ICE Navigation Support

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The first in-situ measurements at a comet occurred on 11 September 1985 when the International Cometary Explorer (ICE) passed through the tail of Comet Giacobini-Zinner approximately 7870 km downstream of the nucleus. Encounter took place 7 years after the spacecraft's original launch on 12 August 1978 as the International Sun Earth Explorer 3 (ISEE-3), part of a three-spacecraft project to study the interaction between the solar wind and the Earth's magnetosphere. Transfer to an interplanetary trajectory (and the name change) was performed via a 119-km-altitude, gravity-assist, lunar swingby on 22 December 1983. Navigation support during interplanetary cruise and comet encounter was provided by orbit determination utilizing radio metric data from the DSN 64-meter antennas in Goldstone, California and Madrid, Spain. Orbit solutions yielding predictions of 50-km geocentric delivery accuracy in the target aim plane were achieved during interplanetary cruise and at comet encounter using 6-to-12-week data arcs between periodic attitude-change maneuvers. One-sigma two-way range and range rate residuals were consistently 40 meters and 0.2 mm/s or better, respectively. Non-gravitational forces affected the comet's motion during late August and early September 1985 and caused a 2300-km shift in the orbit of the comet relative to the spacecraft. This necessitated a final ICE orbit trim maneuver 3 days prior to encounter. Near-real-time assessment of two-way 2-GHz (S-band) Doppler pseudo-residuals during the June and July 1985 trajectory change maneuvers aided in calibration of the spacecraft's thrusters in preparation for this final critical maneuver. Post-flight analysis indicates tail centerline passage was achieved within 10 seconds of the predicted time and geocentric position uncertainty at encounter was less than 40 km.

I. Introduction

A. Historical Overview

ICE was initially launched on 12 August 1978 as one of three spacecraft participating in a study of the interaction between the solar wind and the Earth's magnetosphere. Then known as ISEE-3, its instruments made measurements of particles and fields in the solar wind upstream of the Earth. Four years were spent in a six-month-period "halo" orbit in the vicinity of the Sun-Earth L_1 libration point located approximately 1.5×10^6 km (0.01 AU) from the Earth in the direction of the Sun along the Sun-Earth line (Refs. 1 and 2). The gravitational and centrifugal forces on an object on station at a libration point are in balance. Transfer-orbit and halo-phase geometries are illustrated in Figs. 1 and 2. Occasional station-keeping was required to maintain the halo orbit about the libration point. Although inherently unstable, this configuration eliminated problems of the intense solar radio noise background, which would have plagued tracking a spacecraft located exactly at the L_1 libration point (Fig. 3).

On 10 June 1982, a propulsive ΔV maneuver of 4.5 m/s was used to nudge ISEE-3 out of its halo orbit and onto a geocentric flight path which included excursions into the Earth's geotail. Geotail mission phase geometry is illustrated in Figs. 4 and 5. During this phase of the mission, the flight path carried ISEE-3 into the vicinity of the Moon on four occasions. Lunar swingby dates are noted at points S_1, S_2, S_3, and S_4. Lunar swingby distances varied from 11.1 to 14.2 lunar radii. Propulsive ΔV maneuvers in conjunction with lunar gravity assists during these distant flybys were used to control the motion of the line of apsides, thereby permitting ISEE-3 to spend considerable time deep in the Earth's geotail. At one point, ISEE-3 spent over 3 months in the geotail at distances in excess of 200 Earth radii (RE). The maximum geotail distance was 236.6 RE on 30 June 1983.

All the geotail phase trajectory acrobatics between June 1982 and June 1983 were merely the prelude for the final two orbits of the Earth, which culminated with a propulsive trajectory correction maneuver (TCM) in November 1983. This targeted ISEE-3 for a close trailing-edge flyby of the Moon in late December 1983 (Fig. 6). A total of 15 propulsive correction maneuvers were carried out between 10 June 1982 and 23 November 1983. Four of these were planned and 11 were subsequent small trims required to correct for maneuver execution errors. Analysis and design of the entire sequence of maneuvers is discussed in Refs. 3, 4, and 5.

Targeting for the final lunar swingby was designed to place the spacecraft on a trajectory which would encounter Comet Giacobini-Zinner (G-Z) six days after its 5 September 1985 perihelion passage. As an added bonus, this same trajectory afforded ICE the opportunity to make measurements in the solar wind upstream of Halley's Comet late in March of 1986 (Fig. 7). This would occur several weeks after Halley was to play host to an armada of five visiting European and Japanese spacecraft (Russia's Vega 1 and Vega 2, ESA's Giotto, and Japan's Sakigake and Suisei).

From initial launch, the ISEE-3 mission was supported by the Ground Spaceflight Tracking and Data Network (GSTDN) with orbit determination (OD) performed at the Goddard Space Flight Center (GSFC). At the comet encounter distance of 70.5 $\times$ 10^6 km (0.47 AU), the spacecraft was well beyond the range of GSTDN. This necessitated the total transfer of support from GSTDN to the Deep Space Network (DSN) in January 1984. During December 1983, GSFC and the Jet Propulsion Laboratory (JPL) formally carried out parallel tracking and OD support. Responsibility for maneuver analysis and design remained at GSFC for the duration of the mission.

B. Spacecraft Description

The ICE spacecraft is depicted in Fig. 8. The cylindrical, drum-shaped spacecraft is spin stabilized, with its spin axis oriented perpendicular to the ecliptic plane. The tower, extending in the direction of the north ecliptic pole, supports the medium-gain-phased array 2-GHz (S-band) antenna, which has a flat, disk-like pattern. Table 1 provides a compilation of navigation-related spacecraft characteristics.

Orbit and attitude control are provided by a system of hydrazine engines on pods mounted on the outside and bottom of the main cylinder. The system consists of 12 canted nozzles to provide radial, axial, and spin rate thrusting control. Design goals were to allow propulsive ΔV maneuvers in any direction without perturbing the spin axis orientation. Solar radiation pressure forces acting on the spacecraft did, however, result in torques which slowly altered the spacecraft's attitude. Periodic attitude change maneuvers were necessary to keep the Earth centered in the antenna beam.

C. Navigation Challenge

Navigation support for ICE has been unique in several aspects. First and foremost was the large uncertainty in the predicted September 1985 position of the target at the time of interplanetary transfer orbit insertion in December 1983. From covariance studies, uncertainty in Comet G-Z's time of perihelion passage on 5 September 1985 was perhaps 0.1 day. This represented an anticipated along-track error of approximately 3 $\times$ 10^5 km, and complicated the targeting for the critical low-altitude gravity-assist lunar swingby. This critical event occurred several months before the first ground-based optical observation even confirmed the return of the comet to the inner solar system. Secondly, covariance analysis to demonstrate the capability of a limited subnet of the DSN to meet the ICE mission navigation requirements made assumptions in regard to anticipated tracking data quality. This was done prior to any DSN experience with the generation of radio metric data in conjunction with a transponder of the type aboard the probe. Finally, with the NASA decision that responsibility for orbit determination and maneuver design be split between two agencies, there was a need for verification of dynamics modeling and trajectory propagation compatibility between JPL and GSFC.

The premission navigation covariance analysis and DSN navigation support of the lunar swingby and early interplanetary cruise are described in detail in Refs. 6, 7, and 8. Ephemeris improvement efforts at JPL (led by D. K. Yeomans) utilizing ground-based optical observations gathered by the Astrometry Network of the International Halley Watch (IHW) are described in Refs. 8 and 9.

II. Metamorphosis to Cometary Explorer

The period from July to November 1983 was used by the DSN and JPL to demonstrate orbit solution compatibility in a mission operations support environment. From 1 December 1983 through 3 January 1984, the DSN and JPL provided backup tracking and orbit determination support to GSFC. This meant that complete orbit solution turnarounds were required as often as every two days at both centers. GSFC processed the GSTDN data, while JPL solutions utilized DSN-generated data. Mission planning was thereby able to make use of two independent orbit solution results for flight path analysis in preparation for the critical 22 December 1983 close lunar swingby.

To avoid the necessity of having to model maneuvers, orbit solutions were attempted between trajectory correction or attitude change events while ISEE-3 was in high Earth orbit. Trajectory correction maneuvers calculated using either JPL or GSFC orbit solutions were essentially the same. DSN two-way radio metric tracking data from two 34-m antenna sites yielded unbiased 1-sigma residuals that were consistently 0.2 mm/s for 60-s count-time Doppler and 30 to 50 m for range.

Targeting for the critical close lunar swingby began with a trim maneuver on 10 November 1983. A small execution error resulted in prediction of a lunar impact. On 23 November 1983, this situation was corrected by a small trim maneuver at the apoapsis of the spacecraft's final orbit of the Earth. From there, it began a month-long plunge toward the Moon (Fig. 6). The subsequent interplanetary trajectory of ICE relative to the orbits of both Comet G-Z and Halley's Comet is illustrated in Fig. 7. Spacecraft heliocentric inertial velocity at the lunar swingby was on the order of 30 km/s. A velocity vector change of 1 m/s at Earth-Moon departure was capable of producing up to a 50,000-km change in the Comet G-Z closest approach distance. The parameter of most importance in determining the lunar aim point was the final flyby altitude. Maneuver analysis indicated that a closest approach 119 km above the surface was desired. Trim and attitude change maneuvers were planned for 8 December and, if necessary, as many as two later opportunities for trim maneuvers prior to perilune were included in the mission sequence of events. Orbit solutions were performed three times a week. A minimum of 4 or 5 days' data arc was required to obtain solutions with reasonable uncertainties. On 1 December 1983, DSS-63 (the 64-meter antenna in Spain) became available to occasionally provide tracking support. Having three stations prior to encounter greatly enhanced the tracking geometry. The sequence of orbit solutions following the 23 November trim maneuver suggested that the actual trajectory was so close to nominal that only the planned 8 December attitude adjustment was performed. Perilune passage occurred on 22 December 1983 at 18:45:15.2 (ET) as ISEE-3 raced past the trailing limb of the Moon at an altitude of 119.4 km. At that moment, the spacecraft's identify formally underwent the change from ISEE-3 to ICE.

The JPL navigation team's use of DSN-generated radio metric Doppler and range data predicted the radius and time of closest approach to the Moon to better than 1 km and 1 s, respectively, during mission operations support. Post-perilune solutions have further reduced uncertainties in these swingby parameters to less than 100 m and 0.1 s. Discussion, in more detail, of the close lunar swingby is provided in Reference 8.

III. Cruise Orbit Determination

After 6 January 1984, tracking and data acquisition support of ICE was limited to the DSN 64-meter subnet. However, during the first year of interplanetary cruise, only one antenna, DSS-63, was available. Beginning in mid-December 1984, occasional passes were provided by DSS-14, at Goldstone. In mid-January 1985, DSS-63 went down for modifications, leaving only DSS-14 to provide support. After June 1985, both stations supported the mission through the comet encounter.

Daily DSN two-way tracking coverage was provided from lunar swingby until 10 January 1984. Afterwards, coverage was nominally 2 passes a week. One pass provided range-rate data coverage above a 15-degree elevation angle, horizon to horizon. Approximately 10 range points were collected over a subinterval of 30 minutes. The second pass was shorter in duration, limited to elevation angles above 30°, and typically only collected Doppler data. More frequent passes were provided for 10 days after attitude change maneuvers, which occurred at approximately 3-month intervals. Orbit solutions were limited to the data arcs between maneuvers. Data weights were 100 m for range and 1 mm/s for range rate. Residuals throughout the interplanetary phase continued to be unbiased and 50 m and 0.2 mm/s, 1 sigma, for range and range rate, respectively.

Comet encounter conditions were determined relative to the then-current Comet G-Z ephemeris. Cruise orbit solutions consistently predicted a comet miss distance of approximately 62×10^3 km on the sunward side of the comet. This would be outside the anticipated cometary coma. Trajectory correction was put off until June 1985 to allow comet ephemeris improvement based on post-recovery optical observations.

IV. Comet Giacobini-Zinner Recovery

Comet G-Z, with an orbital period of 6.5 years, was first described in 1900 by Michel Giacobini at the Nice Observatory in France. The comet was rediscovered in 1913 by Ernst Zinner at the Remeis Observatory in Bamberg, Germany. Its orbit is inclined at 32° to the ecliptic plane and varies from perihelion near the orbit of the Earth to aphelion between the orbits of Jupiter and Saturn. Early 1984 marked the eleventh opportunity for recorded Earth-based observation of the comet. The ICE encounter with Comet G-Z was planned at the nodal crossing of the ecliptic at a heliocentric distance of 1.03 AU six days after Comet G-Z's perihelion passage.

To effect an early telescopic recovery of the comet in 1984, an orbit and search ephemeris was computed based on astrometric observations from the three previous Comet G-Z apparitions in 1965, 1972, and 1979. The ephemeris was then distributed to observatories capable of observing objects with the extremely faint predicted magnitude of approximately 23.

An observing team using the 4-m aperture telescope at Kitt Peak National Observatory near Tucson, Arizona successfully recovered the comet on 3 April 1984. Confirmation (pre-recovery) images were then quickly reported from plates recorded 28 January 1984 at the European Southern Observatory in La Silla, Chile and for 28 March 1984 (again at Kitt Peak). When the recovery observations were included in an orbital solution update, the required correction to the predicted perihelion passage time was only +0.01 day.

By means of precise ephemerides from the Astrometry Network of the IHW, Comets Halley and Giacobini-Zinner were both recovered very close to their predicted positions. Both the successful recovery of Comet Halley on 16 October 1982 at Mt. Palomar and the Comet G-Z recovery on 3 April 1984 at Kitt Peak were made when the comets were far fainter than magnitude 23, making these two cometary recoveries the faintest on record. Conditions remained favorable for ground-based observations through August 1984 and again beginning early 1985. A total of 1031 observations were processed. They represented 72 observatories in 21 countries.

V. Comet Encounter

A. Homing In

With the availability of updated comet orbit solutions incorporating post-recovery observation data, the ICE/G-Z radius of closest approach remained about 62.5×10^3 km on the sunward side of the nucleus. As confidence in the comet's orbit increased in the spring of 1985, conditions became favorable for a TCM to move the ICE aim point into the tail. By May 1985, the predicted 11 September position uncertainties were on the order of 1000 km for Comet G-Z and 50 km for ICE. On 5 June 1985, a ΔV of 39 m/s altered the trajectory. This moved the encounter to a point about 17.8×10^3 km from the comet on the anti-Sun side of the nucleus.

By the first week in July, formal uncertainty in the predicted 11 September ICE aim point (based on a 4-week data arc) was about 100 km, but solution stability and small residuals provided the confidence for a go-ahead on 9 July with a 1.25 m/s ΔV orbit trim maneuver. The purpose was to reduce the flyby distance to 10,000 km and get the trajectory on course for passage through the center of an aberrated tail. Tail aberration results from the comet's motion through the solar wind, which is flowing radially outward from a rotating Sun. The tail was modeled to lag the Sun-comet line by 5.4° and lie 0.1° above the comet orbit plane.

Post-trim orbit solutions indicated aberrated tail passage would be at a nucleus distance of about 9880 km and less than 100 km off the tail centerline. With perhaps as much as a 1000-km uncertainty in Comet G-Z's predicted position and only an intelligent guess for the tail aberration angle, the ICE Flight Dynamics Director, R. W. Farquhar, kept a watchful eye on Comet G-Z's ephemeris updates.

B. The Comet Burps

Observations which became available the last week of August indicated that non-gravitational forces were having an effect on Comet G-Z's motion. These forces may have been the result of explosive gas jetting due to the boiling off of volatiles within the icy nucleus as the comet approached its 5 September 1985 perihelion.

Orbit solutions for ICE from 20 August onward provided geocentric position uncertainty in the target aim plane (B-plane) under 50 km (Fig. 9). These statistics included conservative consideration of station location errors and a 10-percent error in the coefficient of reflectivity. However, updated comet ephemerides began to indicate a change in the predicted comet relative aim point. The encounter point on 11 September seemed to jump 2300 km to a point 7830 km downstream of the nucleus and over 600 km ahead of the aberrated tail axis. This effect is illustrated in Fig. 10.

C. The Final Trim

A decision now had to be made in regard to the final trajectory correction maneuver, planned for 8 September. Two mission requirements controlled trajectory design: that ICE intercept the tail centerline 10,000 km downstream from the nucleus, and that encounter occur at 11:00 UTC. The scientific rationale for the first requirement is discussed in Ref. 9. The second requirement placed encounter near the time of ICE meridian passage at the 305-m Arecibo Radio Astronomy Observatory in Puerto Rico (Ref. 10). The project decided to leave the encounter distance unchanged and risk encountering the comet within 8,000 km of the nucleus. A small propulsive ΔV of 2.34 m/s was implemented to retarget for tail centerline passage. ICE was now on course for its historic encounter deep within the comet's visible coma at a point hidden from the view of Earth-based observers.

D. Bullseye Confirmed

The final ICE orbit solutions before 8 September 1983 coupled with the nominal a priori final trim ΔV predicted tail center closest approach on 11 September at approximately 11:02:24 UTC. This agrees closely with the latest orbit solutions in conjunction with the final definitive Comet G-Z ephemeris based on observations through 26 September 1985, which yielded an encounter time of 11:02:22 UTC at an encounter distance of 7870 km.

If modeled as a 1-km radius sphere with a density equal to water ice, the mass of Comet G-Z is less than 10^{-12} that of the Earth. Hence, the ICE flyby caused no detectable Doppler shift in the two-way 2-GHz (S-band) radio metric tracking data. The principal signature for determination of the actual closest approach would come from magnetometer detection of spacecraft passage through the comet's neutral (or plasma) sheet. This is illustrated in Fig. 11 and discussed in Ref. 9. The X-Y plane lies in the plane of the comet's orbit.

The vector helium magnetometer aboard ICE reported entrance and exit from the magnetotail at 10:59:40 UTC and 11:07:40 UTC, respectively (Ref. 11). This implies a centerline closest approach of 11:03:40 UTC, assuming symmetry and no wagging of the tail. However, Fig. 12 (Ref. 11) illustrates the magnetic field observations obtained during the comet tail traverse. Centerline passage is indicated by the sign reversal of the X-component of the magnetic field at approximately 11:02:30 UTC. The 70-second difference between tail centerline crossings defined by tail entry and exit times and plasma sheet passage can be explained by motion of the tail during the traverse. Such motion is supported by the magnetometer and other instrument measurements during the encounter.

Plasma sheet orientation is dictated by the external interplanetary magnetic field. The ICE experiment measurements now indicate spacecraft passage through the sheet at an incidence angle of 30°. The plasma sheet is believed to participate with any motion of the ion tail. Hence, there may have been some degree of luck in the close agreement of the time of plasma sheet centerline passage determined from orbit solutions for ICE and for Comet G-Z with that determined from magnetometer measurements.

E. Postmortem

At encounter, the spacecraft's velocity relative to the comet was 21 km/s. The 8-minute transit time through the tail implies a magnetotail diameter on the order of 10^4 km. Within the magnetotail was a plasma sheet approximately 10^3 km in thickness. The tail itself was enclosed in an extended coma at least 10^5 k in radius.

Figures 13 and 14 illustrate the post-encounter reconstruction of Comet G-Z's tail passage geometry. Tail centerline passage is indicated at about 11:02:25 UTC, several seconds after closest approach. This differs by 5 seconds from the centerline passage time cited above on the basis of a magnetic field reversed detection and 3 seconds from the final pre-encounter predictions.

Analysis of ICE's orbit solutions after 8 September provides confidence that the spacecraft geocentric position uncertainty at encounter was less than 40 km. In comparison, the geocentric Comet G-Z position uncertainty at the same time was about 400 km. Discussions with investigators associated with the magnetometer give confidence that the time of tail-centerline plasma-sheet passage, based on instrument measurements, and the joint spacecraft/comet orbit determinations agree to better than 10 seconds.

VI. Maneuver Support

The 2-GHz (S-band) two-way range and range rate residuals from ICE orbit solutions throughout the mission were comparable to those of other deep space missions supported by the DSN. Residuals from the 12-week data arc used for the definitive encounter orbit solution (9 September through 9 November 1985) were typical of all data arcs during the interplanetary phase of the mission. These are displayed in Figs. 15 and 16. The standard deviation of range rate residuals was consistently 0.2 mm/s for 600-second Doppler count times. Maximum range rate residual amplitudes were always less than 0.7 mm/s.

The ICE orbit inclination to the ecliptic is approximately 0.5° and the spacecraft spin axis is maintained nearly normal to the ecliptic. Therefore, out-of-plane and in-plane orbit corrections were provided by combinations of continuous axial thruster burns and pulsed radial thruster burns, respectively. Pulse sector widths could be varied in the radial burn mode. Individual radial burn pulses imparted a velocity change of 7 mm/s.

Real-time monitoring of the range rate pseudo-residuals (observed minus calculated predicted measurements derived from an earlier orbit solution) allowed resolution of the line-of-sight component of maneuver-induced velocity changes to the sub-mm/s level. Near-real-time evaluation by this technique of the TCM performed on 5 June 1985 indicated "hot" burns, which agreed closely with the later non-real-time maneuver evaluation at the Goddard Flight Dynamics Facility (FDF). During the 9 July 1985 trim maneuver, the number of pulses in the final radial mode burn was altered based on the observed line-of-sight velocity changes. Non-real-time maneuver evaluation again confirmed the validity of the technique. The June and July maneuver evaluations both indicated "hot" burns. Enough data was now in hand to perform a recalibration of the thrusters in preparation for the final 8 September trim maneuver.

Real-time monitoring of the pseudo-residuals during the final trim indicated a maneuver execution error at approximately a 0.7-percent level. A change of 2 in the planned total of 287 pulses for the final radial burn was indicated, but not implemented in light of both the effort required to alter the command sequence and the uncertainty in the comet ephemeris. More discussion of the JPL/GSFC interaction in regard to the June, July, and September orbit adjustment maneuvers is contained in Section 3 of Ref. 12.

VII. What's Next?

A 1.2-m/s radial ΔV implemented on 27 February 1986 and a 38.5-m/s axial ΔV executed on 7 April 1986 are part of the long-range plan to allow ICE to return to the vicinity of the Earth in the year 2014. The orbit of ICE from April 1986 through August 2014 is illustrated in Fig. 17 relative to a fixed Sun-Earth line. Numerical integration of the current ICE orbit indicates approach to both the Earth and Moon at about 5×10^5 km on 10 August 2014. When ICE is in the vicinity of solar opposition during 1998-1999, the spacecraft will appear to be within 2.5° of the Sun (10 solar radii) during a 14-month period from September 1998 to October 1999. If link margins are adequate and the s/c remains healthy during this time frame, the opportunity may exist for radio science investigations of the solar corona.

ICE may perform another mission if the spacecraft survives until 2 days short of its 36th birthday. Through 7 April 1986, the ICE spacecraft had performed a total of 106 separate propulsive trajectory, attitude, and spin-rate change maneuvers. Of the original 89 kg of hydrazine onboard at launch, 29 kg remain available. A propulsive ΔV in conjunction with another close lunar swingby could achieve recapture into Earth orbit. On the assumption that passage through the Comet G-Z coma and tail subjected ICE's surface to a bombardment of dust and ions, it is conceivable that NASA may have a candidate for a low-cost sample-return mission.

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Table 1. Spacecraft Characteristics

Feature	Description/value/resolution
Bus shape	16-sided cylindrical drum
Bus height	1.58 m
Bus diameter	1.77 m
Mass	479 kg at launch
	Experiments = 104 kg
	Hydrazine = 89 kg = 430 m/s ΔV
Antennas	
Radial (4)	92 m end to end
Axial (2)	14 m end to end
Solar array	2 bands around cylinder
	182 W at 82 V (at launch)
Spin rate (Sun) sensor (2)	$\pm 1.0°$ (nominal rate = 19.75 ± 0.2 rpm)
Attitude sensor	$\pm 0.25°$ (0.1° with 4-week data arc)
Hydrazine thrusters (12)	1.1 N
Transponders (2)	2-GHz (S-band) for tracking, telemetry, and command

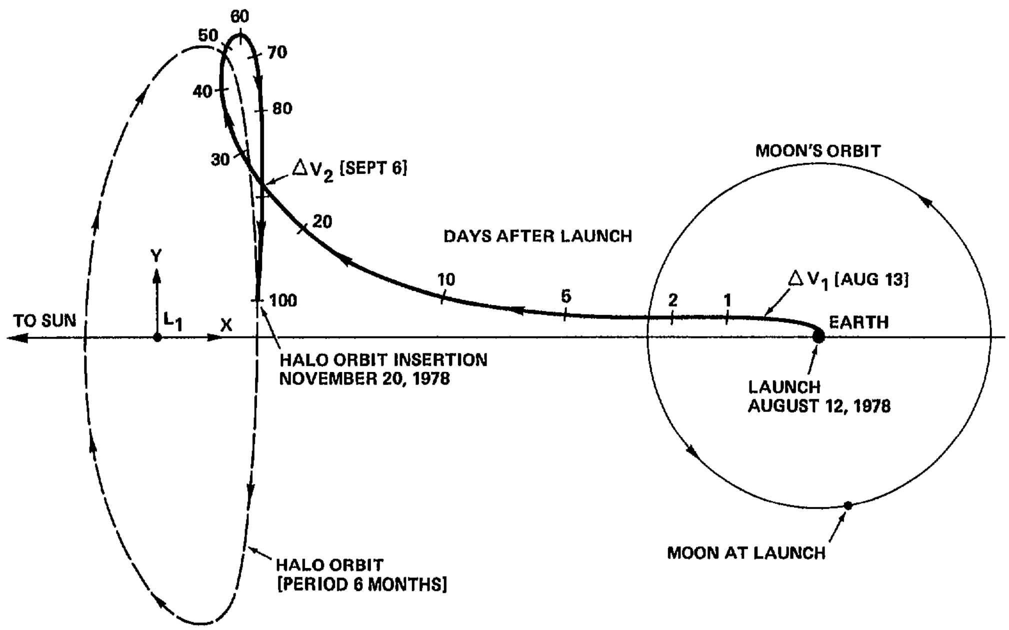


Fig. 1. Transfer trajectory to halo orbit relative to fixed Sun–Earth line

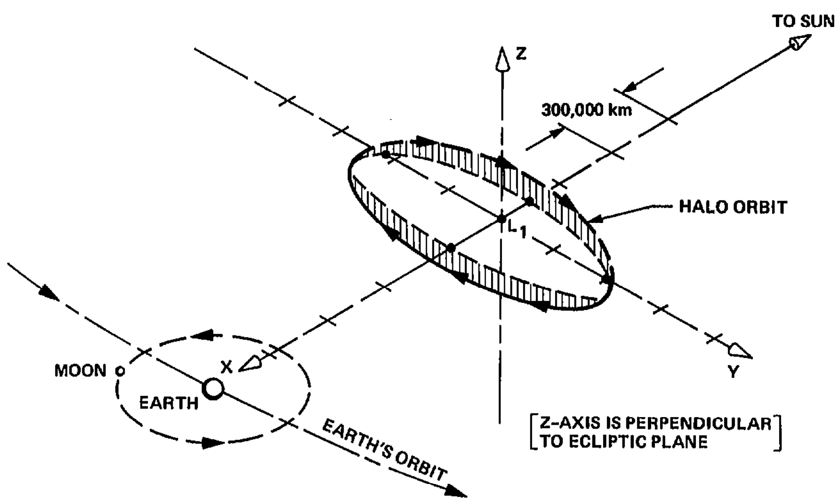


Fig. 2. Halo orbit around the Sun–Earth L_1, libration point

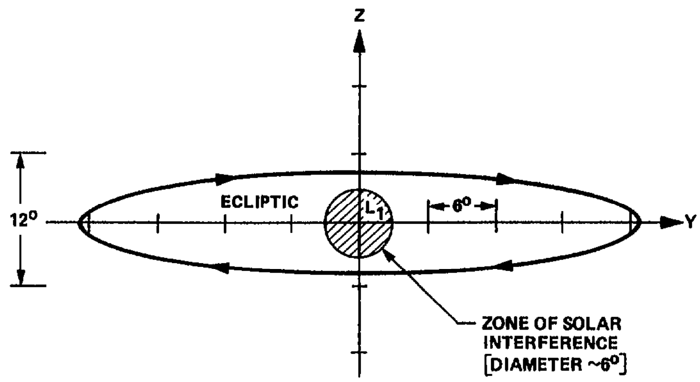


Fig. 3. Halo orbit as seen from Earth

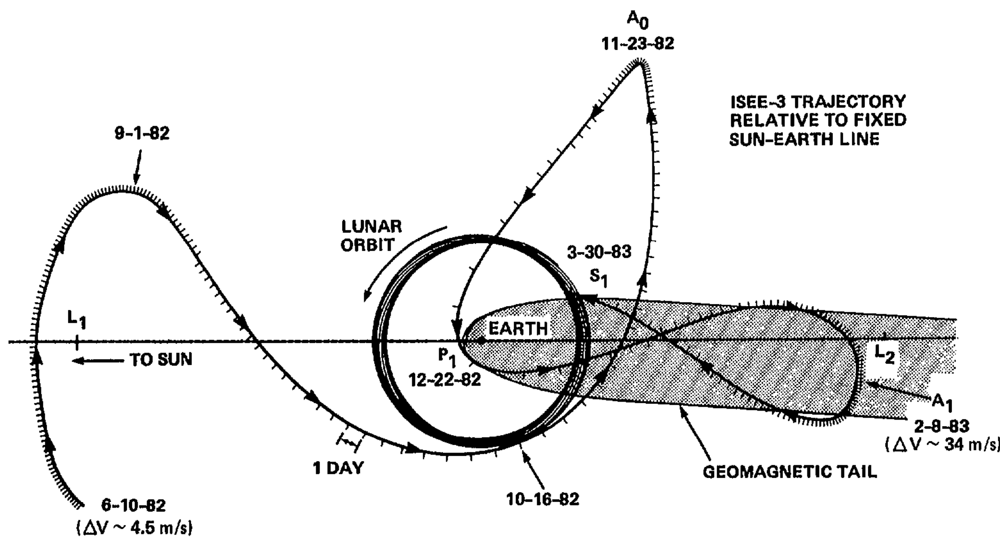


Fig. 4. Transfer from L_1 halo orbit to geomagnetic tail relative to fixed Sun–Earth line

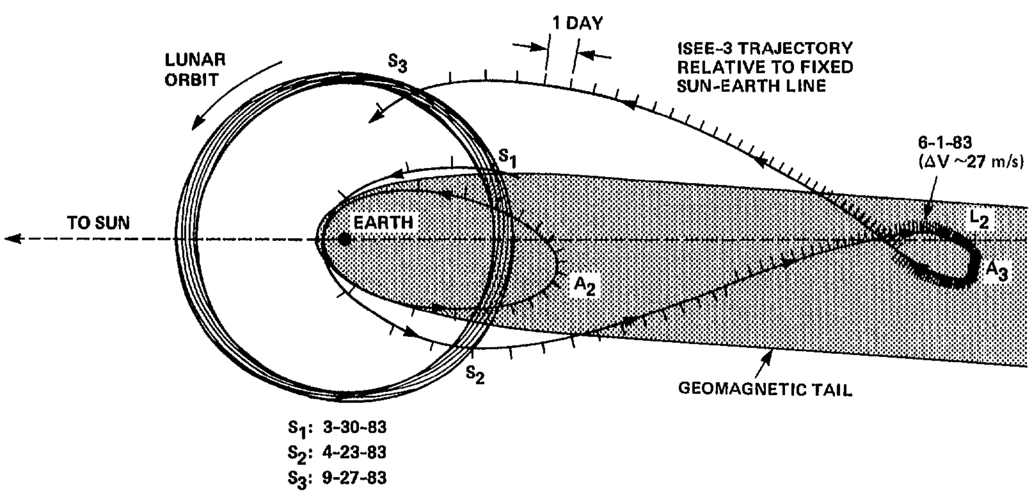


Fig. 5. Five-month geotail excursion relative to fixed Sun–Earth line

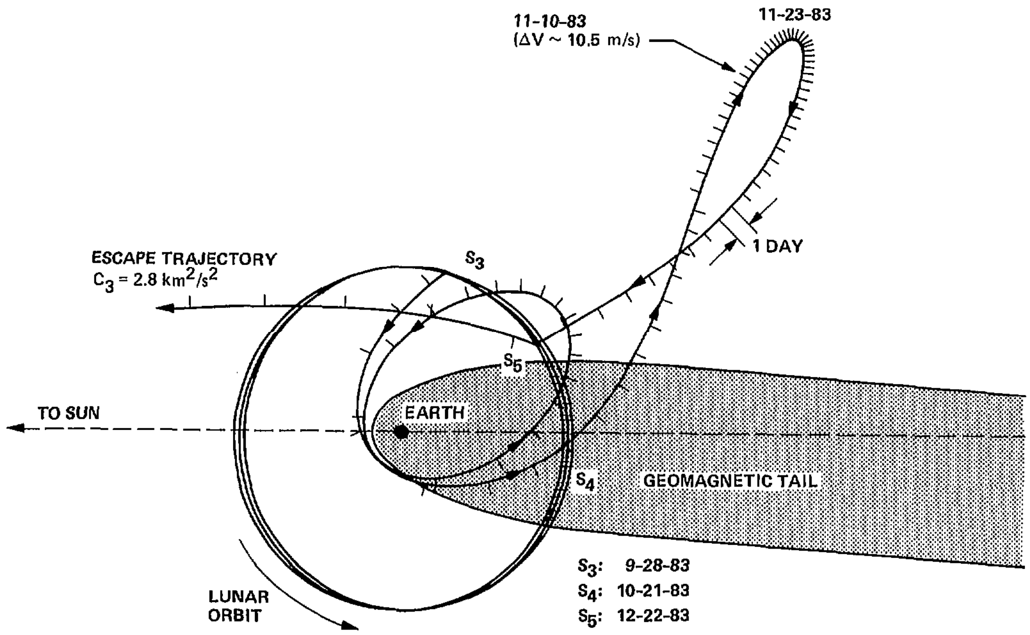


Fig. 6. Escape trajectory relative to fixed Sun–Earth line

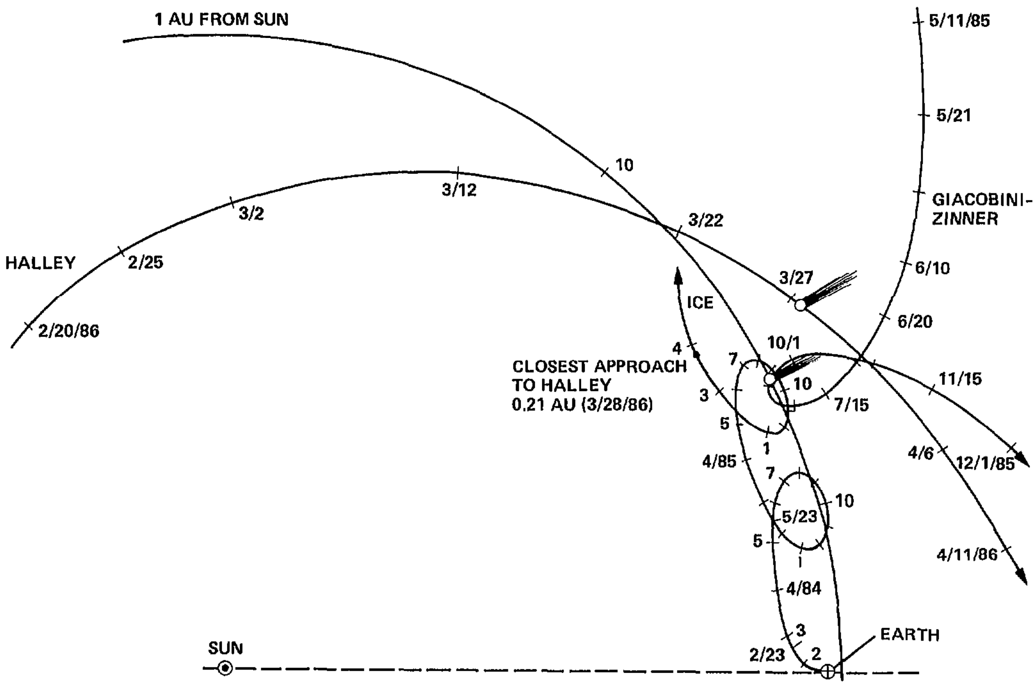


Fig. 7. ICE, Halley's Comet, and Comet G-Z trajectories relative to fixed Sun–Earth line

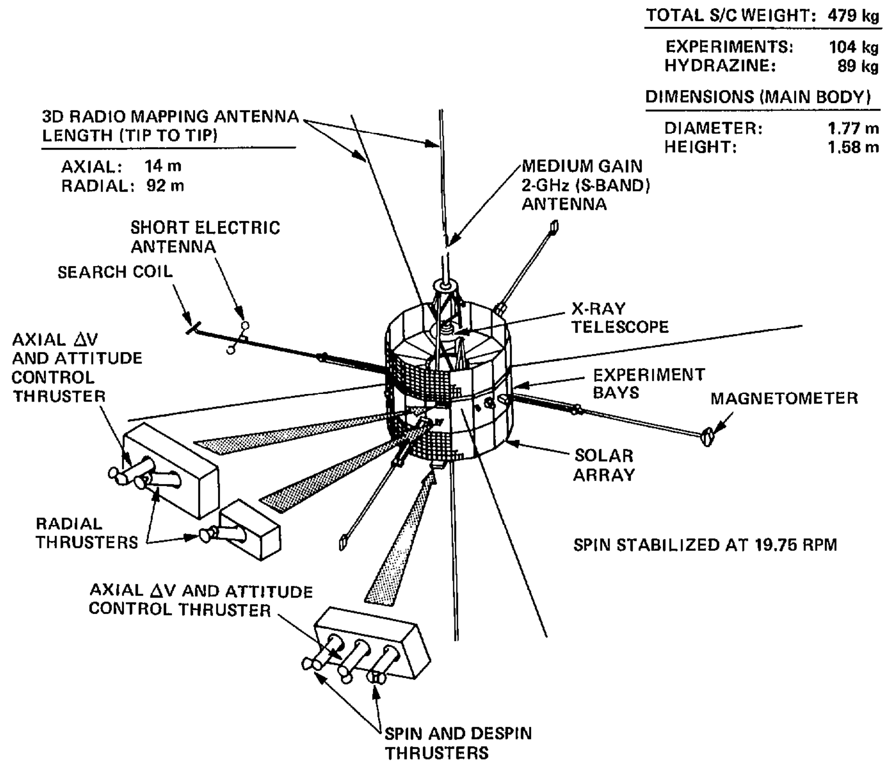
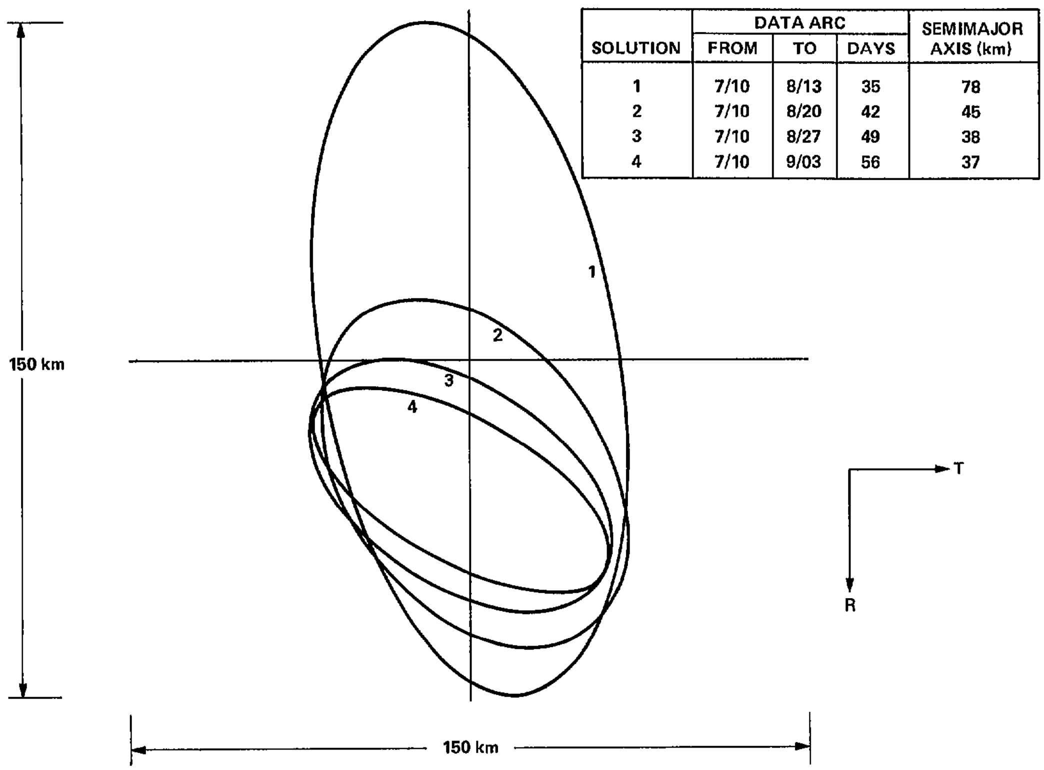
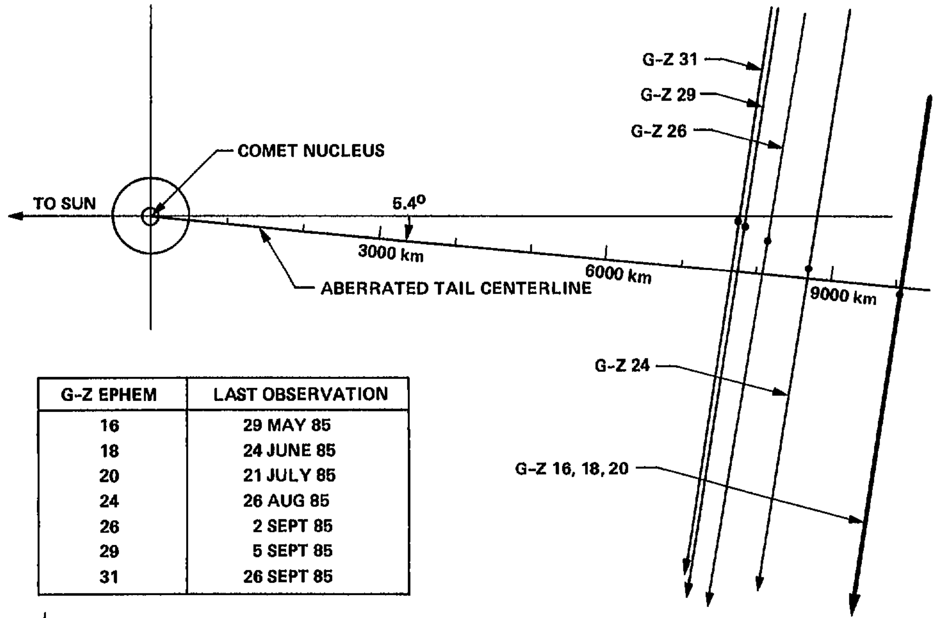


Fig. 8. ICE spacecraft



SOLUTION	DATA ARC FROM	TO	DAYS	SEMIMAJOR AXIS (km)
1	7/10	8/13	35	78
2	7/10	8/20	42	45
3	7/10	8/27	49	38
4	7/10	9/03	56	37

Fig. 9. ICE pre-encounter target aim plane error ellipses



G-Z EPHEM	LAST OBSERVATION
16	29 MAY 85
18	24 JUNE 85
20	21 JULY 85
24	26 AUG 85
26	2 SEPT 85
29	5 SEPT 85
31	26 SEPT 85

INDICATES COMET ORBIT PLANE PASSAGE

Fig. 10. Projection of the ICE trajectory before 8 September final trim onto the Comet G-Z orbit plane as a function of comet ephemeris

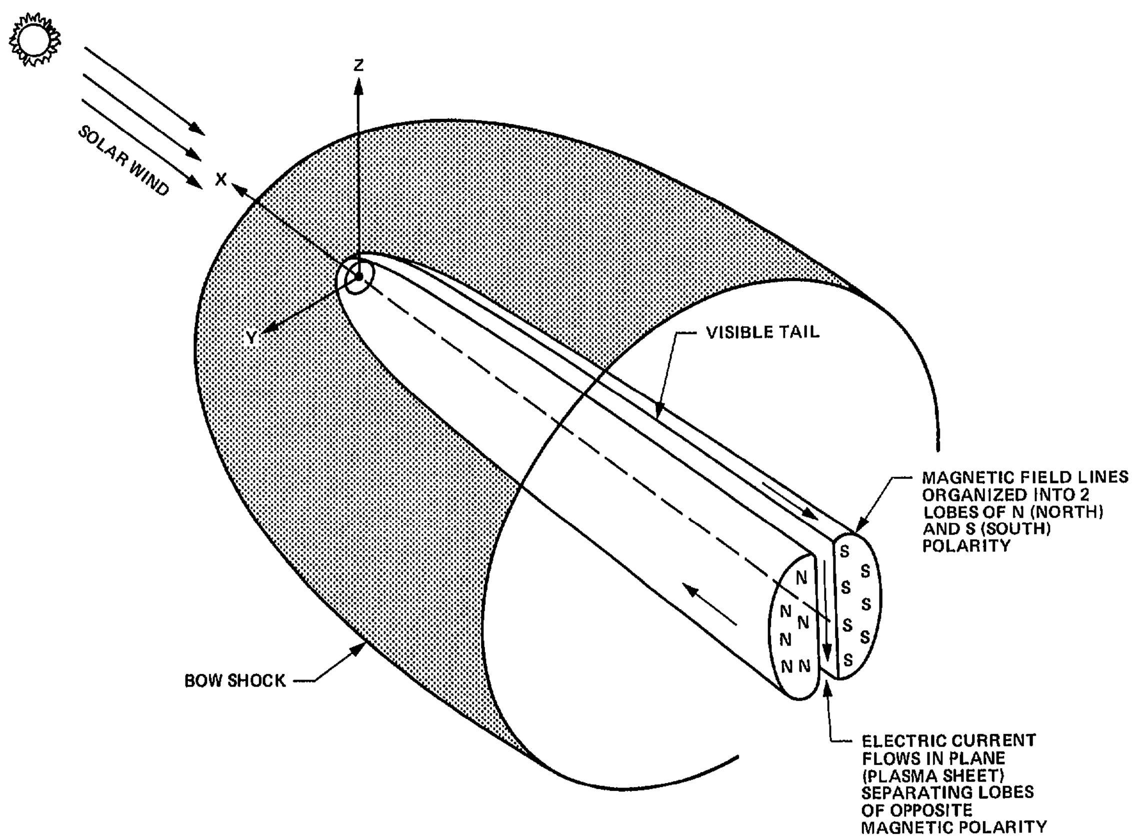


Fig. 11. Comet with visible ion tail composed of magnetic lobes separated by plasma sheet (from Ref. 9)

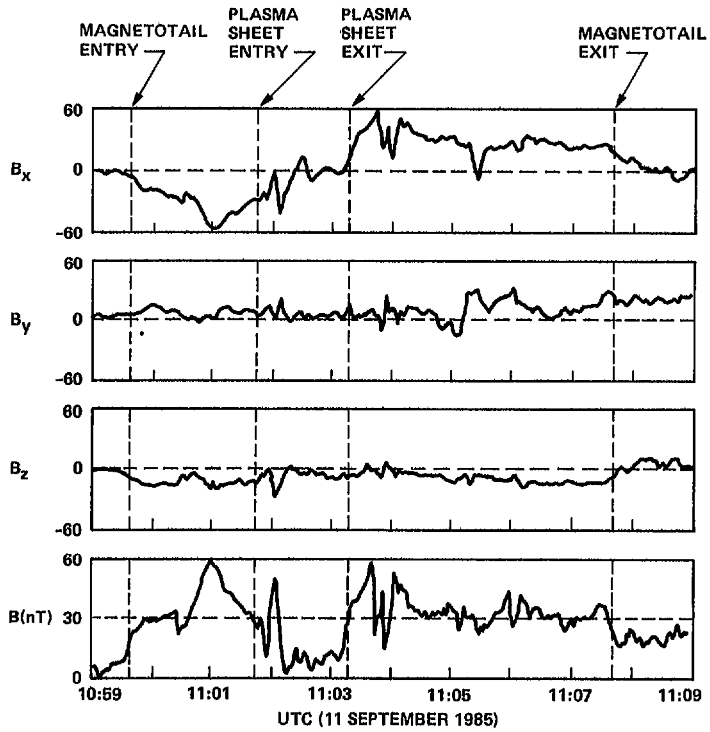


Fig. 12. ICE magnetometer magnetic field observations during the Comet G-Z magnetotail traverse

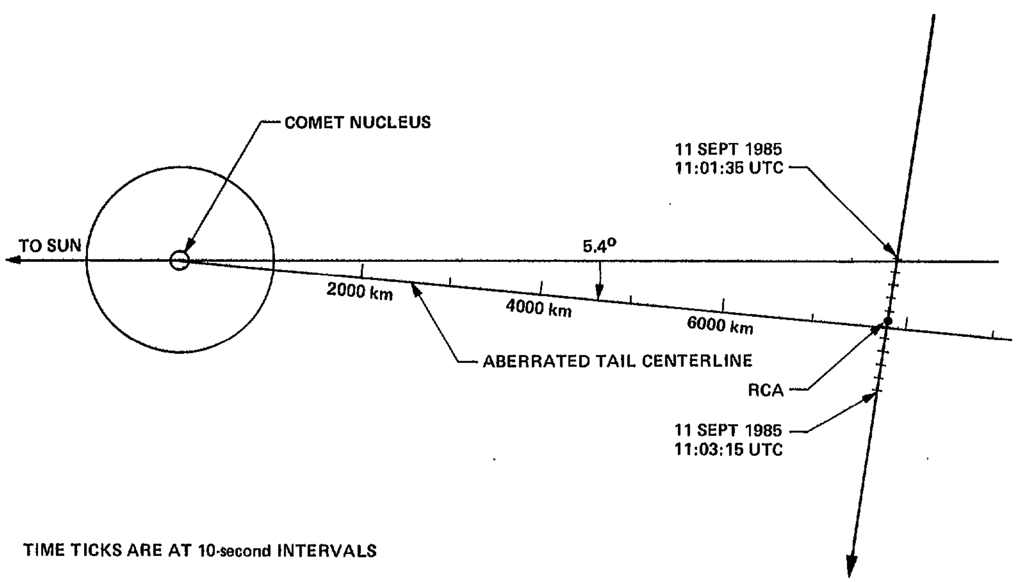


Fig. 13. Projection of ICE encounter trajectory onto the Comet G-Z orbit plane relative to a fixed Sun–Comet line

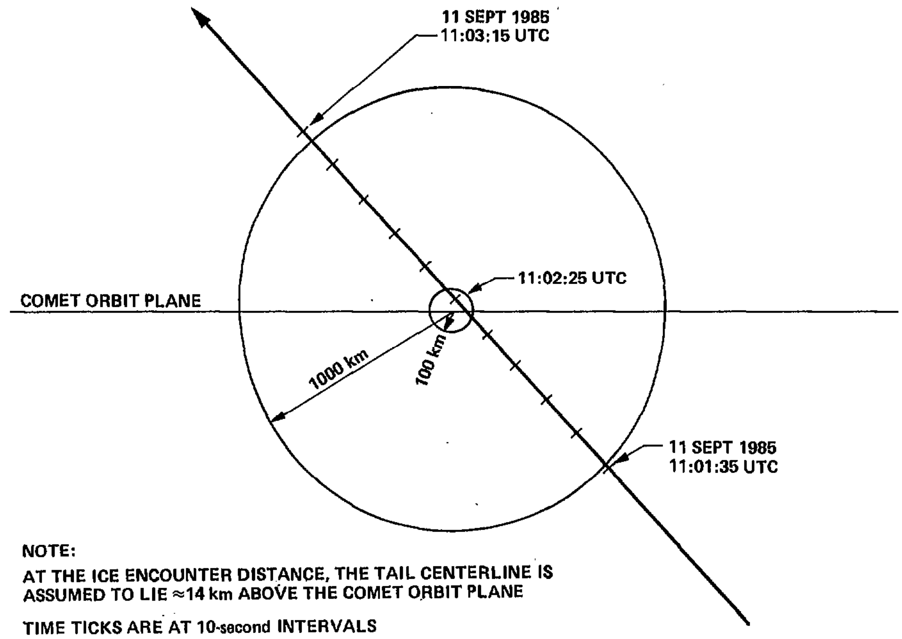


Fig. 14. Projection of ICE encounter trajectory as viewed along the aberrated tail centerline looking toward the nucleus

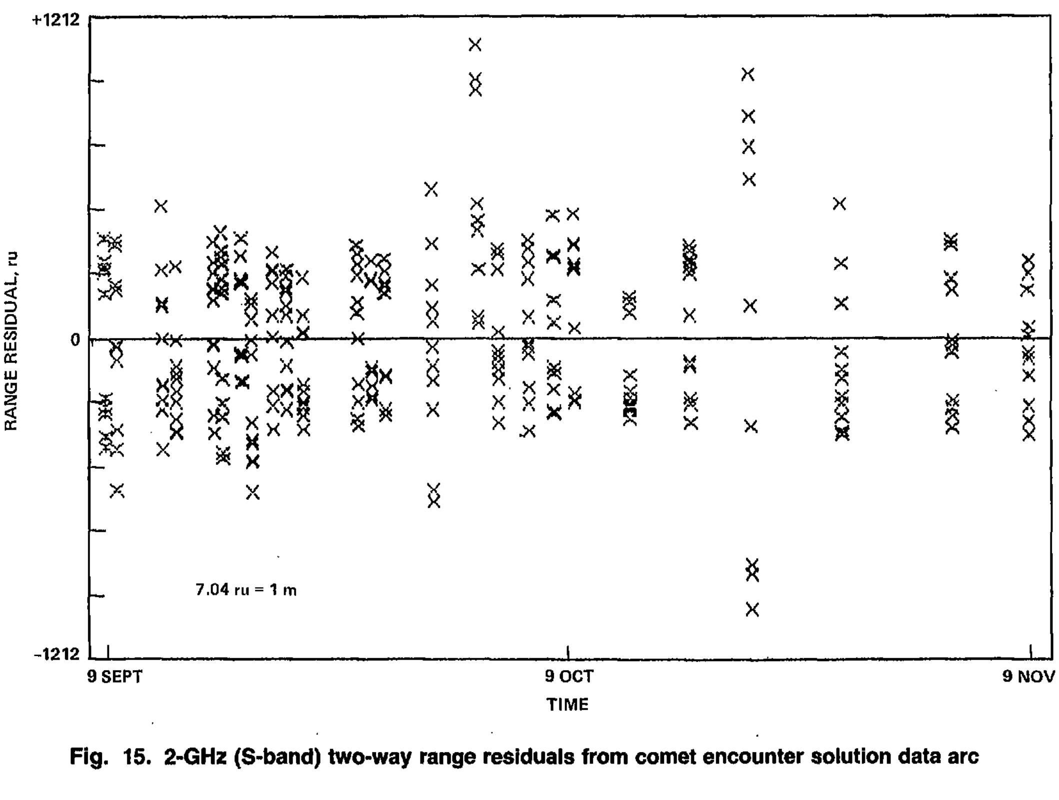


Fig. 15. 2-GHz (S-band) two-way range residuals from comet encounter solution data arc

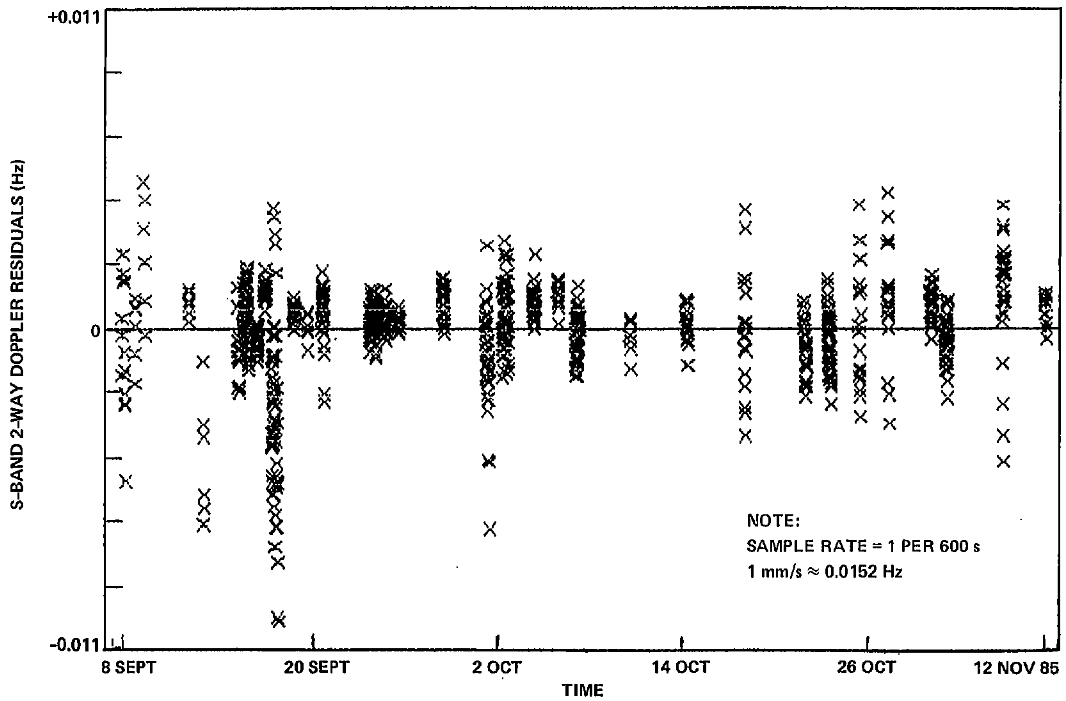


Fig. 16. 2-GHz (S-band) two-way range rate residuals from comet encounter solution data arc

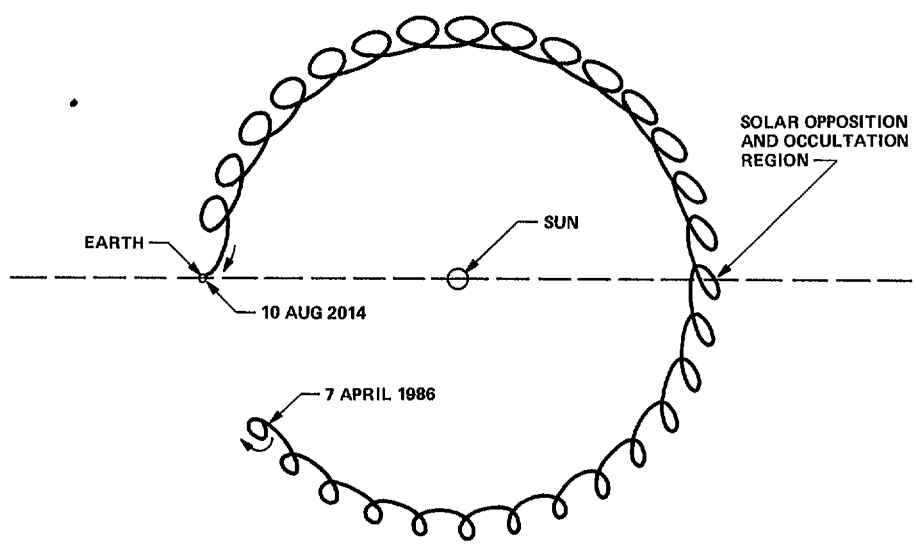


Fig. 17. ICE trajectory April 1986 to August 2014 relative to a fixed Sun–Earth line