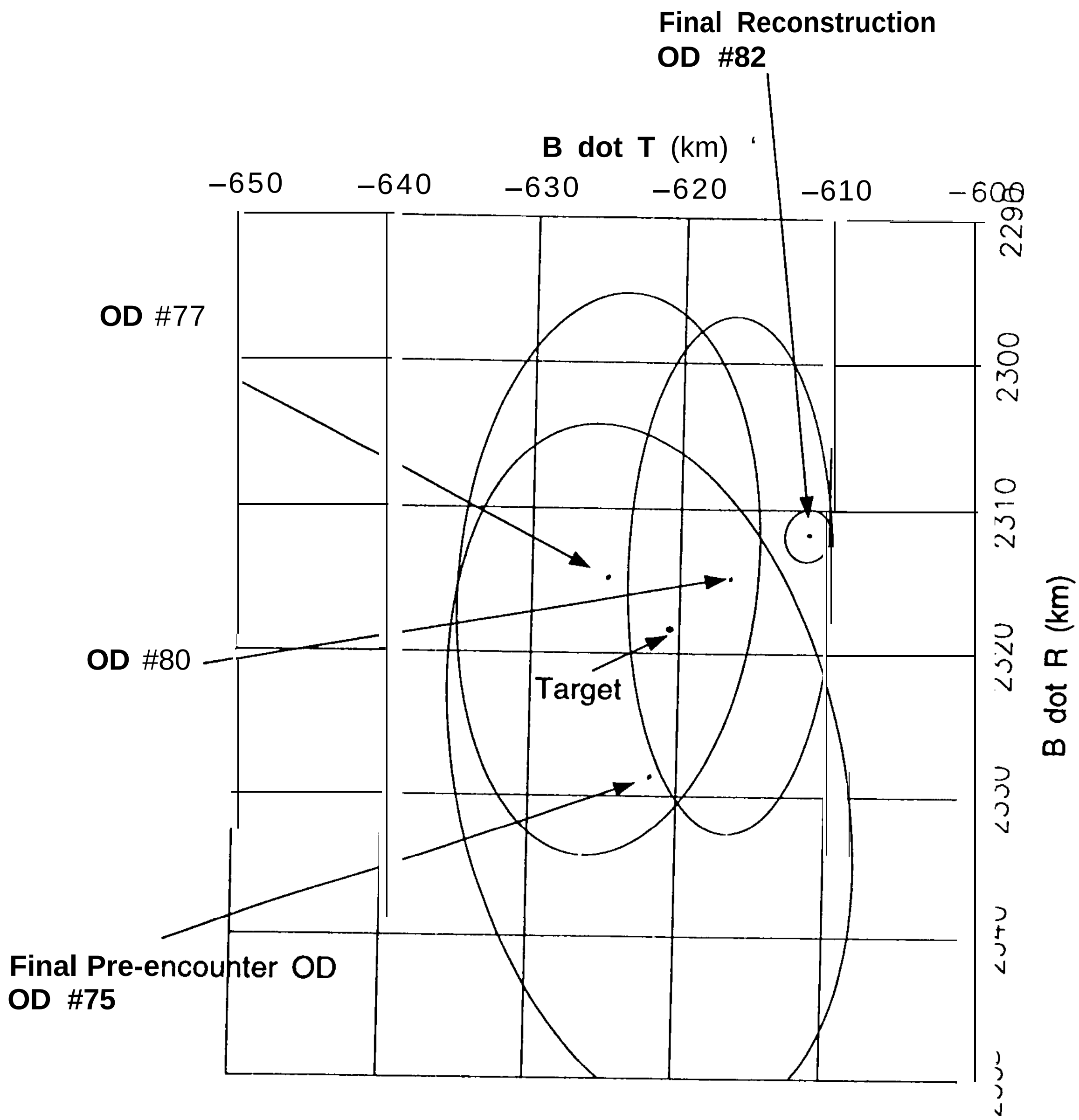


Figure 11: Comparing post-encounter orbit reconstruction solutions.

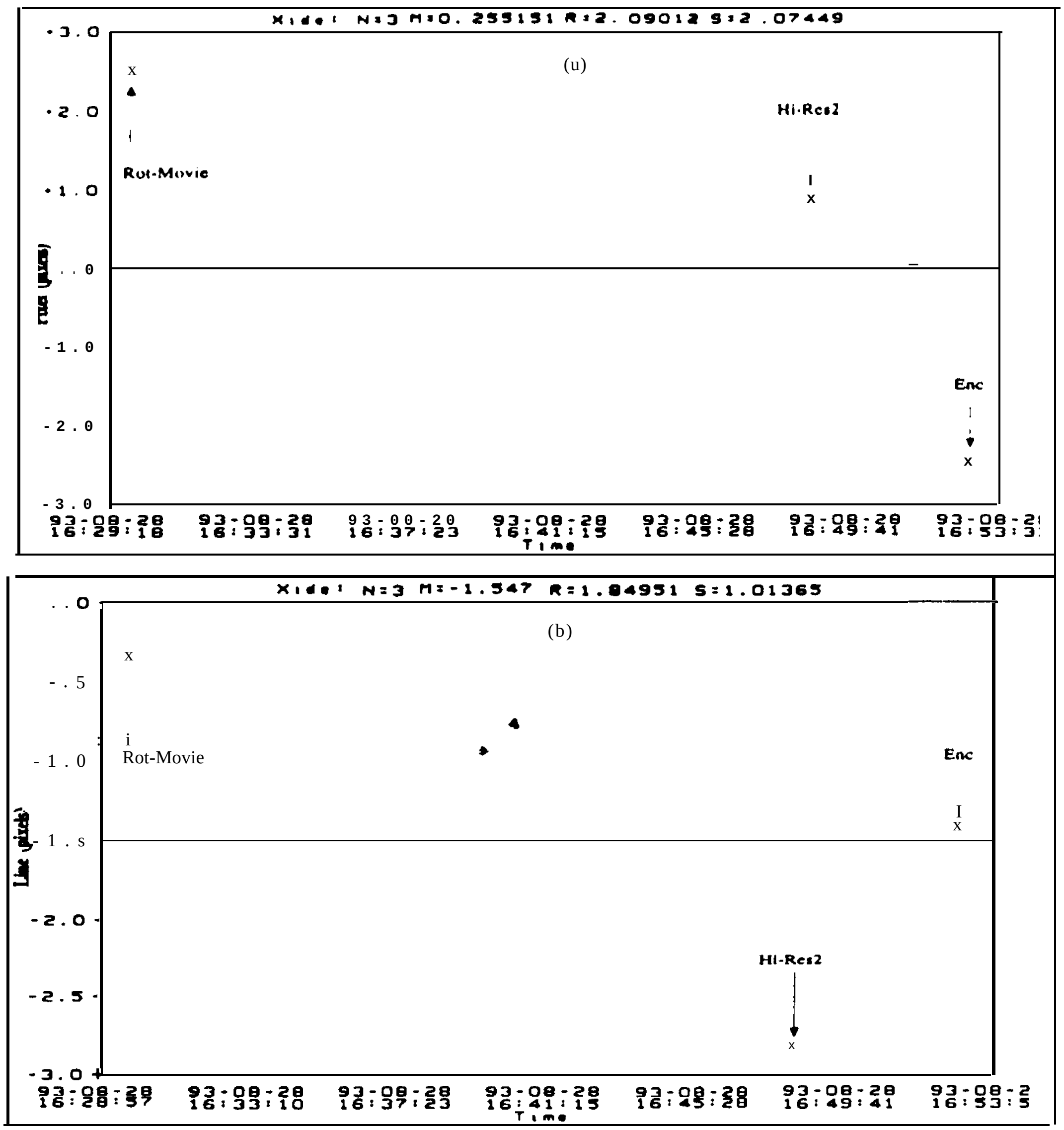
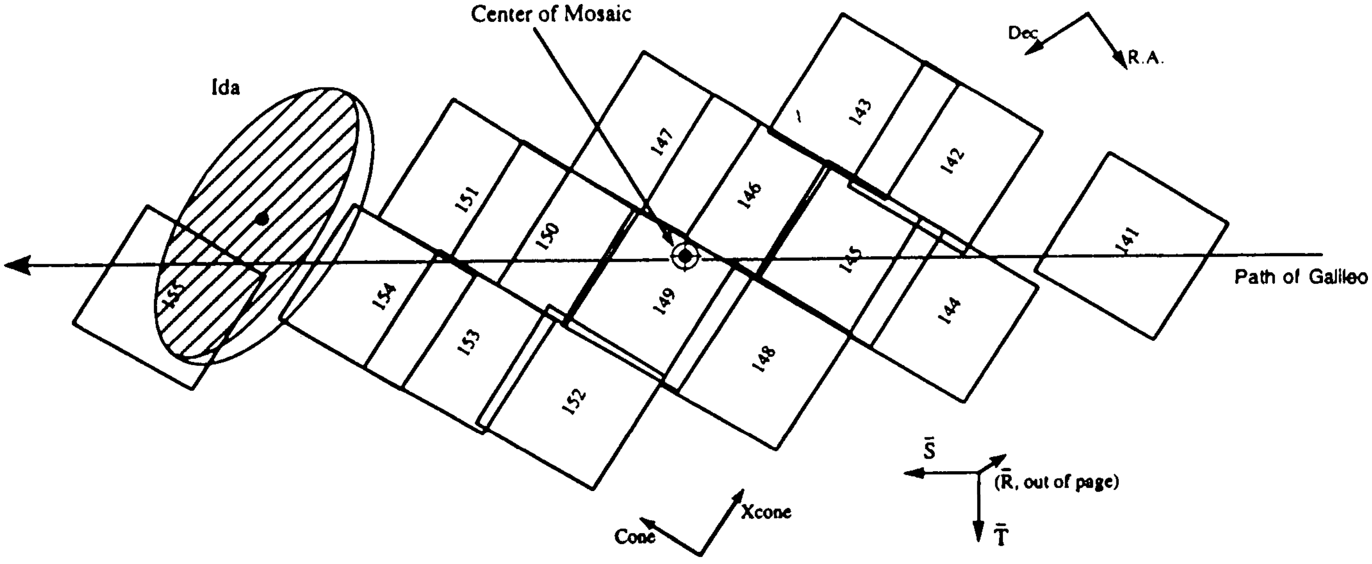


Figure 14: OD #82 science image residuals in(a) pixel and(b) line elements



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