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ICE Telemetry Performance

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Acquiring telemetry data from the International Cometary Explorer (ICE) at its encounter with the comet Giacobini-Zinner on September 11, 1985 proved to be among the more difficult challenges the DSN has met in recent years The ICE spacecraft began its life as an earth-orbiting monitor of the Solar Wind At the comet, ICE was nearly 50 times as distant as in its initial role, with its signal strength diminished nearly 2500 times. Collecting enough of that weak signal to provide meaningful scientific data about the comet required unique new telemetry capabilities and special handling by the DSN. This article describes the development and validation of the DSN telemetry capability for ICE from its early planning stages through the successful comet encounter.

I. Introduction

When it was launched in 1978, the ISEE-3 (International Sun-Earth Explorer) was a mild-mannered observer of the Solar wind on its way to the Earth. In late 1983, some time after the close of the ISEE primary mission, and after much debate and complicated orbital maneuvering, the ISEE-3 spacecraft had a new name, the International Cometary Explorer (ICE), and was on its way to an encounter with comet Giacobini-Zinner (Refs. 1, 2). As ISEE-3, the spacecraft orbited the Earth with the Sun at a distance of 0 01 Astronomical Units (AU), or 1 percent of the distance from the Earth to the Sun. At the encounter with Giacobini-Zinner on Sept. 11, 1985, the ICE would be at a distance of 0.47 AU, or nearly 50 times as far away as the spacecraft had been during its primary mission. That increase in distance effected a corresponding decrease in received signal strength by almost 2500 times, and posed a significant challenge for the DSN to provide the support needed by the ICE.

The ISEE-3 spacecraft was supported by the 26-m antennas of the Ground Spaceflight Tracking and Data Network (GSTDN), in an environment characterized by high link margins and corresponding wide tolerances for link parameters. Those tolerances had to be tightened and much of the margin consumed in order to provide the desired data return from the comet encounter. The spacecraft has two separate transmitters on different frequencies in the 2 GHz band which were used interchangeably for telemetry and radio metrics when it was supported by the GSTDN. For the comet mission, both transmitters were used for telemetry, and the DSN 64-m antennas at Goldstone and Madrid were given new low-noise Maser amplifiers which enabled them to simultaneously receive the two downlinks from ICE and combine the signals to achieve a doubling of the rate at which comet data could be acquired. The Maser amplifiers for the lower of the two ICE frequencies were not available until early 1985 for validating the comet encounter performance predictions.

II. Preliminary Planning and Analysis

Planning and performance analysis for the ICE mission had started by early 1981. A flight to Halley's comet was considered for a time, but dropped because the distance at that encounter would have been too great, and because an ISEE encounter with Giacobini-Zinner could be done better and be done first. Preparations for the comet mission included careful measurements by the Goldstone DSS of the received power in the two downlinks of ISEE-3. The channel A signal (2270 MHz), which fell within the tuning range of the standard DSN equipment was measured on November 30, 1981,[1] and then measurements of the relative power in the two ISEE-3 downlinks followed in early 1983. These measurements were used to calibrate and refine the telemetry link design control tables for the anticipated comet encounter.

Performance of the DSN's telemetry receiving systems for the ICE was estimated from the standard references,[2] which had been based upon analysis done in support of Helios and the Pioneers several years ago. In the meantime, the DSN's sequential decoders had been replaced with faster ones, the DSN's receivers were capable of a narrower bandwidth operation, and the ISEE's signal characteristics were different than the earlier spacecraft so that the overall telemetry receiving system performance could be expected to be modestly improved over that predicted from the reference. The link analysis showed that reception from ICE at Giacobini-Zinner encounter at the desired 1024 bps data rate would be feasible by combining the two downlinks received by the DSN 64-m antennas. But margins would be slim, about 1 dB or so,[3] and a few assumptions were still awaiting verification. Arraying with the adjacent 34-m antennas was examined as a possible enhancement and considered as not being too difficult since the new arraying capability under development to support Voyager at Uranus and Neptune would be available.

The ISEE spacecraft rotates at about 19 rpm and has a four-lobed antenna pattern which sweeps past the earth once each rotation. The impact of this rotation on the telecom link was assessed from the pre-launch antenna pattern measurements, which suggested that peak to peak level variations of the 2217 MHz signal were limited to only 0.2 dB, but that the 2270 MHz signal would exhibit about 2.2 dB peak to peak variations. For the purpose of link planning, the expected signal level was ascribed to be at the minimum for the antenna pattern. It was recognized, however, that measurements of the signal level would typically show the average, about 1 dB higher than these predicts. Link performance testing and the assessment of expected performance based upon this testing were carried out with respect to the average observed Symbol SNR. The bookkeeping to compare actual against predicted levels included this 1 dB.

One assumption made in the early link analysis which later became a concern was that the effect of the comet environment upon the telemetry link could be neglected. The models of the dust tail for the comet kept open the possibility that the spacecraft itself could be damaged early in the encounter. Severe telemetry link degradation could be one of the results. As insurance against that potential, Cornell University's Arecibo Observatory in Puerto Rico was instrumented to receive ICE telemetry, and the Symbol-Stream combining capability was devised to combine the ICE signals as received simultaneously at two distinct DSN sites. The time of the ICE crossing of the comet tail was scheduled to fall within the simultaneous field of view of the Arecibo Observatory and the DSN sites at Goldstone and Madrid. These developments are described elsewhere in this issue (Ref. 3, 4).

III. Decoder Analysis and Single-Channel Tests

Surprises which were encountered in testing the DSN receiving/decoding configuration for ICE led to an extensive analysis and testing activity throughout 1984. The analysis work, already reported (Ref. 5), extended the older analysis of the DSN's sequential decoding performance to faithfully represent the current configurations of DSN and ICE spacecraft. This detailed analysis agreed well with the extrapolation that had been done using the older reference material. But analysis alone is not enough – the system itself must perform as well. The extensive self-monitoring capability of the DSN sequential decoders was used in conjunction with the Madrid 64-m station and the ICE spacecraft to characterize the DSN decoder behavior. The accumulated result of these tests was agreement with the analysis to within the experimental uncertainty.

Performance tests during 1984 were limited to channel A (2270 MHz) by the extant DSN equipment. Full configuration tests had to await the installation of the new Maser amplifiers (Ref. 6), and the signal combining equipment (Ref. 7). Telemetry performance parameters which were monitored included those which characterize both the input and output of the sequential decoder. The AGC-estimate of received carrier power, the observed symbol SNR and symbol error rate, the decoder deletion rate, and the decoder computation count were all monitored by the DSN Telemetry Processor and communicated to the Network Operations Control Center where

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[1] D. J. Bell and R. D. Shaffer, "Final Results from ISEE-3 Carrier Power Measurements," IOM 3392-82-86 (internal report), Jet Propulsion Laboratory, Pasadena, Calif., May 21, 1982

[2] *Deep Space Network/Flight Project Interface Design Handbook, Vol. I. Existing DSN Capabilities* (Document 810-5, Rev. D, internal report), Module TLM-40, DSN Telemetry System Data Decoding pp. 1–19, Jet Propulsion Laboratory, Pasadena, Calif , 1984.

[3] D J. Bell, "ISEE-3 Telemetry Downlink – 1984–1990," IOM 3392-83-100 (internal report), Jet Propulsion Laboratory, Pasadena, Calif., May 31, 1983.

they were recorded for final analysis. New plotting display software was needed and was developed by the DSN Performance Analysis Group to present this data for effective understanding.

Most of the performance data were gathered during routine spacecraft support passes within which ranging operations occurred. With ranging active, the spacecraft configuration is such that the single channel signal level would drop by 2 dB to near its threshold region. Changes in the spacecraft-earth distance during the period of testing allowed the SNR region around threshold to be probed without resorting to artificial means of manipulating the signal.

Figure 1 shows the accumulated effect of the 1984 testing. Not all data points are included here, to avoid an unreadable clutter. Those from late in the year which are not shown are consistent with those shown. The background lines of this figure are from the analysis (Ref. 5), and correspond to expected decoder deletion rate for the DSN decoder using receiver bandwidths of 3 Hz or 10 Hz. Experimental data points are calibrated into this background via the observed symbol SNR at the input to the decoder. Data points are indicated by large crosses, with arm lengths representing two-sigma uncertainty in the observation. The numbers which label each data point are the Day-of-Year (DOY) in 1984 on which they were acquired. Where a Tee mark is used in place of a cross, it means simply that there were no deletions observed in that interval, and the top of the Tee indicates the top of the two-sigma uncertainty range. The bottom of that range is zero. The inferred threshold of acceptable performance is indicated by the vertical hashed bar at 0.5 dB of Symbol SNR at the input to the decoder.

Figure 2 is one example of the raw data plots which entered into the analysis. This data corresponds to 1984-DOY-185, with a spacecraft pass from about 0330 to 1230 GMT. Data were acquired on this date using the 3-Hz receiver bandwidth only. The period of lowered SNR is the ranging interval, which appears to have two distinct segments For 0640–0650, the symbol error rate (SER) was 8.8 percent, representing a symbol SNR of -0.3 dB, and giving a deletion rate of 1.7 percent. For 0650–0720, the SER was 8.2 percent for an SSNR of -0 1 dB, which gave a deletion rate of 0.25 percent. Here, as in other tests, the SER, an output of the decoder itself, is used as the calibrator because of the smaller statistical scatter on that observable. The main part of the non-ranging interval of 7 hours showed no deletions, giving two-sigma confidence that the deletion rate is below 0.8×10^{-4}, at the SSNR of 1.0 to 2.0 dB. These three points all appear on Fig. 1 tagged with #185.

The sequential decoder's workload, the number of computational steps needed to decode a block, is a sensitive measure not only of the SNR of the symbol stream which the decoder receives, but also of the alignment and proper operation of the receiving and data detection equipment. Plotting the computation count against the observed SER eliminated confusion from short-term variations in signal level and provided a tool for assessing correctness of gain settings, combiner ratios, etc. in the upstream equipment. Figure 3 is a plot of decoder computation count per frame (DCF) vs symbol error rate (SER) for a pass which represented good performance on the 2270 MHz channel. Deletions occur whenever the computations needed to decode a given block exceed the number available before work must be started on the next block. Deletion of individual random blocks has become likely whenever the average computation per bit exceeds about 5 (or log DCF about 3.3), which occurs around the SER of 7.5 percent, or Symbol SNR of 0.2 dB, somewhat below the declared threshold level.

It was later learned that the DCF vs SER graph for the 2217 MHz channel would be in agreement with Fig. 3, despite the presumed difference in antenna patterns. This and other factors led to the examination of the antenna rotation patterns in the observed data, and to the surprise discovery that both the 2217 and 2270 MHz channels showed strong variations in signal level with the rotation angle of ICE (Ref. 8).

Twice during 1984, on DOY 148 and 157, attempts were made to retune one of the Maser amplifiers on the Madrid 64-m antenna to receive the lower frequency ICE signal to validate telemetry performance with it. When calibrated onto a chart like Fig. 1, using the SSNR at the decoder input, the performance of this channel was consistent with Fig. 1 data. However, in absolute signal level terms when compared against predicts, the link performance was significantly below that expected. At the time, that difference was ascribed to a side-effect of tuning the Maser beyond its normal range.

IV. ICE Encounter Support Configuration

Near its encounter, the ICE was provided nearly continuous coverage. The two 64-m antennas at Spain and Goldstone each listened to both of the two ICE downlink signals with separate low-noise Maser amplifiers and narrowband phase-locked receivers. A coherently detected baseband from each of the two channels was fed to a resistive combiner at each site. A resistive combiner was chosen for use here because it was simple to build, install, and test, and was adequate for the purpose with the small bandwidth of the ICE signal (Ref. 7). The nearby 34-m antennas, one at Madrid and two at Goldstone, also listened to the 2270 MHz signal from ICE and provided another detected baseband to the resistive combiner at that site. Two combiners were operated at each site during the encounter, the prime unit combining all available signals, and a second as backup combining only the two strong signals from the 64-m antenna.

As noted earlier, the ICE was scheduled to be within the narrow field of view of the Arecibo Observatory during the crossing of the comet tail. To enable it to support ICE at that time, Arecibo was provided with new receiving equipment for the ICE 2270 MHz downlink and telemetry equipment from the GSTDN (Ref. 3). Actual spacecraft support was provided for only a few days around encounter, preceded by periods of installation and testing.

The DSN 64-m antenna in Australia was not configured to receive both ICE downlinks because of the limited visibility from its southern latitude due to the northern declination of the ICE spacecraft at encounter. However, it was provided with a two-port resistive combiner to allow both the 64-m and the 34-m STD to combine for support of the lower data rates.

Additional support to ICE over the Asian longitude was provided by the new 64-m deep space station at Usuda Japan which was built by the Japanese Institute for Space and Astronautic Sciences for support of their Planet-A mission to Halley's comet (Ref 9) This support was arranged in exchange for DSN support to Planet-A, and was enabled by the installation of equipment from the DSN. This equipment included DSN telemetry data acquisition computers, and a very low noise Maser amplifier from the DSN Advanced Systems area Even though only the 2270 MHz downlink was received, the high aperture efficiency of the new antenna coupled with a low noise listen-only configuration to give the Usuda station almost the same overall performance as the two channels into the DSN 64-m antenna.

V. Combined Channel Testing

Testing for the planned encounter support configuration began early in 1985, as soon as the new equipment had been installed at the Goldstone Complex. Early tests were hampered by problems with initial operation of the newly-designed wide bandwidth low noise Maser amplifier for the 2217 MHz channel. Comparison tests between the two channels repeatedly showed the received SNR of the 2217 MHz channel to be below that of the 2270 MHz channel, contrary to expectation, but observed drifts in Maser performance were identified as the probable cause. It was only after the new Maser had successfully emerged from its break-in period that it became clear that the early tests in Spain had correctly indicated the lower performance in the 2217 MHz channel. An extensive search for probable cause uncovered only corrections on the order of a few tenths of a dB for the DSN antenna gain. Incorporating all identified adjustments, the 2217 MHz channel SNR was about 1 dB below the expected level.

As encounter approached, the only leads which had not been fully explored pertained to the spacecraft configuration or antenna attitude during the tests in 1983. These tests had shown the 2217 MHz channel power level to be about 1 dB stronger, compared to the 2270 MHz channel, than had been expected on the basis of pre-launch analysis. Hence, the appearance of weakness in the performance of the 2217 MHz channel could be eliminated if the 1983 tests were ignored. This lead was not followed because it did not appear that the knowledge gained thereby could have improved the link performance at encounter.

During the summer, several hundred hours of link performance statistics were accumulated and plotted from telemetry monitor data. Except for periods when a recognized degradation occurred, the 2270-MHz channel performance statistics were consistent with the predicted level and the 2217-MHz channel consistently showed the 1 dB lower performance than predicted. Meanwhile the combined performance was consistently about 0.5 dB below predicts and showed less than 0.2 dB degradation as compared to the sum of individual channels.

Figure 4 illustrates these points with data from a successful test on 1985 DOY 185 (July 4). Points to indicate the predicted levels have been added by hand, and the approximate residuals for the 2217-MHz channel and for combined data are indicated by the double-headed arrows. Figure 5 shows the test at 1024 bps on DOY 207 where again there was about a 0.5 dB residual between the predicted and observed performance for the combined data. This was reasonably consistent through the two months prior to encounter at the Goldstone 64-m system.

Most of the performance data for the combined performance were acquired at 512 bps, in part because the spacecraft was further away from June through August than it would be at encounter, and in part because the Network was not yet fully ready to support the planned encounter rate of 1024 bps. Operation at the 1024 bps data rate began 1985 DOY 226, and showed performance which was consistent with the 512 bps performance data after correcting for the 3 dB change in data rate In addition, early 1984 comparisons of predicted (minimum) vs observed (average) SSNR for the 2270 MHz channel at the higher data rates showed positive residuals of 0.8 to 1.0 dB, consistent with the difference between minimum and average SSNR for the rotating spacecraft. As noted before, equipment to handle the 2217 MHz channel signal was not available at that time.

VI. Expected Encounter Performance

Figure 6 is a sketch of the performance profile for the ICE encounter day. Each of the individual sites which would be supporting the encounter is shown. The indicated link margin for the specific time of encounter was low enough that the added 0.5 dB from arraying with the 34-m antennas was believed to be important to ensuring overall success. In the figuring of the contribution of the 34-m antennas, differences in antenna effective areas, system temperatures, and the loss due to the time delay of the DSS-12 signal were included. Because of the geometry, this time delay was no problem for the several hours around encounter, but reduced the DSS-12 contribution to only 0.1 dB by end of pass

Variations in observed performance are indicative of a tolerance which should be placed upon that expected for encounter. There is a short-term scatter in SER of about 0.2–0.3 dB, which could be an antenna pointing (conscan) artifact. There appears to be a gradual within-the-day downward drift in performance at both Goldstone and Madrid which accumulates to 0.2–0.4 dB by end of pass – i.e., in daylight hours. There is a day-to-day scatter of 0.3–0.4 dB. And there is at Goldstone one telemetry string (TPA-3) which continued to underperform the others with baseband (array) inputs. The performance profile for encounter was set to approximate the lower end of the day-to-day variations The probable tolerance about this profile was +0.7/–0.2 dB. Performance of the Goldstone 64-m antenna prior to encounter tended to be near the upper end of this range, while that at Madrid was at the lower end

Arecibo performance is discussed in Ref. 3 The received signal was nominally above telemetry threshold for all elevation angles of 75 deg or higher, and the received carrier level was about 3 dB higher at 80 deg than at 75 This implied that the telemetry margin at Arecibo would be on the order of 3 dB for the comet tail crossing which occurred at an elevation of about 85 deg. The Arecibo performance profile as sketched is mildly conservative, and was in fact exceeded by about one dB.

Usuda performance with one receive channel was comparable to, or slightly in excess of, that of the Goldstone 64-m antenna with the two channels combined (Ref. 9). The contributors to this were a higher antenna efficiency (62.4 dBi gain), and lower system temperature (14.5 K) in a listen-only configuration. These factors combined to make the Usuda effective performance about 2.7 dB stronger than that of the Goldstone 64-m single channel diplex configuration, or comparable to that of the Goldstone two-channel.

VII. Summary: ICE Encounter

The passage of ICE through the tail of comet Giacobini-Zinner took place on 1985 Sept 11, at approximately 1104 GMT. All three supporting sites, Madrid, Arecibo, and Goldstone, reported good performance and successfully acquired spacecraft data during the tail crossing Figure 7 shows the observed performance of the two DSN sites for this time interval. Madrid essentially performed at the expected level, while Goldstone's performance exceeded it Arecibo operated above threshold for almost 2.5 hours on the encounter pass, far longer than on any other day. Such problems as did occur were minor and did not affect more than one site at a time. There is no sign of the anticipated degradation due to comet dust or other factors in the vicinity of the comet. All supporting sites acquired ICE data at the desired 1024 bps data rate.

In summary, the International Sun Earth Explorer-3 was retargeted for an encounter with comet Giacobini-Zinner with the expectation that scientific data about the constituents of the comet's tail could be acquired at a data rate of 1024 bps. Link margins were very slim, even though the DSN was being outfitted to receive and combine both downlinks from the spacecraft. Several times prior to the encounter, problems arose which threatened the viability of the expected support. But in the final analysis, the expectations were fulfilled, and much new data (described by the scientists as very exciting) were acquired about the comet.

Acknowledgment

Successful support to the International Cometary Explorer is the product of the labors of many devoted people. Some of these are the authors of the many companion articles referenced in this article. Other key JPL contributors include W. L. Martin, T. O. Patterson, and S. S. Kent, plus the many unnamed workers of the DSN Operations Organization and Performance Analysis Groups who provided extra attention and effort when it was needed.

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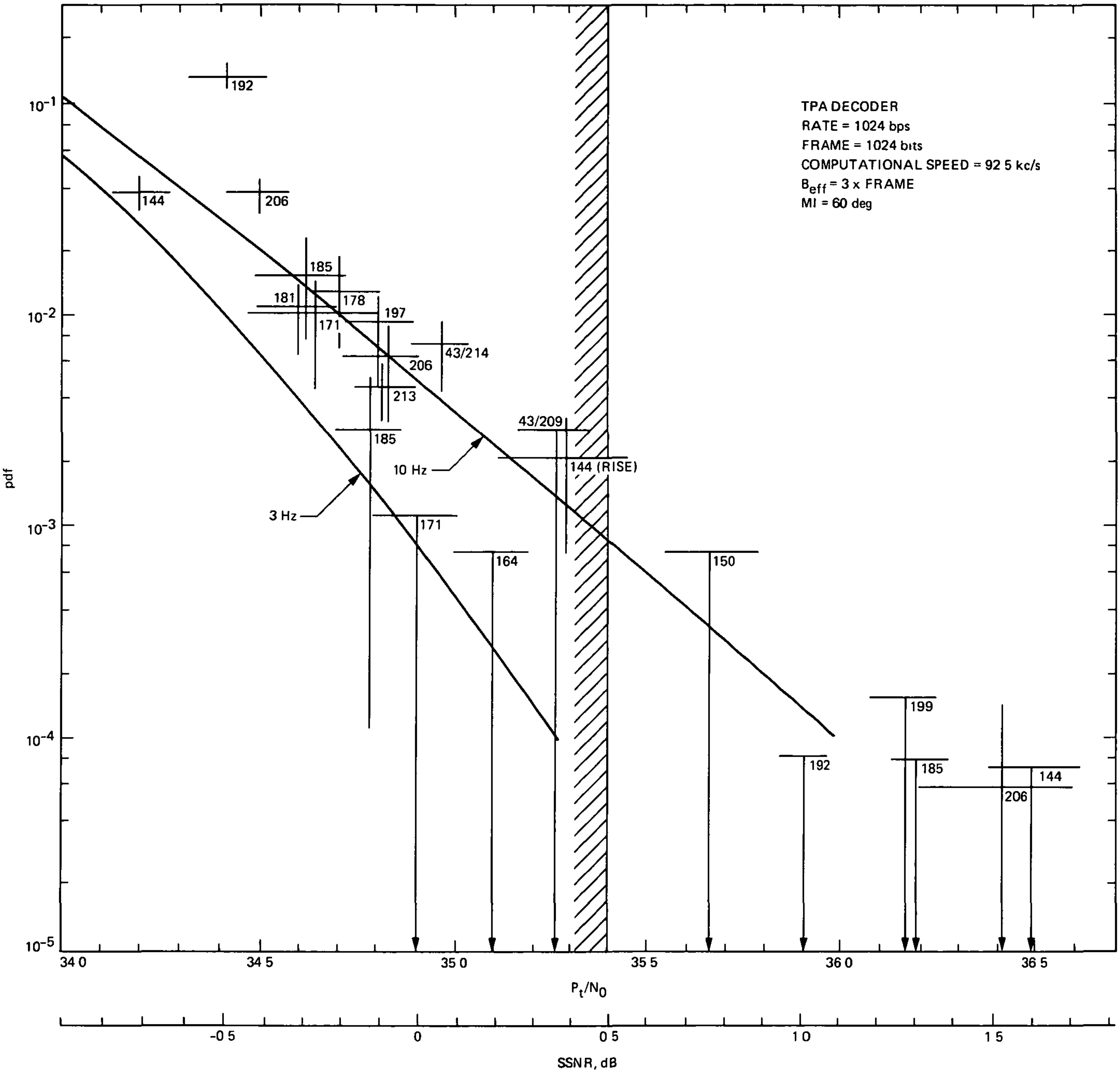

Fig. 1. Test summary and performance curves for single channel tests

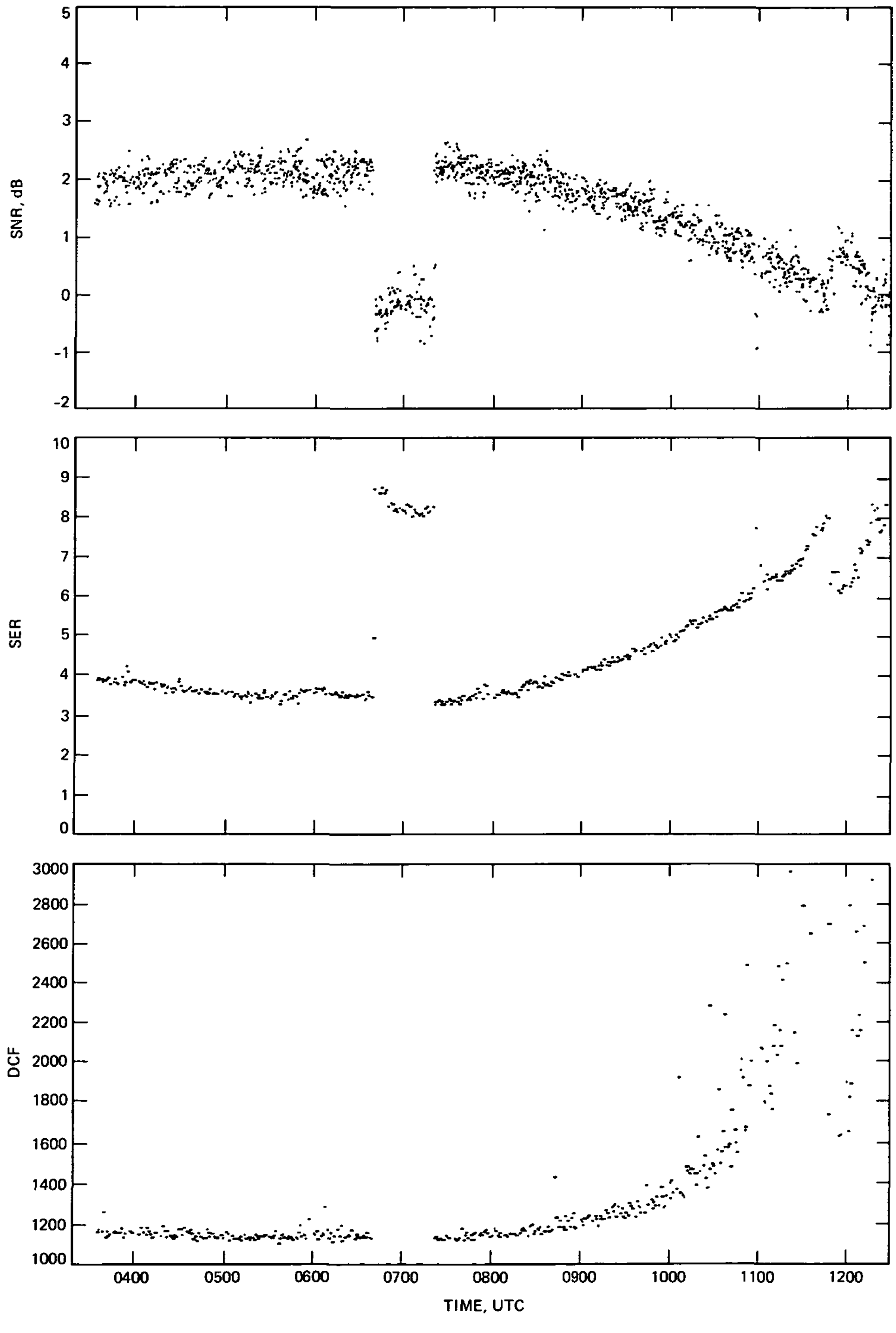

Fig. 2. Performance of Madrid 64-meter system for 1984 DOY 1985

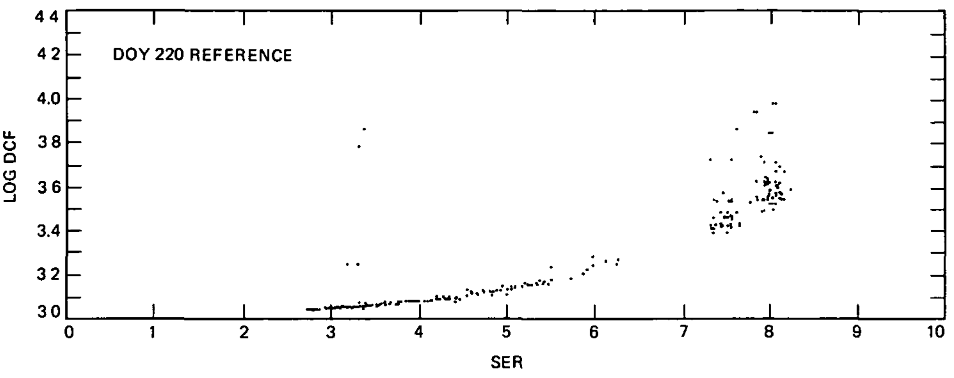

Fig. 3. Decoder computations vs symbol error rate

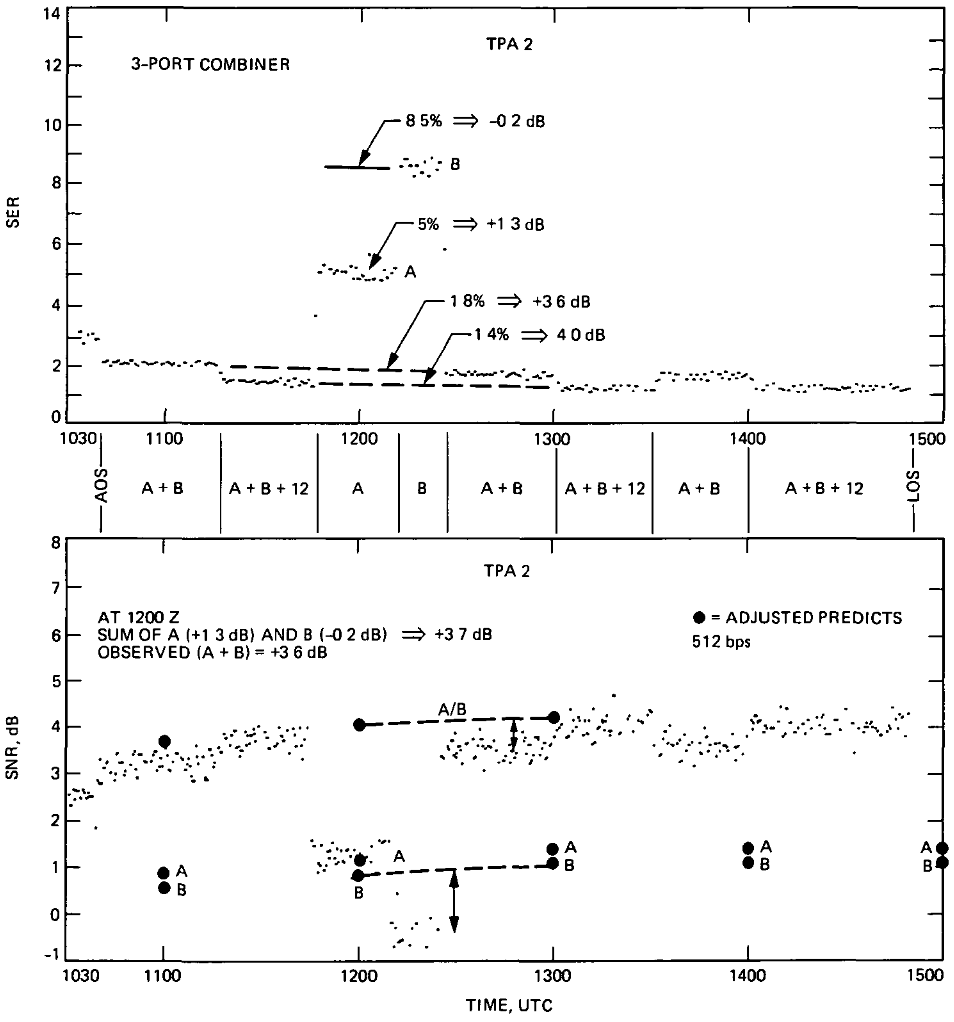

Fig. 4. Performance of Goldstone at 512 bps on 1985 DOY 185

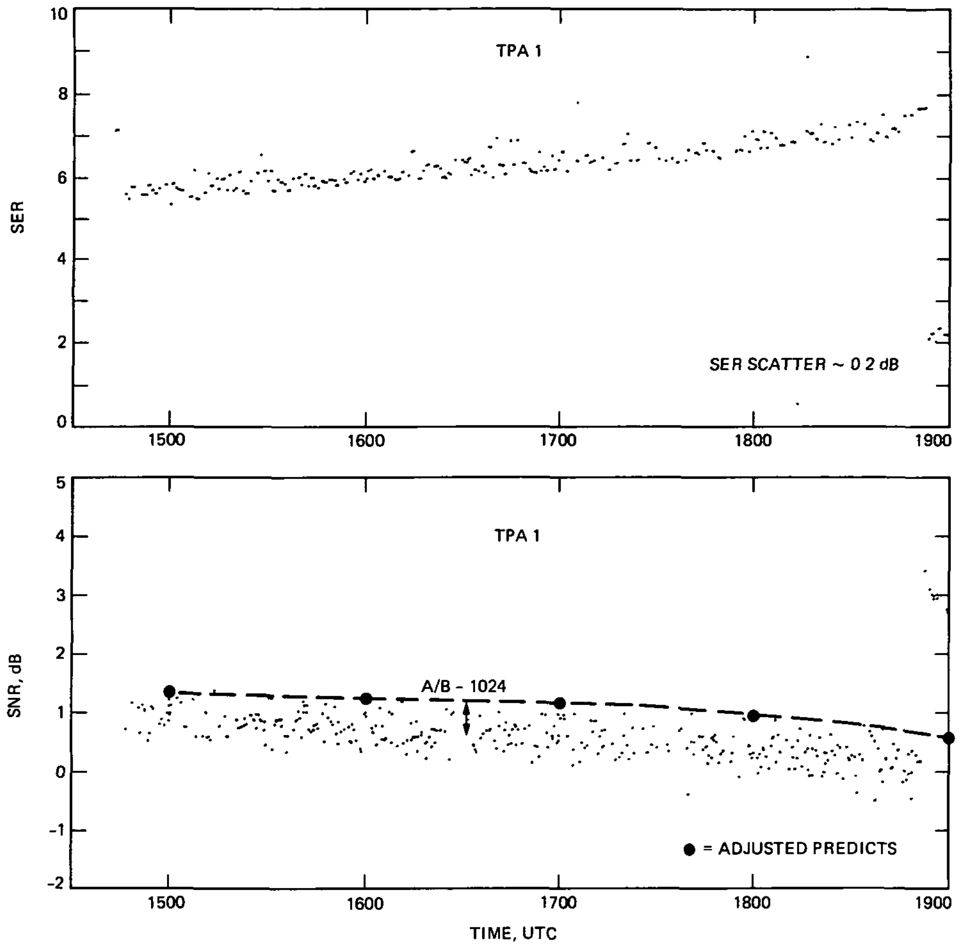

Fig. 5. Performance of Goldstone at 1024 bps on 1985 DOY 207

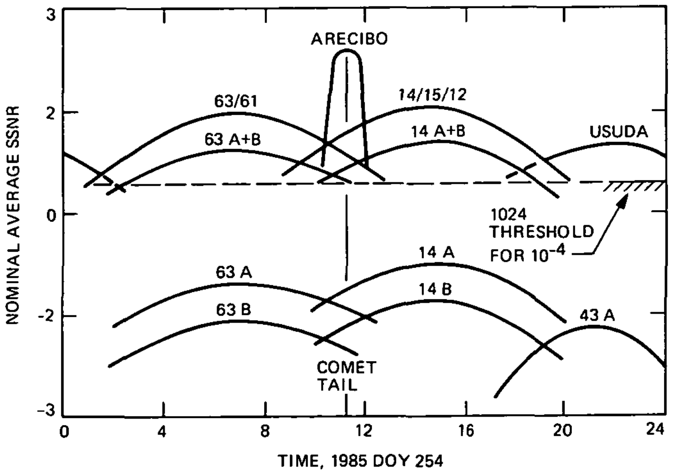

Fig. 6. Expected Encounter-day link performance for ICE

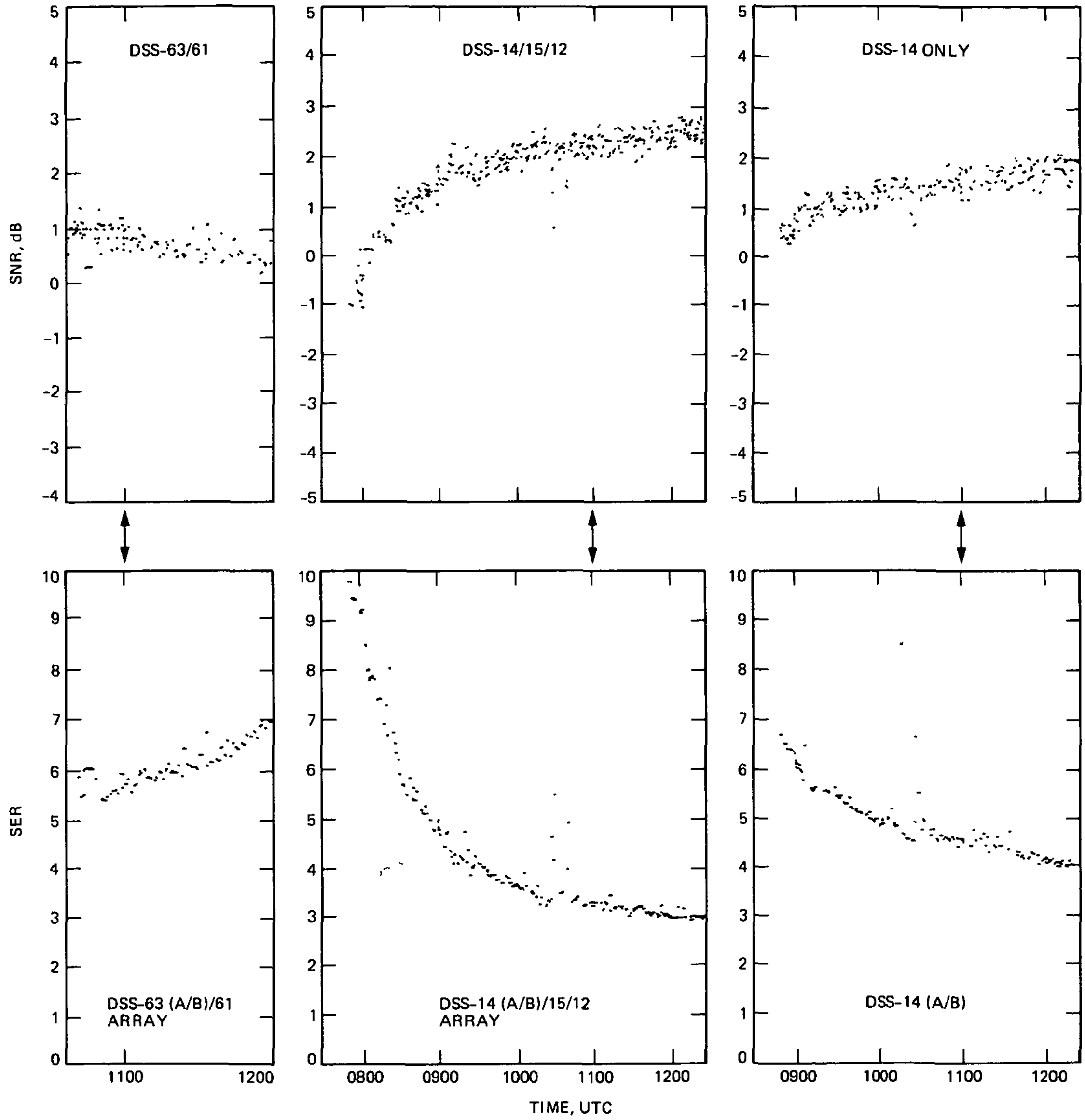

Fig. 7. Observed ICE link performance at Encounter. Comet tail crossing = 1104 Z on DOY 254