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Intercontinental Antenna Arraying by Symbol Stream Combining at ICE Giacobini-Zinner Encounter

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Deep space tracking stations on different continents were arrayed during the encounter of the International Cometary Explorer (ICE) spacecraft with the comet Giacobini-Zinner during September 9 through 12, 1985. This is the first time that telemetry signals received on different continents have been combined to enhance signal-to-noise ratio. The arraying was done in non-real time using the method of symbol stream combining. The improvement in signal-to-noise ratio was typically 2 dB over the stronger of the two stations in each array.

I. Introduction

Symbol stream combining is a promising method of antenna arraying to enhance telemetry performance. Its main advantage over baseband combining is that much less data need to be transmitted from the stations to the combiner location. For example, for the Giacobini-Zinner data rate of 2048 symbols/s, the data rate for symbol stream combining is 16 kilobits per second (kb/s), whereas the data rate for baseband combining is approximately 90 Mb/s, or 6 MHz analog bandwidth. The savings are 3 to 4 orders of magnitude either in ground communications link capacity, for a real-time system, or in data storage capacity, for a non-real-time system (Ref. 1).

The theoretical performance of symbol stream and baseband combining is the same, except for minor differences in synchronization losses and in data transmission losses in a real-time baseband combiner with an analog ground link. On balance, there is a slight advantage for symbol stream combining of 0.2 dB ±0.2 dB (Ref. 1).

The International Cometary Explorer (ICE) spacecraft encounter with the comet Giacobini-Zinner presented an ideal opportunity to demonstrate symbol stream combining, and, at the same time, to provide enhanced reliability to the mission. As ICE passed through the comet tail, on September 11, 1985, the spacecraft was visible from the DSN complexes at Goldstone, California, and Madrid, Spain, as well as from the Arecibo Radio/Radar Observatory in Puerto Rico. Neither Goldstone nor Madrid has sufficient antenna aperture to reliably receive the signal at 1024 bits per second (b/s) (2048 symbols/s), in the event of signal loss due to the comet tail. Thus, Arecibo acted as a real-time backup capability, and symbol stream combining between Goldstone and Madrid provided a non-real-time backup capability with sufficient antenna aperture to provide reliable signal reception in the event of the above-mentioned degradations.

Symbol stream combining was also performed between Usuda, Japan, and Goldstone, between Canberra, Australia, and Usuda, and between Canberra and Goldstone. An additional benefit to the combining system is that it recorded the telemetry symbols prior to decoding, thus providing redundancy in case of failure of the real-time decoders.

II. System Description

Figure 1 shows the overall block diagram of the non-real-time symbol stream combining system. Data are recorded in real time to magnetic tape at the Deep Space Network (DSN) stations and Usuda. The tapes are then brought to JPL where the symbols from station pairs are combined on a VAX 750 computer.

The combining software produces a tape of combined data in the same format as the original tapes. Statistics for both input tapes and the output tape are also produced by the combining software. These statistics include input and output symbol signal-to-noise ratios (SNRs), signal levels and dc offsets and data stream alignment points. The combined output symbol stream is then decoded in a VAX 750 computer, and an output tape of decoded data is produced in the same standard format as for data decoded at DSN stations.

A. Station Configurations

All data received for the non-real-time combining process, except for Australia, were produced using the 64-m antennas in a stand-alone mode and a Telemetry Processing Assembly (TPA) Modcomp Computer at each station. The ICE spacecraft transmits data from two antennas mounted on top of the spacecraft. Identical data symbols are transmitted on two S-band carriers: channel A at 2270 MHz and channel B at 2217 MHz. Except for day of year (DOY) 255, the spacecraft data rate was 1024 b/s. On DOY 255 the data rate was 512 b/s.

From both Spain and Goldstone, data from channels A and B were received on one 64-m antenna, and combined using resistor networks. Data received from Usuda were channel A only. Data received from Australia were channel A only, with one 64-m antenna and one 34-m antenna arrayed. Figure 2 shows the configuration of the Madrid and Goldstone stations and the resistor combining network.

B. Recording

Soft symbols quantized to 8 bits were recorded at Usuda using a MARK III telemetry string and at Goldstone, Spain, and Australia using MARK IV telemetry strings. The MARK III and MARK IV TPA software were modified to accommodate the soft symbol recording requirements. These modifications included changes to the TPA/SSA coupler commands so that the coupler would pass the full 16-bit quantized symbol from the Symbol Synchronizer Assemblies (SSAs) to the TPAs. The modified software strips off the high order 8 bits, which are merely the extended sign of the symbol value, packs the low order 8 bits into 16-bit words, and stores these words into buffers in the standard Original Data Record (ODR) format shown in Figure TLM-3-13-2 of the 820-13 document. These buffers are written to the magnetic tape. One tape record comprises five of these buffers, for a total of 2850 symbols per record. Tape handling, which included the ping-ponging between the two TPA tape drives and the operator prompts to the Local Monitor and Control (LMC), is performed in the standard TPA fashion. The soft symbol recording software is invoked from the LMC with the same commands that invoke the standard TPA software.

C. Combining

The combiner program was written in VAX/VMS FORTRAN and can take inputs from tape, disk or a combination of tape and disk. The program performs three functions: alignment, SNR and weight estimation, and combining.

The data are stored on tape in ODR format. The two incoming streams of records must be shifted relative to one another because the different geographical locations of the stations result in different arrival times of the same symbols at different stations. Data which are recorded when two stations were receiving spacecraft data simultaneously are combined by the program.

The alignment is done in two steps. First, a rough alignment is performed using the time tags in the headers of the ODR record. The time tags indicate the ground received time of the last bit in a block of data and are accurate to 1 ms. Once the tapes from each station have been aligned using the time tags, the difference between two adjacent time tags on the same tape is used to compute the symbol alignment positions within a data block. The data are then separated from the header portion of the record and placed in a separate array for the second step, fine alignment. The symbols from the two tapes are cross correlated for the 2850 lags closest to zero delay, as predicted from the above alignment. These values are used to compute a correlation threshold. The point at which the greatest correlation value occurs is the symbol alignment point, provided that this peak value exceeds the threshold.

SNRs and weights are computed for each data stream, for every record. The algorithm to compute SNR and symbol stream weights uses sums of absolutes and sums of squares and is described in Ref. 2. The 2850 symbols used to estimate SNRs and combined weights are sufficient to result in a loss due to weighting errors of less than 0.02 dB. SNR variations caused by rotation of the spacecraft transmitting antenna are described in Ref. 3.

In the combining step the data symbols and weights are used to produce a single output data stream. To combine the two streams, two aligned symbols are each multiplied by their weights and added together to produce the combined output symbol. This process is repeated for each symbol to produce a combined output stream. The combined data are placed back into the data portions of the first tape's record. This record is then written out to tape, ready for decoding. The SNR of the combined symbols is estimated using the same algorithm as for the input symbols, and the combining efficiency is calculated. This efficiency (in dB) is the sum of the input SNRs, less the SNR of the combined symbols.

D. Decoding

Decoding is performed by a software decoder written in "C" language on a VAX 750 computer. This sequential decoder is based on the Fano algorithm and uses soft quantized input symbols, as described in Ref. 4.

The decoder also performs the task of frame synchronization, by correlating the channel symbols with a known "tail pattern." For the ICE code, the total frame size is 1024 bits (2048 channel symbols), where 984 bits are information and 40 are tail. The particular tail pattern used is (at the encoder input):

{0,0,0,1,0,0,1,0,1,1,1,1,1,1,0,0,1,0,0,0,0,0,0,1,1,
0,0,1,1,1,1,1,1,0,1,1,1,1,1,0}

Since the code rate is 1/2 and the constraint length K is 24, there are 80 channel symbols due to the tail, of which

$$80 - 2(K-1) = 34$$

form a fixed pattern, independent of the data. Synchronization is based on these 34 fixed symbols:

{-1,1,1,1,1,1,1,-1,1,-1,1,1,1,1,-1,-1,1,1,-1,-1,1,
1,-1,1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,}

and is continuously checked and reacquired if necessary.

The decoder has two kinds of output: one is the actual decoded data and the other is statistics on the probability of frame deletion, average number of computations per frame, and information on which frames were deleted.

E. Output Tape

The output decoded data are written to a tape in DSN-Goddard Space Flight Center (GSFC) format.

III. Results

All data received simultaneously from station pairs were combined successfully and decoded. Figure 3 shows the DOY and times of data received. Encounter day was September 11, 1985, DOY 254. For days 252, 253, 254, and 255, data were received from Goldstone and Usuda. Data were received from Spain and Australia for DOY 254. Overlap times were approximately 1.5 hours for Goldstone and Usuda, 5 hours for Goldstone and Spain, 4 hours for Goldstone and Australia, and 4 hours for Usuda and Australia.

Figures 4 through 7 were produced from data generated by the combiner program. They show the SNR of the two input symbol streams, the SNR of the combined symbols and the efficiency of the combining process, as functions of time.

Figures 4(a), (b), (c), and (d) show the Usuda–Goldstone results for the four days. All data were at a bit rate of 1024 b/s except for DOY 255. At the 1024-b/s data rate, the symbol SNR for Usuda is typically 2 dB, increasing slightly with time as the antenna elevation angle increases. Performance of the telemetry string used at Goldstone for symbol recording was somewhat weaker than that used for real-time data. The SNR from the Goldstone 64-m antenna decreases from approximately 0.2 dB to -0.7 dB as the elevation angle decreases. The combining efficiency is approximately -0.3 dB. A short signal outage is apparent at Usuda on DOY 253. The results at 512 b/s, DOY 255, are similar but with 3 dB higher SNRs.

Figure 5 shows the Goldstone–Spain results for DOY 254. The symbol SNR increases at Goldstone and decreases at Spain as the elevation angles change. The combined SNR is typically 3.7 dB, and the efficiency is -0.1 dB. There were several short intervals of lower SNR at Spain and one such interval at Goldstone.

Figure 6 shows the Goldstone–Australia results for DOY 254. Results are similar to the above, with more change in SNR due to antenna elevation. The combined SNR is typically 2.7 dB, and the efficiency is -0.3 dB.

Figure 7 shows the Usuda–Australia results for DOY 254. Because Usuda and Canberra are close to each other longitudinally, the symbol SNRs increase and decrease together. The combined SNR is typically 3.7 dB, and the efficiency is -0.3 dB.

A. Combiner Efficiency

The combining efficiencies varied from –0.1 to –0.3 dB. There is some small loss in the combining process, due to imperfect weighting of the data from the different stations and due to quantization, but these losses are believed to be less than 0.1 dB. There is some error both in defining and in measuring the symbol SNRs, because the signals are time-varying and the measurement assumes constant SNR. Another possible cause of inefficiency is the time-varying nature of the signal strengths, and the differences in this time-varying nature for the different stations. These differences are due to reception of channel A only at some stations and channels A and B at other stations, and due to ground antenna conscan. Examples of these variations are given by Nadeau (Ref. 3). Exact characterization of the effects of these variations on combiner efficiency is outside the scope of the present work.

B. Decoding Results

The software decoder and synchronization system was used successfully to decode a number of combined data tapes.

Due to the high SNR, no frame deletions occurred in decoding the combined symbols, nor did frame synchronization errors occur. This confirmed that the data had been properly combined, formatted, and correctly interfaced with the decoder. Except for Usuda, the uncombined symbol streams did not have high enough SNRs for this error-free decoding. This dramatically illustrates the usefulness of symbol stream combining.

IV. Summary

This work establishes the feasibility and the utility of intercontinental antenna arraying by symbol stream combining. Data were taken at four tracking complexes in California, Japan, Spain, and Australia. Data were successfully combined on all four antenna pairs where there was mutual visibility of the spacecraft. Most important, all data were successfully decoded, demonstrating the reliability and applicability of the system.

References

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3. Nadeau, T., "Periodic Variations in SNR of Signals Received from ICE Spacecraft," *TDA Progress Report 42-84*, this issue.

4. Pollara, F., "A Software Simulation Study of a Sequential Decoder Using the Fano Algorithm," *TDA Progress Report 42-81*, Jet Propulsion Laboratory, Pasadena, Calif., pp. 40–46, May 15, 1985.

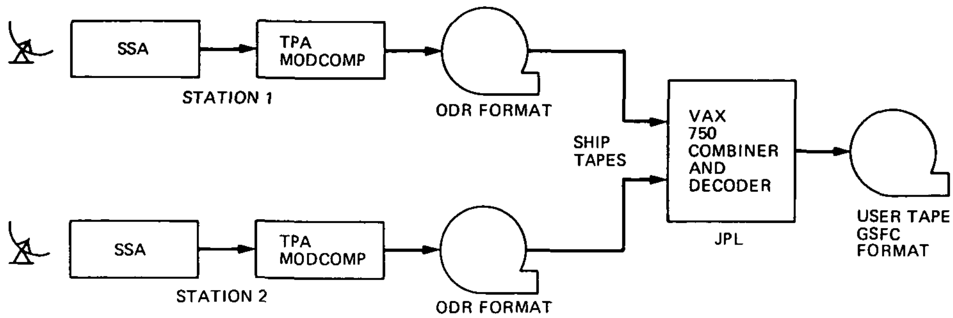

Fig. 1. Non-real-time symbol stream combiner block diagram

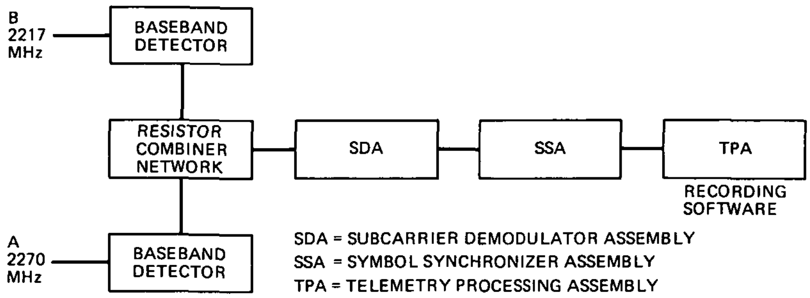

Fig. 2. Symbol stream recording hardware block diagram

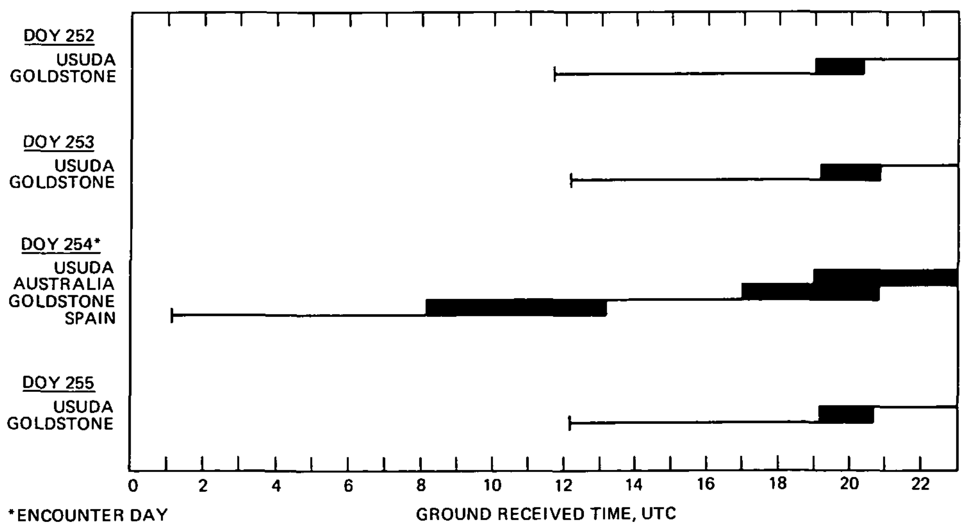

Fig. 3. Tracking coverage

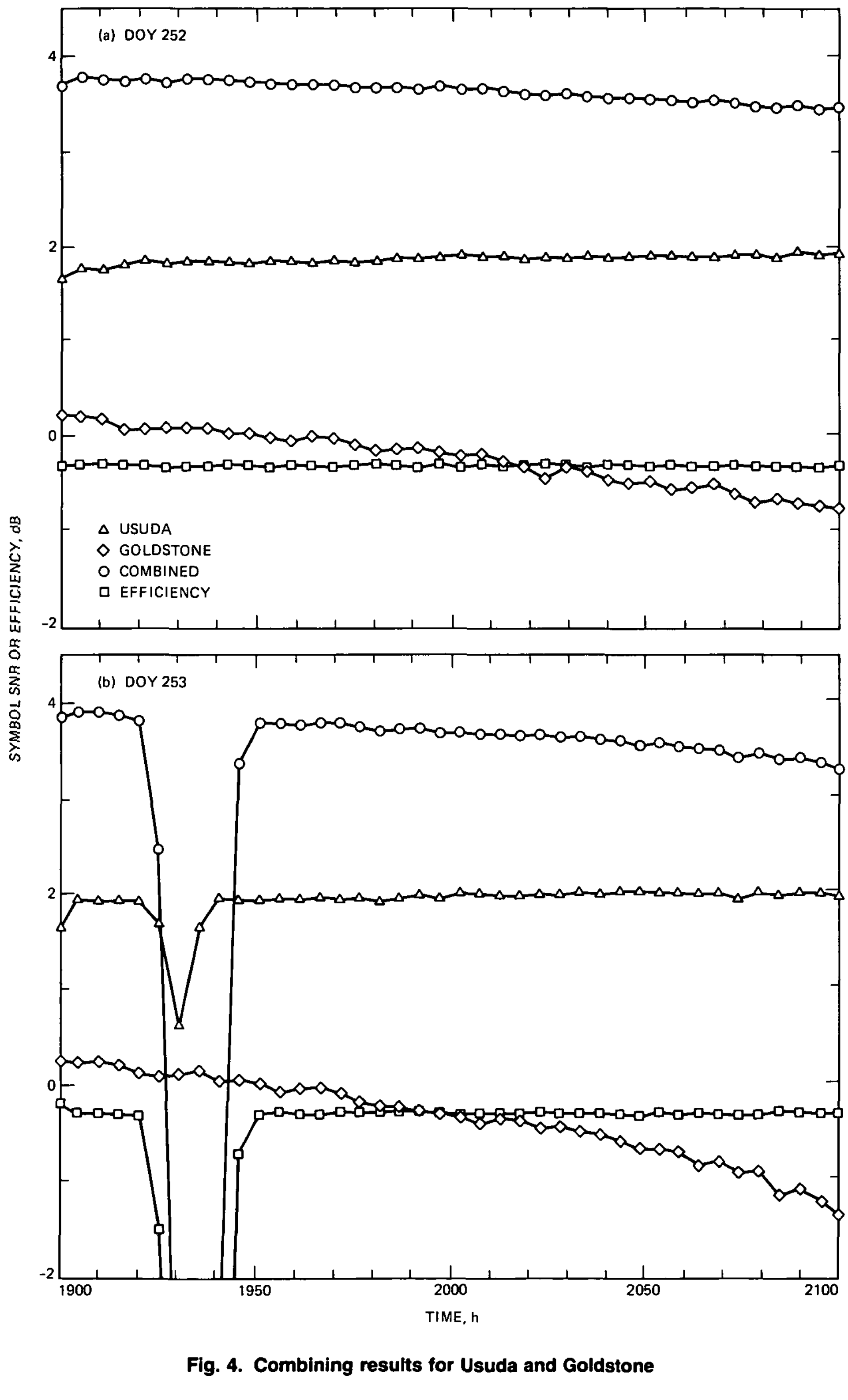

Fig. 4. Combining results for Usuda and Goldstone

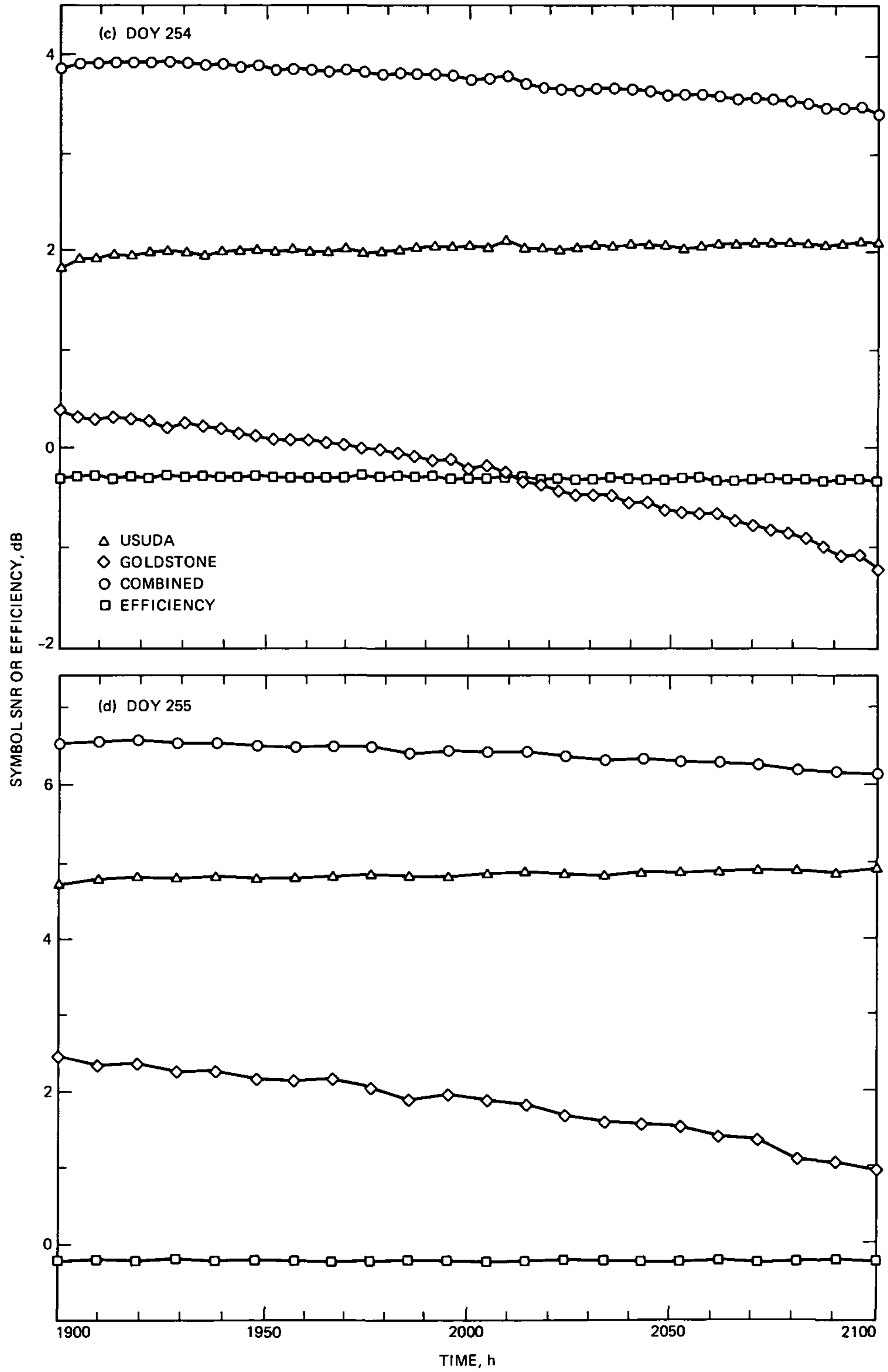
(c) DOY 254
4
2
0
-2
△ USUDA
◇ GOLDSTONE
○ COMBINED
□ EFFICIENCY
SYMBOL SNR OR EFFICIENCY, dB
(d) DOY 255
6
4
2
0
1900
1950
2000
2050
2100
TIME, h

Fig. 4 (contd)

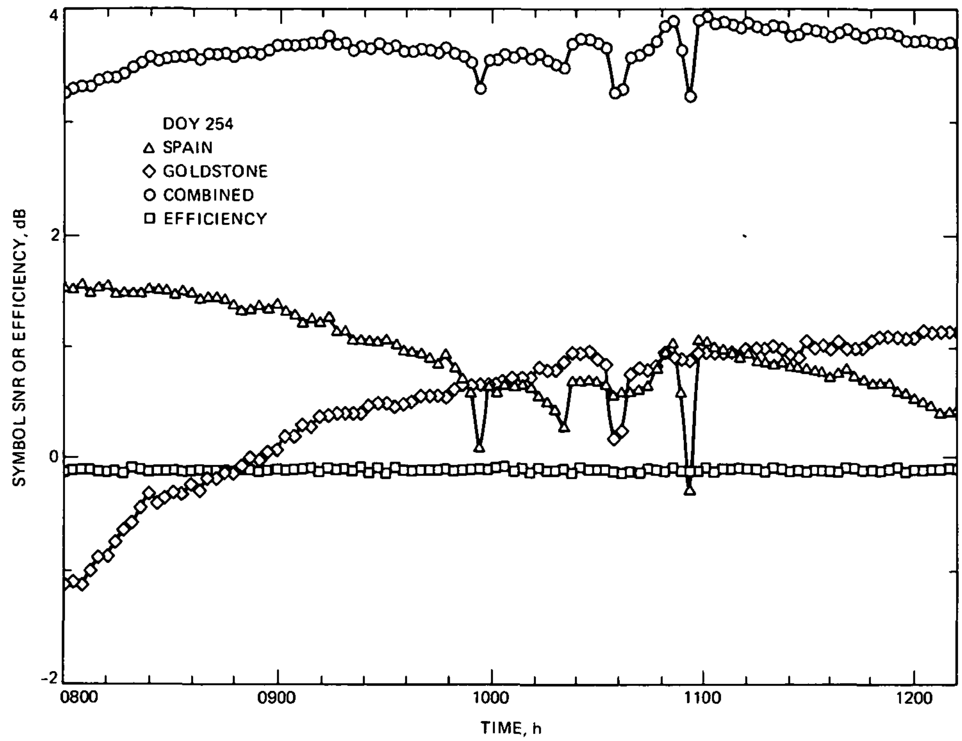

Fig. 5. Combining results for Goldstone and Spain

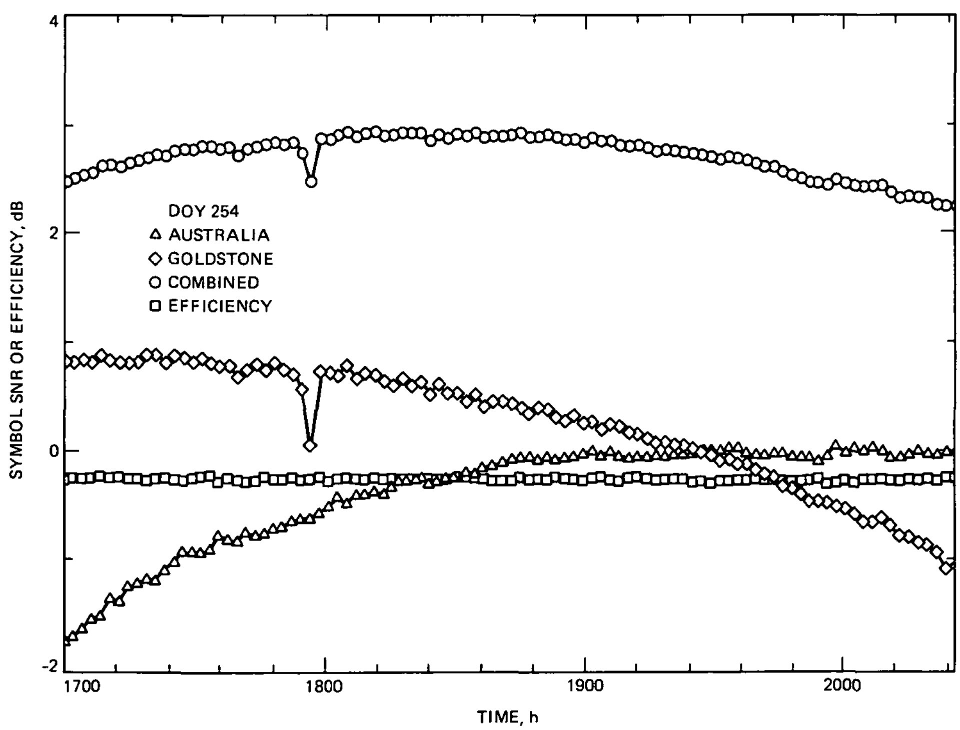

Fig.6. Combining results for Goldstone and Australia

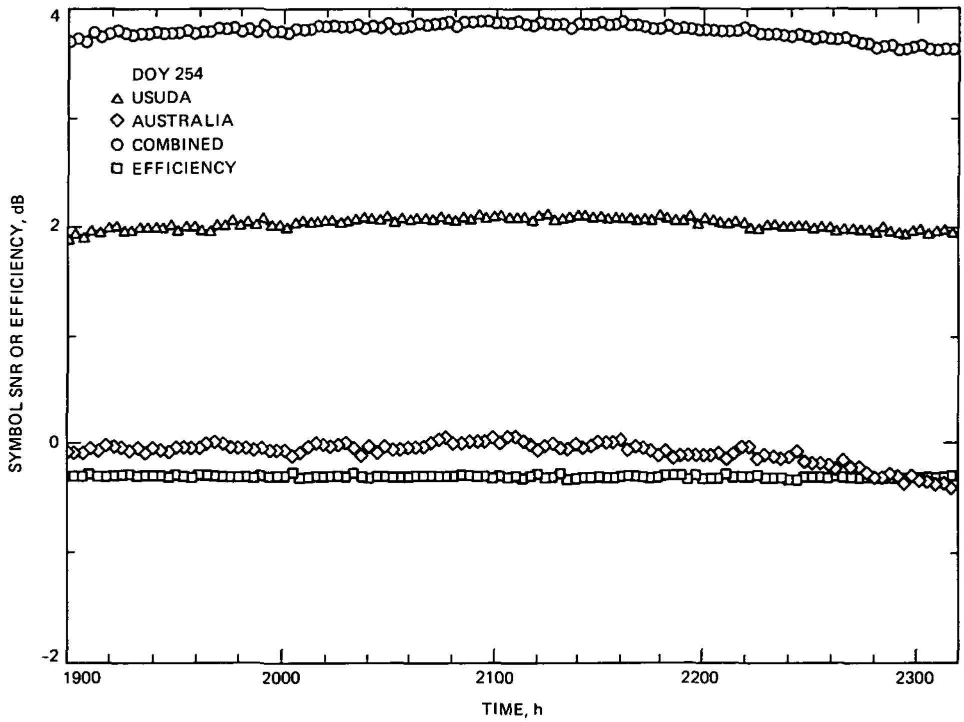

Fig. 7. Combining results for Usuda and Australia