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ICE Encounter Operations

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This article documents the operations encompassing the International Cometary Explorer's (ICE) encounter with the Comet Giacobini-Zinner on September 11, 1985 The ICE mission presented new challenges for the Deep Space Network (DSN) 64 meter subnetwork Because of poor telemetry link margin predicted for Giacobini-Zinner (GZ) encounter, supplemental support by the Japanese Institute for Space and Astronautical Sciences 64-meter antenna at Usuda, Japan and the 305-meter Arecibo Radio Observatory in Puerto Rico was required. To improve the 64 meter subnetwork telemetry performance the following were also implemented: (1) Real time antenna array of 64 meter and 34 meter at a single complex and the required performance testing. (2) Non-real time antenna array of two complexes was implemented as a backup in the event of ground or spacecraft failure Other articles following this one provide details.

I. Introduction

The International Sun Earth Explorer (ISEE-3) was launched in 1978. ISEE-3 spent the next five years in Earth orbit where its prime task was to measure the solar wind. During this period the 26 meter antenna operated by the Ground Spaceflight Tracking and Data Network (GSTDN) was used for ISEE-3 support. In December 1983, using a Lunar swingby, the ISEE-3 spacecraft was sent on a new mission to intercept the comet Giacobini-Zinner (GZ) on 11 September 1985. The ISEE-3 spacecraft was renamed for the new mission, International Cometary Explorer (ICE). The ICE deep space mission placed the spacecraft at a greater distance from its previous Earth orbit mission In January 1984, the ICE spacecraft went out of range of the 26-meter antenna and required support from the Deep Space Network (DSN) 64-meter antenna for the remainder of the mission The ICE mission achieved its prime goal on 11 September 1985 when it became the first spacecraft to encounter a comet; in this case the comet was Giacobini-Zinner.

II. Spacecraft Systems

The ICE spacecraft is a 16-sided cylinder which is 1.61 meters tall and 1.74 meters wide There are two bands of solar arrays above and below an equipment platform where most of its payload of scientific instruments is mounted (Fig. 1). The solar array provides for all of the power requirements of the spacecraft. If an undervoltage condition occurs, the spacecraft will shutdown automatically. The array currently provides approximately 160 Watts to the spacecraft. The load of using both transponders is 138 Watts. Power management within the spacecraft is an important item to monitor. To ration electric power aboard the spacecraft, all of the heaters in the propulsion system were to be shut off during the comet encounter

The propulsion system is arranged in two independent and redundant systems consisting of 12 jet thrusters and 8 fuel tanks. This system is used for all despin, spin-up, trajectory corrections, and attitude control manuevers. The spacecraft rotates around the central axis of the cylinder at a rate of approximately 20 revolutions per minute. The spin axis is maintained in an orientation perpendicular to the plane of the Earth's orbit around the sun. The spacecraft orientation sensor system consists of two fine sun sensors and a panoramic attitude scanner.

The ICE telecommunications links are two identical and independent systems. The two transponders operate on separate S-band frequencies and can operate simultaneously. This fact was utilized by the DSN to design a system to effectively combine the two signals which allowed the ICE project to meet one of its goals of providing a high bit rate of information throughout the encounter (Ref. 1). Two separate transmitters with an output power of 5 Watts each radiate through a medium gain antenna with 7 dB gain over an effective beamwidth of 12°. The polarization of the two transmitted signals are right hand and left hand circularly polarized.

The spacecraft carries 13 scientific investigations or experiments (Table 1). A few of these investigations utilize appendages to measure conditions around the spacecraft without spacecraft interference. Magnetic fields are measured by two search coils located at the end of two 3-meter-long booms that extend in opposite directions out from the cylinder. Also, four long wires which are 91 meters tip-to-tip extend radially from the cylinder and are used to map radio waves along with two other antenna that are located along the spin axis both on top and below the spacecraft. The experiments aboard the spacecraft have directly affected the strategy for targeting the spacecraft on its comet intercept.

A. Mission Goals and Objectives

ICE was targeted to pass on the anti-sunward side of Comet Giacobini-Zinner, that is, directly through the tail. The lack of a camera and other remote sensing devices gave the ICE Project scientists no choice. The next decision was where in the tail to go, and they picked a target that was 10,000 km down the tail from the nucleus, a value compatible with avoiding a comet wake region and still having a 99 percent or greater probability of intersection (Ref. 2).

The expected science return falls into three areas.

(1) The physics of the cometary bow shock. to evaluate the location, strength, structure, and related particle acceleration and to determine the extent of the foreshock.

(2) The physics of the interaction between the interplanetary magnetic field and the cometary plasma and an evaluation of the ionization phenomena and turbulence characteristics.

(3) The physics of the comet tail.

All of these goals produce a requirement of monitoring the spacecraft for a complete solar rotation (27 days) prior to the comet encounter at the encounter bit rate to ascertain what phenomena are caused by the comet environment and what is normal for that area of the solar system. The Giotto spacecraft was to also measure solar wind during the ICE comet encounter.

III. Comet Giacobini-Zinner

A. Where It Is

The orbit of Comet Giacobini-Zinner takes it around the Sun about once every 6.6 years. It is named for two astronomers who discovered it independently of each other 13 years apart Giacobini of the Nice Observatory in France initially found it December 20, 1900 and Zinner found it October 23, 1913 at Remeis Observatory in Bamberg, Germany. Apparitions or observations of the comet have been made since then and good orbit was known. For a comet intercept mission, a precise orbit would have to be updated from these previous sightings. To facilitate this, D. Yeomans of JPL and J. Brandt of GSFC collected comet data and documented it in *The Giacobini-Zinner Handbook* (Ref. 2)

B. How Did ICE Get to the Comet?

A key point in planning a spacecraft voyage to a celestial body is that one must have adequate knowledge of its orbit several years in advance of the proposed encounter to plan and develop the mission. In the case of ICE, Comet Giacobini-Zinner had been observed since 1900 and its orbit was predictable. The ICE spacecraft though was already in space and would need to be retargeted. It did not have enough propellant aboard to get to Comet Giacobini-Zinner without an assist. A novel solution to this dilemma was proposed by R. Farquhar, the ICE Flight Director (Ref. 3).

Farquhar proposed a complex set of orbital maneuvers to get there. The onboard hydrazine propulsion system was used starting in mid-June 1982 to move the spacecraft back toward Earth from its orbit at the Earth-Sun libration point.

In mid-October 1982, the spacecraft had intersected the Moon's orbit and was thrown outward and behind the Earth, passing across the Earth's geomagnetic tail. Figure 2 shows the orbit of the spacecraft during these maneuvers. The most crucial of these maneuvers occurred on December 22, 1983 when the trajectory carried the spacecraft toward the Moon. The spacecraft passed behind the Moon and spent more than 30 minutes in its shadow during its passage within 120 km of its surface (Ref. 4) It was renamed the International Cometary Explorer, its previous name was the International Sun Earth Explorer-3. Lunar gravity altered the spacecraft's trajectory and accelerated it toward Comet Giacobini-Zinner. Figure 3 illustrates this critical Lunar flyby which increased its velocity from approximately 4800 km/h to 8000 km/h.

The flyby accomplished two important criteria for a successful comet intercept. The first was that the spacecraft achieved the required orbital energy to leave the Earth-Moon system and the second was a close targeting for a comet that no one had seen since 1978 Figure 4 illustrates the ICE trajectory relative to a fixed Sun-Earth line and shows the relative positions of the spacecraft, Comet Giacobini-Zinner and Halley, the Sun and Earth referenced to calendar dates. The looping motion of the spacecraft is due to its elliptical motion around the sun. When it is further from the Sun than the Earth (G-Z encounter = 1.03 AU), the Earth orbits around the Sun at a velocity that is faster than the spacecraft and the Earth seems to catch up to it. The comet intercept by ICE was timed to occur only 6 days after the 1985 perihelion of September 5. The plane of the comet's orbit is tilted by 31.9° with respect to the ecliptic plane; although at perihelion it is only slightly above it. This means the comet's tail should be at its brightest and greatest length which is estimated to be 500,000 km from a photo during the 1959 apparition for its encounter with ICE.

Ultimately, a major trajectory maneuver was executed on June 5, 1985 after JPL (Yeomans) had updated the comet ephemeris from over two months of reliable worldwide observations Two trim maneuvers were also made on July 9 and September 6 to correct for any burn errors. The final trim retargeted the spacecraft to a point 7815 km from the comet's nucleus, but kept the original intercept time of 11:04 UTC on September 11, directly above the Arecibo Radio Observatory only 70 million kilometers from Earth.

IV. Data Acquisition for Encounter

A. Telecommunication Needs

From the previous discussion of the spacecraft systems, mission goals and the Comet Giacobini-Zinner intercept point, the technical requirements were determined for what was needed to support the ICE encounter. These requirements were as follows:

The ability to receive the 2217.5 MHz downlink frequency at DSS-14 and DSS-63 (Ref. 5).

The ability to symbol synchronize biphase-modulated carrier frequencies (Ref. 6).

The ability to format decoded telemetry data into an agreed upon DSN-GSFC interface data block (Ref. 7).

The ability to combine the two spacecraft downlink channels (Ref 1)

The ability to array together the telemetry output of the 34-meter and 64-meter antenna at each DSN complex.

Deliver a tunable S-band 400 kW klystron for commanding (Ref. 8).

The ability to uplink at 2090.66 MHz without interfering with the newly acquired ability to simultaneously receive the 2217 5 MHz downlink frequency (Ref. 9).

To implement the Usuda, Japan 64-meter antenna to fill the gap caused by the Canberra complex poor spacecraft look angle (Ref. 10)

To implement an R & D non-real time decoding system as an insurance policy to guarantee data acquisition (Ref. 11).

To determine the orbit of ICE from its geotail mission through its comet intercept (Ref. 4).

To integrate the Arecibo support with ICE operations (Ref. 12).

All of these requirements featured implementations that were accomplished along with the Mark IV upgrade.

B. Worldwide Coverage

The DSN's plan for supporting the ICE encounter required array support throughout the 36 hours prior to and after the comet intercept In Madrid, both DSS-61 and DSS-63 were arrayed. In Goldstone, DSS-15, DSS-12, and DSS-14 were arrayed, and in Canberra, DSS-42 and DSS-43 were arrayed. Even with this all-out support, the DSN would be strained at the distance of the encounter to maintain the slim link margin. Accordingly, that was why the Usuda, Japan and the Arecibo Radio Observatory support was requested (Refs. 10, 11, 12, and 13).

The Usuda 64-meter site would be used to gather valuable pre-encounter and post-encounter telemetry between the

Goldstone array period and the Madrid support This configuration was first checked out in mid-May, and in a pre-encounter test in late May, they successfully supported the 1024 bit rate at an Earth-spacecraft distance comparable to the encounter time frame. In fact, conditions would only get better because the peak elevation angle would increase almost 30 degrees.

The maneuvering of the spacecraft back in 1983 had the Arecibo Radio Observatory in mind the whole time. The intercept of the comet was planned to occur within the very short view period that this observatory could listen to the ICE spacecraft. This insurance policy was not taken out by NASA until early in 1985. The implementation by GSFC was complete in August; and the first test pass occurred August 19.

V. Encounter Operations

A. Test and Training

To ensure successful operations throughout the worldwide coverage for the ICE encounter, many configuration tests were run at all sites. DSN array testing began in early June at the Goldstone complex. These tests provided analysis for an encounter configuration to optimize the link margin performance. Findings are documented in this issue (Ref 13) but some meaningful work bears mentioning in the next few paragraphs.

There were a number of significant problems and solutions that were brought to light and engineered under the auspices of these tests. The most crucial of these problems was the testing of the hardware to be used for encounter arraying operations. The device that was used throughout testing and training was what will be referred to in this article as a "resistive combiner" (Ref. 1). Five combiners were built for the DSN, specifically for ICE dual telemetry combining and intra-complex arraying. They were multi-input port (two, three, or four), single or triple output port devices which allowed operational flexibility to ICE operations and testing (Fig. 5). Access to the combiners was designed to be easy and efficient via patchcord in the baseband patch panel. Baseband receiver telemetry phase detector output would be patched directly into an input port and the output of the combiner would be patched directly to a telemetry string consisting of a Subcarrier Demodulator Assembly (SDA), Symbol Synchronizer Assembly (SSA), and a Telemetry Processor Assembly (TPA). The combiner needed external monitoring to validate its performance. An individual telemetry string provided two assessments of proper performance — the SSA measured signal-to-noise ratios and the sequential decoder provided a symbol error rate statistic. Thus, when array testing was underway, all available telemetry strings were used to measure configuration setup conditions and long term performance. Soon, DSN station operations were adept at using this equipment for ICE arraying and frequency combining In addition, a nagging problem was found early with both Voyager 2 and ICE array testing at Goldstone and a prepass calibration procedure was developed to effectively handle a receiver phase detector imbalance which could occur from routine adjustments to the equipment. Ultimately, Goldstone testing provided an operable system that consistently performed to expectations with little maintenance and was easily configured for array support

The array testing at Madrid did not begin until mid-August. A problem with baseband combining within the 64-meter antenna was found which threatened the encounter support there. The problem was a consistently low output of approximately 0.5 dB in SNR from each of the receivers when receiver baseband was used for the decoding process instead of a 10 MHz intermediate frequency (IF) receiver telemetry output. This had not occurred at either Goldstone or Canberra during their testing. Station engineering proposed and tested a configuration where this 10 MHz IF was used instead of receiver baseband. Intensive crew training was the next important step in using this configuration for encounter support.

Understandably, a conservative configuration was planned for the encounter support. The array configuration was the prime data sent to the project. A backup telemetry string was used to decode the frequency combined signals within the 64-meter antenna at each complex. As an added insurance policy a research and development "soft symbol" recording was made on site for non-real time decoding purposes (Ref. 11) These configurations provided excellent results.

B. Operations

The ICE Comet Giacobini-Zinner encounter provided real-time science highlights to the ICE Principal Investigators at Goddard Space Flight Center. Telemetry was sent via high speed data line from three tracking complexes simultaneously. The Madrid, Spain DSN complex sent arrayed data from their 34-meter and 64-meter antennas, while the Goldstone DSN complex sent data from an array of both of their 34-meter antennas with their 64-meter antenna. The Arecibo Radio Observatory also sent data to GSFC during the overlap of Madrid and Goldstone (Fig. 6). The multiple data streams allowed the scientists to choose the best data stream to insure that this historic first comet intercept would not be missed.

Array performance at all complexes was better than predicted. ICE Project scientists reported a direct intercept of the Comet Giacobinni-Zinner. Ground antenna telemetry performance was at an all time high. No detectable spacecraft degradation was observed after the comet encounter.

ICE encounter operations were performed in a very professional and flawless manner by the many participants and supporting facilities. The encounter support was deemed outstanding by the ICE Project Manager, JPL and NASA management.

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Table 1. ICE investigations

Title	Principal Investigator	Affiliation	Experiment Status
Solar Wind Plasma*	Bame	Los Alamos National Lab	Electrons only (Ion Portion Failed)
Plasma Composition*	Ogilvie	GSFC	Operational
Magnetometer*	Smith	JPL	Operational
Plasma Waves*	Scarf	TRW Systems	Operational
Energetic Protons*	Hynds	Imperial College, London	Operational
Radio Waves*	Steinberg	Paris Observatory, Meudon	Operational
X-Rays, Low Energy Electrons	Anderson	UCB	X-Rays and E > 200 keV (Low Energy Electron Portion Failed)
Low Energy Cosmic Rays	Hovestadt	MPI	Partial Failure (Ulezeq)
Medium Energy Cosmic Rays	von Rosenvinge	GSFC	Operational
High Energy Cosmic Rays	Stone	CIT	Partial Failure (Isotope Portion)
High Energy Cosmic Rays	Heckman	UCB/LBL	Partial Failure (Drift Chamber)
Cosmic Ray Electrons	Meyer	University of Chicago	Operational
Gamma Ray Bursts	Teegarden	GSFC	Partial Failure (PHA Memory)

*Significant experiments during a comet tail encounter

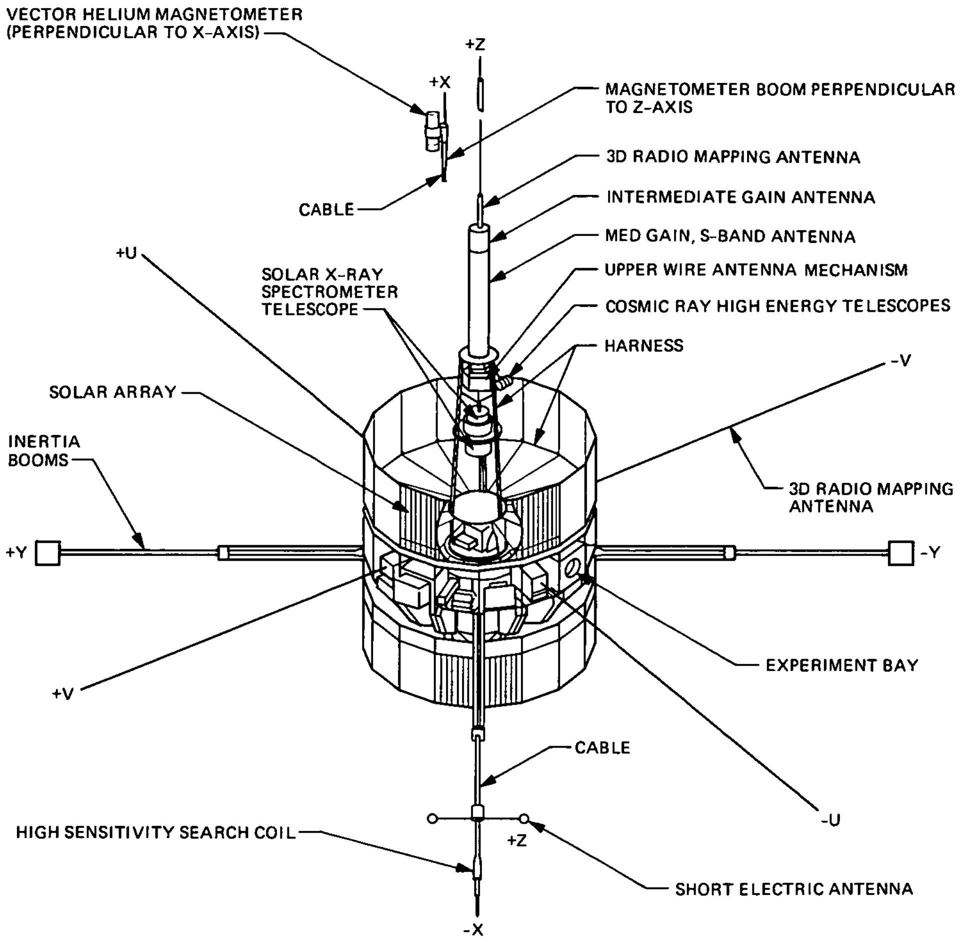

Fig. 1. ICE spacecraft

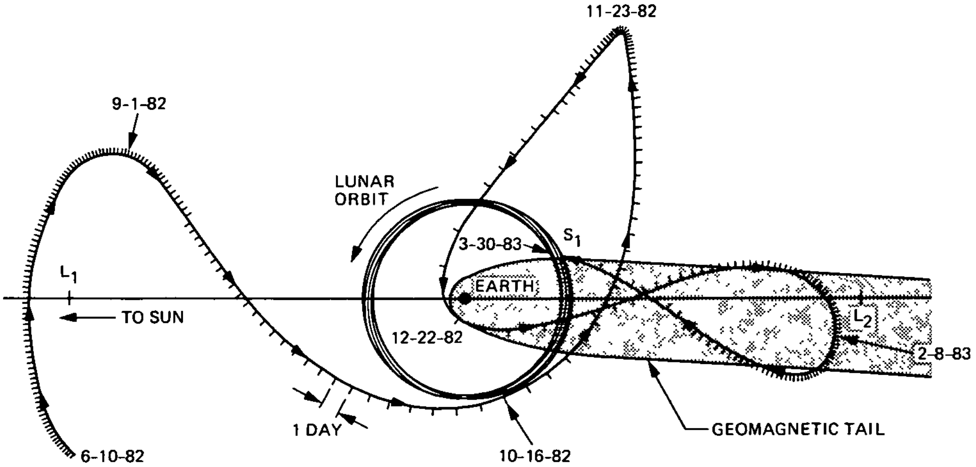

Fig. 2. Geomagnetic tail trajectory

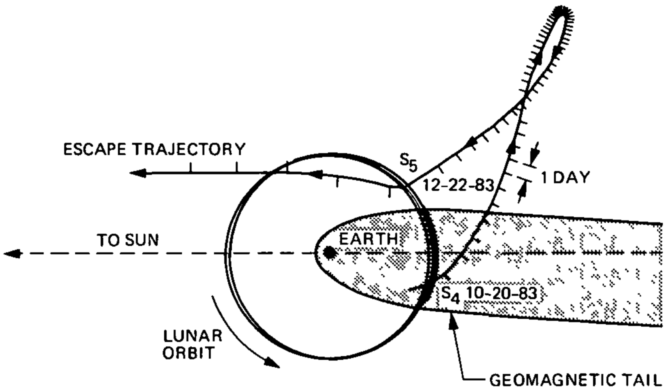

Fig. 3. Lunar flyby trajectory

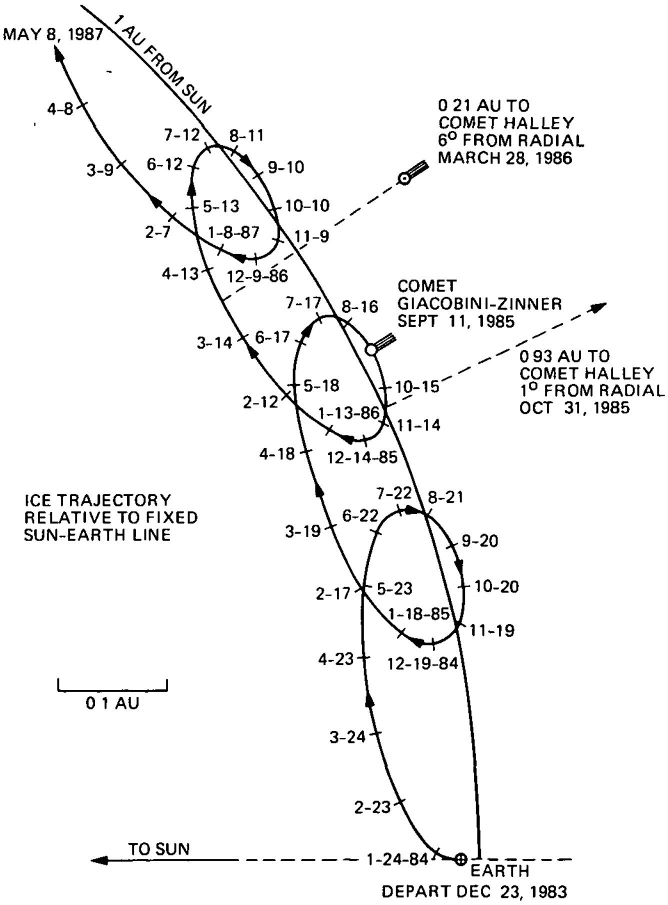

Fig. 4. ICE trajectory relative to fixed sun-earth line

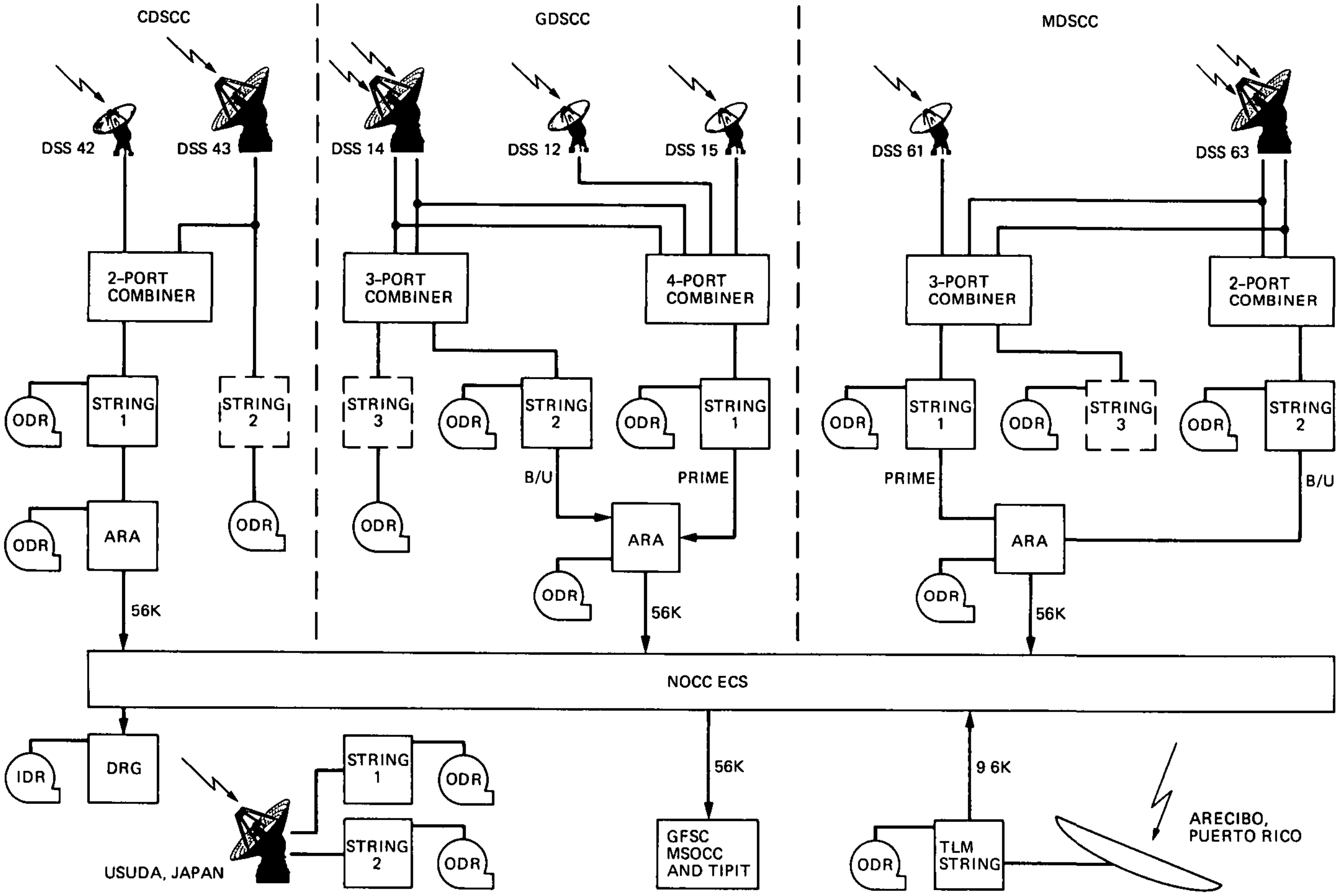

Fig. 5. ICE Encounter support configuration

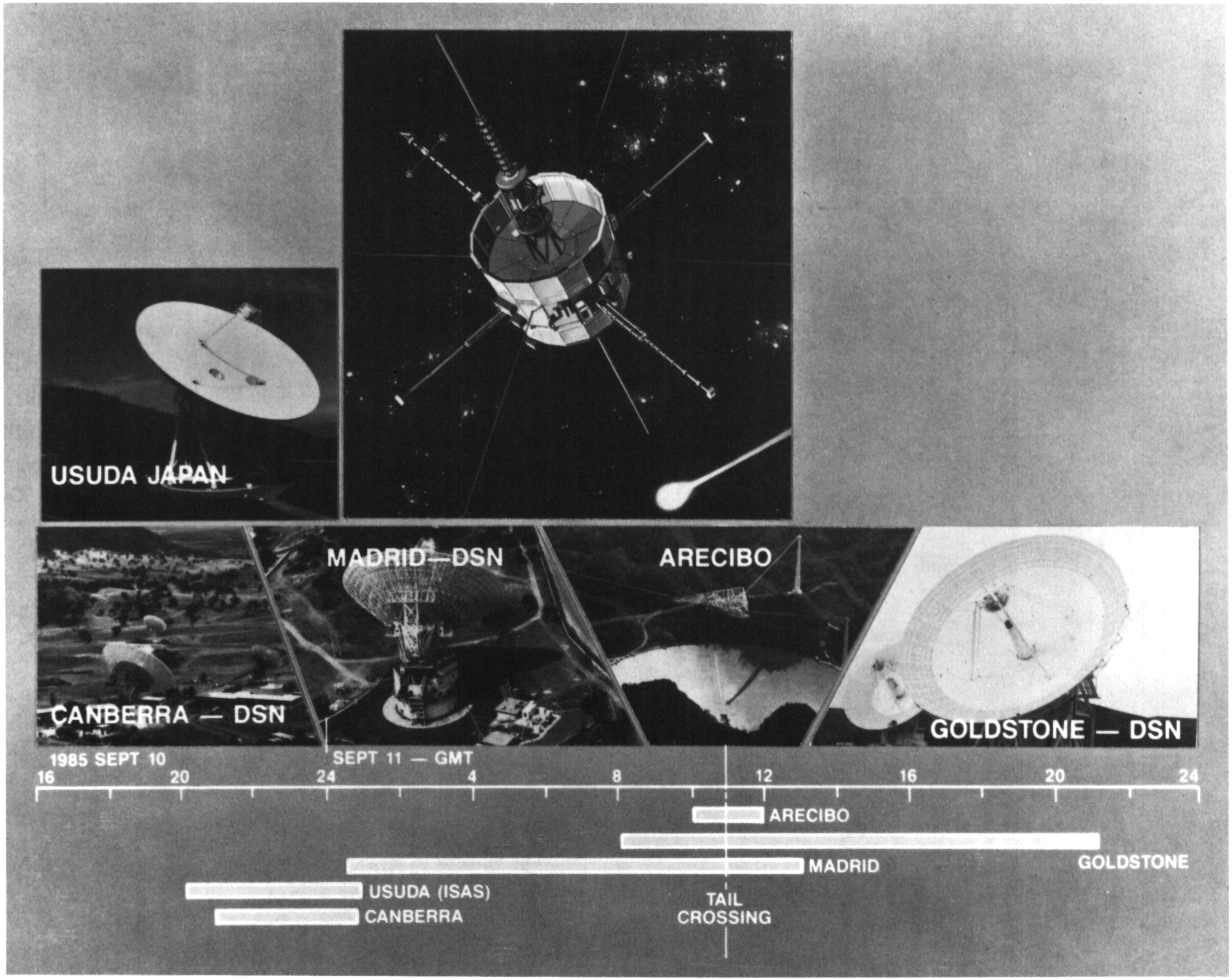

Fig. 6. Encounter support timeline