Antenna Arraying of Voyager Telemetry Signals by Symbol Stream Combining

W. J. Hurd, J. Rabkin, M. D. Russell, and B. Siev
Communications Systems Research Section

H. W. Cooper
Radio Frequency and Microwave Subsystems Section

T. O. Anderson and P. U. Winter
DSN Data Systems Section

Telemetry signals received from the Voyager 2 spacecraft at Deep Space Stations at Parkes and Canberra, Australia, on February 6, 1986, were combined by the method of symbol stream combining. This second demonstration of symbol stream combining followed the International Cometary Explorer (ICE) demonstration at Giacobini-Zinner encounter in September 1985. The Voyager demonstration was at a symbol rate of 43.2 ksymb/s, compared to 2 ksymb/s for ICE. Recording, playback, and combining at this higher rate were demonstrated. The average symbol signal-to-noise ratio (SNR) of the combined data was 2.84 dB, or 0.23 dB less than the sum of the SNRs of the two input symbol streams. This 0.23 loss from ideal combining was due to use of 4-bit quantization of the input symbol streams and imperfect scaling. A practical implementation with 8-bit quantization could achieve combining losses of under 0.05 dB over a wide dynamic range of input signal levels.

I. Introduction

Use of symbol stream combining for arraying antennas to enhance telemetry performance was first demonstrated in 1985. Signals from the International Cometary Explorer (ICE) spacecraft were combined as the spacecraft encountered the comet Giacobini-Zinner (Ref. 1). The data rate was 2 ksymb/s. This paper describes a second demonstration, using data from Voyager 2 taken February 6, 1986, at a data rate of 43.2 ksymb/s. This higher rate was enabled by changes in both the data acquisition and the combining systems.

The basic system configurations for symbol stream combining and baseband combining are shown in Fig. 1. First, consider real-time systems. In baseband combining, a broadband ground communications link is used to transmit the baseband signal to the local station where the combining is done. The link bandwidth is typically 5 MHz. The combined baseband signals are processed by the telemetry detector (subcarrier demodulator and symbol synchronizer and detector) and the decoder at the local station. In symbol stream combining, the signals at the two stations are processed through telemetry detection. The symbol streams are represented as sequences of digital numbers. The symbols from the remote station are transmitted over a digital link to the local station where they are combined and decoded. The symbol quantization is typically 4- to 8-bits. For 8-bit quantization and the maximum symbol rate of 43.2 ksymb/s for Voyager at Neptune encounter, the link data rate is 346 kb/s. These data can be transmitted with an order of magnitude less link capacity than required by the baseband system.

Now consider non-real-time combining. For the Parkes baseband array, the baseband signal was low-pass filtered and then sampled at 6 MHz with 4-bit quantization, and recorded with a digital recording rate of 24 Mb/s. The symbol stream data for the present demonstration were quantized to 4 bits and recorded at 173 kb/s, for a two-orders-of-magnitude savings in recording rate over baseband combining.

The reduced data rates for real-time and non-real-time realizations are the main advantages of symbol stream combining over baseband combining. Combining is also easier, since the data rate is lower, and combining can be done in either hardware or software. Combining performance is at least as good for symbol stream combining as for baseband combining, with losses of 0.05 dB ± 0.05 dB possible in an 8-bit quantized symbol stream combining system. Total system losses for the Parkes baseband array are specified as less than 0.4 dB, due to inability to measure performance much better than this operationally.

Other telemetry system losses are approximately the same using symbol stream or baseband combining. Carrier tracking (radio) losses are the same. Subcarrier and symbol tracking losses will be small in a demodulation system designed for low symbol SNRs, such as the DSN Advanced Receiver. Subcarrier losses are kept small at all symbol SNRs of interest by the new technique of Hurd and Aguirre (Ref. 2).

II. Combining Theory

This section presents the basic relationship for telemetry arraying by symbol stream combining. Losses due to quantization of the symbol values are discussed. Then the methods used to estimate SNR are presented. Finally, overall performance is summarized.

A. Problem Formulation

A block diagram showing the mathematics of symbol stream combining is given in Fig. 2. The input detected symbols from Stations 1 and 2 are denoted by X_{1i} and X_{2i} for the i^{th} symbol. These may be quantized by the detection, recording, ground link communications, or combining process, to obtain Y_{1i} and Y_{2i}. These values are multiplied by weights W_1 and W_2, and the products are summed to obtain the combined symbols, Z_i. The Z_i may be further quantized to form the symbol values S_i, which are processed by the decoder. From now on, we neglect this output quantization, since it is normally a property of the decoder rather than of the combiner. That is, decoders typically quantize the inputs to 3 bits. This dominates the resolution of the combiner.

B. Combining Unquantized Symbol Values

The case of no-input quantization has been well analyzed by Vo (Ref. 3). Suppose that the input symbol mean values for binary symbol values ±1 are $\pm m_1$ and $\pm m_2$, that the variances are σ_1^2 and σ_2^2, and that these parameters are constant. Then the input symbol SNRs are

$$R_i = \frac{m_i^2}{2\sigma_i^2}$$

The optimum combining weights are

$$W_i = \frac{m_i}{\sigma_i^2}$$

and the resulting output SNR, i.e., the symbol SNR of Z_i, is

$$R_0 = R_1 + R_2$$

This is the best that can be achieved, and is the same as the best that can be achieved in baseband combining.

In practice, one does not know the input parameters a priori, so they need to be estimated. Vo (Ref. 3) has studied this problem and has determined the loss in output symbol SNR versus the number of symbols used to estimate the SNRs. The SNR estimation method is the absolute moment method, with unbiasing. For input SNRs of –1 dB and –3 dB, the loss is approximately 0.03 dB if 1000 points are used to estimate the SNRs, and under 0.005 dB if 10,000 points are used. The loss is smaller at higher input SNRs.

C. Effects of Quantization

When there is quantization of the input symbols, the probability distributions of the quantized input symbols and of the combined symbols are no longer Gaussian, conditioned on the transmitted symbol values. Performance, or loss due to quantization, may not be characterized accurately by signal-to-noise ratio. However, SNR is a convenient measure, and our approach here is to determine the loss in SNR due to quantization. Even though our approach does not accurately characterize telemetry system performance, it does accurately characterize loss in symbol SNR, and agreement between theory and experimental results confirms understanding and proper operation of the system. The SNR of the quantized and combined symbols is maximized by using the means and variances of the quantized symbols in calculating the weights. Letting primes denote quantization, the weights are

$$W'_i = \frac{m'_i}{(\sigma'_i)^2}$$

where m'_i and σ'_i are the mean and standard deviation of the station i symbols after quantization. Then the SNRs of the quantized symbols are

$$R'_i = \frac{(m'_i)^2}{2(\sigma'_i)^2}$$

and the best achievable output SNR is

$$R'_0 = R'_1 + R'_2$$

If the quantizer losses (in decibels) are the same for both quantizers, then the loss at the output is equal to the loss in either quantizer. Thus, the maximum of the two quantizer losses is a simple upper bound on loss.

Figure 3 shows the input quantization loss in decibels, i.e., 10 $\log_{10}$ (R_i/R'_i), for 4-bit quantization, with various values of m, in units of the quantizer output. The value m = 2.7 corresponds to the nominal value if the 8-bit quantized symbols at the output of a DSN Symbol Synchronizer Assembly (SSA) or Demodulator Synchronizer Assembly (DSA) are re-quantized to the appropriate 4 bits. The other values are for gain variations of 3 dB and 6 dB from the nominal. Note that the loss is sometimes negative, i.e., there is a gain in SNR. This occurs when the quantizer is saturating, which reduces variance more than it reduces conditional mean square. This does not indicate a gain in telemetry system performance, but it does indicate an increase in mean square to variance of the symbol values.

We computed the loss in SNR for the parameters of the demonstration, obtaining a calculated loss of 0.13 dB ± 0.1 dB.

1. **Decoding of quantized and combined symbols.** Prior to the decision to use 4-bit quantization for the demonstration, Pollara and Swanson (Ref. 4) simulated the effect of input symbol quantization, through the decoder, including the effect of 3-bit quantization at the decoder input. The input SNRs and weights were equal. They concluded that the loss due to combining the combiner input quantization is approximately 0.04 dB ± 0.02 dB at input symbol SNRs of –2 dB to –3 dB. From Fig. 3, there is a gain in SNR of 0.1 dB at –3 dB and of 0.04 dB at –2 dB. This illustrates the inadequacy of the mean square to variance SNR approach insofar as characterizing telemetry performance. On the positive side, it concludes that degradation due to quantization is small.

2. **Summary of quantization effects.** We conclude that quantization is the dominant effect on symbol SNR, i.e., it is a much larger effect than the loss in SNR due to imperfect weights. Quantization can cause either an increase or a decrease in SNR, or mean square to variance. The degradation in telemetry performance, through the decoder, is approximately 0.04 dB ± 0.02 dB, for typical cases of interest for Voyager. Accurate characterization of the telemetry performance of a combiner with 4-bit quantization would require extensive simulations over a wide range of quantizer scalings and input SNRs.

D. SNR Estimation for Quantized Symbols

Use of 4-bit quantization has a significant effect on the accuracy of the unbiased moment method of SNR and weight estimation. The quantization noise is very large at low input signal levels, and saturation dominates at high input signal levels. In either case, severe biases occur in the estimates of SNR, mean, and standard deviation.

To overcome this problem, Vilnrotter and Rodemich (Ref. 5) developed a new method of estimating the input parameters from the sample absolute first and second moments. This method is to perform a two-dimensional table look-up to determine m and σ from the sample moments. The method accounts for the DC offset inherent in the quantizer code. Preliminary evaluations of the method indicate that the estimates of SNR have zero bias, ±0.02 dB, for input symbol SNRs from –3 dB to 1.5 dB, and for input means of 1.3 to 3.8. The effect of this on the combiner weight bias causes a negligible loss in combiner output SNR. Random variations in the SNR estimates were also evaluated. For the 5700 points used to estimate SNR in the software combiner, the standard deviation of SNR estimation was approximately 0.017 dB for SNRs from –1 dB to 1 dB. This performance is close to that of the unbiased moment method without quantization, so the effect on weight estimation is similar.

The table look-up method estimates the signal mean and noise standard deviation at the input of the quantizers, rather than at the output. In the demonstration, we used these values to compute the weights. The loss due to using this procedure is negligible because the scaling and SNRs of the two symbol streams were so similar that differential biases are negligible. However, an implementation should change the algorithms to use the estimates of the parameters at the quantizer outputs.

E. Performance Prediction Summary

Performance is dominated by quantization of the input symbols. The only other loss is in use of improper combiner weights, but this can be kept to less than 0.01 dB by using sufficient data to estimate the SNRs and the weights. This assumes that the signal parameters are constant or slowly varying. SNR is not an accurate measure of system performance, because of the nonlinearities. Decoder performance should be considered.

For 4-bit quantization, performance losses can be as low as 0.05 dB with proper quantizer scaling and at the SNRs of primary interest, near decoder threshold.

It appears that use of 5-bit quantization would enable losses of less than 0.05 dB over a wide range of scaling. However, this is not a convenient quantization for non-real-time systems, in which the data are typically stored in byte-oriented storage media. Use of 8-bit quantization would make quantization losses negligible – less than 0.01 dB. Time-varying signal level effects might begin to dominate in some situations, since good SNR estimates require 5000 to 10,000 symbols.

Use of 8-bit quantization is probably the best system trade unless ground communications capacity or storage capacity dominates costs. Losses of under 0.05 dB should be easily realizable, with 0.01 dB possible.

F. Accuracy of Performance Evaluation

Although errors in estimating SNRs, and thus combiner weights do not limit combiner performance, the errors in SNR do limit the accuracy of measurement of SNR loss. Since random effects can be reduced by averaging many estimates of input and output SNR, the main effect is estimation bias. We estimate the error in bias of estimations of the input SNRs to be less than 0.02 dB.

To estimate the output SNR, we assumed that the combined symbols are Gaussian-distributed, with the appropriate conditional mean. This is not strictly true, because they are the sums of numbers that are coarsely-quantized and then weighted. Their distribution is very complex and depends on the exact weights. Therefore, for lack of ability to do any better, we estimated the output SNR by applying the unbiased moment method, implicitly making the Gaussian assumption. We estimate that there is less than 0.1 dB bias in the software combining system.

Counting 0.02 dB for input SNR bias, 0.1 dB for output SNR bias, and 0.01 dB for other effects, we estimate our ability to measure performance to be ±0.13 dB.

We could reanalyze the data to obtain more accurate performance measures. One method would be to decode the combined data, reconstruct the input symbol streams, and recompute all SNR estimates using the "known" symbol values. The demonstration data have high SNR compared to decoder threshold, so there would be almost no decoder errors. Therefore, the SNR estimates would be very accurate. DC offsets, believed to be insignificant and neglected in the other SNR estimation methods, could be accounted for. The accuracy would be 0.01 dB or better.

III. Demonstration Description

The Voyager demonstration combined telemetry data received at Parkes and Canberra, Australia, on February 6, 1986. The symbols were recorded on standard 1600-bpi digital computer tapes which were shipped to JPL for combining. Combining was done by two different methods. Using a hardware combiner, the symbols were combined and decoded at 60 ksymb/s, faster than the 43.2-ksymb/s data rate. This demonstrated that data could be combined and decoded in near-real time, i.e., with no data backlog buildup. The data were also combined in software at slower than real time. This was done to achieve more accurate SNR and performance estimates than achieved in the hardware system.

A. Station Configurations

The station configurations are shown in Fig. 4. The receivers were the Parkes Telemetry Receiver at Parkes and a Block IV DSN receiver at DSS 43, Canberra. The receiver baseband outputs were processed by DSAs, which performed subcarrier synchronization and demodulation, symbol synchronization, and symbol detection. The detected symbols were sent to Telemetry Processor Assembly (TPA) Modcomp computers via specially designed interfaces. These are designated SSTIs, which stands for Symbol Synchronizer Assembly (SSA) – Symbol Stream Combiner (SSC) – TPA Interfaces. The symbol streams were recorded onto TPA magnetic tapes.

1. SSTI. The SSTIs were specially designed, fabricated, and installed for this demonstration. They were required in order to record at the 43.2-ksymb/s Voyager rate. They replaced the standard SSA-TPA couplers used in the earlier ICE Giacobini-Zinner demonstration. The SSTIs accept input 8-bit quantized symbol streams from the DSAs, quantize these numbers to 4 bits, and pack two consecutive 4-bit symbols into one 8-bit byte. The byte streams, at one-half the rate of the incoming symbols, are output to the TPAs over DSN 14-line Standard Interfaces. The SSTIs are also used on playback, to transfer the byte streams read out of the Modcomps to the symbol stream combiner.

2. **TPA software.** The standard Mark IV TPA software was extensively modified to meet the soft-symbol recording requirements and to accommodate the Voyager spacecraft data rate. The system was tested at symbol rates up to 80 ksymb/s, compared to the maximum rate of 43.2 ksymb/s at Voyager Uranus encounter.

The main modifications included removing all Local Monitor and Control (LMC) interfaces, adding operator prompts and directives to the local terminal, removing the commands to the SSA and SSA/TPA coupler, adding the commands to the SSTI and making changes to the magnetic tape handling software. The tape handling changes were made to avoid any unnecessary tape writing delays such as multiple retries on tape errors and time lost switching tapes. The tape handling software rewinds the magnetic tape when the end-of-tape marker is sensed, switches to the alternate tape on the drive, and continues recording without losing data. It prompts the operator to remove the tape just written or read, and to place a new tape on the drive, thereby preparing it for the next tape switch. Approximately every 31 seconds during the recording, the software displays the signal level and the biased SNR estimates. This enables the operator to monitor and control the signal level from the DSA or SSA, and to monitor SNR to assure subcarrier and symbol lock. The data received by the TPA from the SSTI are put into buffers in the standard Original Data Record (ODR) format shown in Fig. TLM-3-13-2 of the JPL Internal Document 820-13 (*Deep Space Network System Requirements. Detailed Interface Design*, Jet Propulsion Laboratory, Pasadena, California, May 1, 1986). Five of these buffers comprise one tape record. Each record has time tags determined by the station clock.

For test purposes, three programs were developed to verify the operation of the recording system. These programs perform pseudo-random noise code verification, count pattern verification, and time-pulse verification.

Playback software was included in the same software package. It reads the soft symbols recorded by the soft-symbol recording software and transmits them to the SSTI. The playback software requires from the terminal operator directives which define the recorded time of the first data and the time at which the transmission is to start. These start times make it possible to line up two sets of symbol streams recorded at two different sites, to within approximately 2 ms. The playback software reads the ODR blocks from the tape, aligns the times, strips off the headers and presents the SSTI with a continuous stream of two-symbol bytes. Approximately every ten seconds during playback, the software displays the current time and the block header time on the block being processed.

B. Installation, Testing, and Operations

The recording and test software and the SSTIs were extensively tested at the JPL Compatibility Test Area, CTA 21, in August 1985. The hardware and software were then shipped to Australia and installed and tested at Parkes and Canberra in October 1985, prior to station configuration freeze for Voyager Uranus encounter. The system was then tested again prior to the first scheduled day of data acquisition. Three days were scheduled for data acquisition. Operations were so smooth on the first day, February 6, that the additional days were cancelled.

C. Near-Real-Time Combining System

The near-real-time combining system was installed and operated in the Compatibility Test Area (CTA-21) at JPL. A block diagram is shown in Fig. 5.

The recorded data are played back using two Modcomp computers. Either TPAs or Area Routing Assembly (ARA) computers can be used if equipped with magnetic tape units and time-code translators. The recorded byte streams, with two symbols per byte, are output from the Modcomps over the DSN Standard Interface to the SSTI, and then to the Symbol Stream Combiner. The SSC has been described in an earlier article (Ref. 6). It (1) unpacks the bytes into symbols, (2) buffers the symbols in two memories, (3) aligns the streams by cross-correlation, (4) measures the power and symbol SNR of each stream, (5) calculates weights, (6) combines the two streams by multiplying each one by the proper weight and summing the two products, (7) measures the output SNR, and (8) displays its status and the three SNRs and records these on a printer and on a floppy disk.

The symbol stream at the combiner output is in the same physical format as symbols at the output of the SSAs or DSAs. These symbols are sent to a Maximum-likelihood Convolutional Decoder (MCD) and a TPA Modcomp for decoding and recording of the decoded data bits. The TPA logs estimates of bit SNR, made in the MCD, onto a printer. During the demonstration, the decoded bits were not recorded due to lack of tape units.

Initial approximate alignment of the data tapes is accomplished by keying the data start time and the playback start time into the Modcomps, via terminals. The computers then read the time tags in the tape data block headers, advance the tapes to the data start times, and then start playback when the CTA 21 station clock reaches the playback start time. Playback rate is controlled by the symbol stream combiner which synchronously clocks two-symbol bytes out of each Modcomp's standard interface. The SSTI and the symbol stream combiner assure that one byte is read from each Modcomp on each clock pulse.

D. Software Combining System

The combining software developed for the ICE Giacobini-Zinner demonstration was modified and used to process Voyager data. Processing was considerably slower than real time because of the relatively high data rate. The main reason for software processing was to achieve more accurate estimates of input and output symbol SNRs than in the near-real-time system. Better SNR measurements are achieved because the near-real-time system does not use all of the symbol values in estimating SNRs due to software speed limitations.

Only two fundamental modifications were required to the existing processing software. The first was to unpack the symbols, which were two per byte, and to enlarge the data arrays. The second was to modify the symbol SNR estimation algorithm for the input symbols. The new (table look-up) algorithm is described in the previous section.

IV. Demonstration Results

Symbol streams were recorded at Parkes and Canberra, DSS 43, on February 6, 1986, Day-of-Year (DOY) 37. The data were combined three times: (1) by software, (2) by the near-real-time system without decoding, and (3) by the near-real-time system with decoding. Different subsets of the data were processed for each case.

A. Software Combining

Figure 6 shows the results of software combining of data from 2228 to 2318 hours. The figure shows the measured SNRs for the two stations and for the combined symbols, and the theoretically achievable combined symbol SNR, which is the sum of the two input SNRs.

The data were combined in blocks of 5700 symbols, corresponding to the amount of data in one physical tape record. Independent estimates of input and output symbol SNRs and combiner weights were made for each block. The SNR estimates were then averaged over non-overlapping sets of 95 blocks, and each point in Fig. 6 corresponds to one of the 95-block averages, or 541,500 symbols. For all data shown, the average input SNRs are –0.37 dB for Parkes and 0.45 dB for Canberra, with a measurement accuracy estimated in Section II.D as ±0.02 dB. The two input SNRs sum to 3.07 dB ±0.02 dB (by summing the SNRs expressed as ratios, not decibels, and then converting to decibels). The average output SNR is 2.84 dB ± 0.11 dB, or 0.23 dB ± 0.13 dB less than the sum of the input SNRs.

The theoretical loss in SNR is due to two sources: weight errors and quantization. From Vo (Ref. 3), we estimate the loss due to weight errors as 0.01 ± 0.01 dB. Loss in mean square to variance due to quantization was calculated for the actual signal conditions at each quantizer, and the effect on the combined symbols was calculated as a loss of 0.13 dB ± 0.01 dB. The total theoretical loss is thus 0.14 dB ± 0.02 dB. Our experimental results of 0.23 dB ± 0.13 dB are within the expected tolerance.

B. Near-Real-Time Combining

Portions of the data were combined on seven separate occasions using the near-real-time SSC system, at CTA-21. The combining rate was 60 ksymb/s, compared to the recorded data bit rate of 43.2 ksymb/s. This demonstrated that symbols can be combined at a rate faster than real time, i.e., without building up a backlog of data at the combiner.

Figure 7 shows the results of near-real-time combining conducted on June 6. The approximate data time span was from 2259 to 2311 hours on the data acquisition day, February 6. Unfortunately, the recorded data times are not accurately known during near-real-time combining, because there is no way to get the time tags from the tape recordings to the combiner system.

In the near-real-time combiner, the SNRs are estimated approximately every 3.2 s of playback time, or every 4.4 s of actual data time. Only 4096 symbols are used in each estimate. Each point shown in Fig. 7 is the average of five SNR measurements. Weights are computed from the SNRs, and smoothed using a ten-measurement time-constant low-pass filter. In Fig. 7, the average symbol SNRs are –0.29 dB for Parkes and 0.52 dB for Canberra, which sum to 3.14 dB. The measured output SNR is 2.90 dB, or 0.24 dB below the sum of the input SNRs. This measurement of loss is almost identical to the software combining loss of 0.23 dB, with an estimated tolerance of ±0.13 dB.

Figure 8 shows the results of combining the same data tapes (but not exactly the same data) at a different time, on May 30. This time, the input data streams were reversed with respect to the combiner channels, compared to the data of Fig. 7. Each point in Fig. 8 represents one measurement of SNR, instead of an average of five measurements, as in Fig. 7, because of the lesser amount of data. The average SNR measurement results are –0.21 dB for Parkes and 0.48 dB for Canberra, which sum to 3.16 dB and 3.02 dB for the output symbols. The measured loss in symbol SNR is 0.14 dB, which is 0.10 dB less than in Fig. 7, and 0.09 dB less than the software result.

Near-real-time combining was done a total of seven times. For the last six times, the measured losses in average SNR were 0.23 dB ± 0.09 dB. The first time the data were combined, the measured loss was 0.42 dB, or 0.19 dB higher than the other times. At first, we thought this higher loss might be due to biases in measuring output SNR, and might be dependent on which symbol stream was input to which processor channel. The last six processing runs used each combination of inputs three times, with no significant differences. Thus, we are uncertain as to the cause of the higher loss the first time the data were processed, but attribute it to configuration or operations error.

In summary, data were successfully combined on seven separate occasions by the near-real-time combiner. Performance was excellent. Except for the first time the data were processed, the loss in SNR was 0.23 dB ± 0.09 dB. This is in close agreement with the software processing, which had an SNR loss of 0.24 dB, with estimated accuracy 0.13 dB.

C. Combining and Decoding in Near-Real Time

Data combined on May 30 simultaneously decoded. The output symbol stream from the combiner was input to an MCD at CTA 21. The combining rate was 60 ksymb/s, versus the recorded symbol rate of 43.2 ksymb/s. Since the MCD and its associated TPA could only accept standard Voyager symbol rates, the bit-rate input to the TPA was 29.9 kb/s, coded (rate 1/2 code).

The estimate of bit SNR made by the MCD was monitored as an indication of decoder performance. The MCD estimates are based on the rate of renormalization of a metric in the decoder. Since the data were coded with a rate 1/2 code, the bit SNR is theoretically twice the symbol SNR. The average estimate was 6.02 dB, with an unspecified tolerance, probably of several tenths of 1 dB. The combined symbol SNR measured by the combiner was 3.02 dB ± 0.13 dB. Despite the measurement tolerances, the measured bit SNR happened to be exactly 3 dB higher than the symbol SNR, as it should be for the rate 1/2 code. This indicated proper decoding.

This demonstration established the ability to combine and decode at a rate faster than real time with the present station equipment, adding only the combiner.

V. Conclusions

Symbol stream combining has been demonstrated to be a practical and low-loss method for antenna arraying of telemetry signals. Combining has been demonstrated at a rate faster than real time, with concurrent decoding, using standard DSN equipment plus the symbol stream combiner.

The main source of loss relative to ideal performance is quantization of the input symbol streams. Simulations by Pollara and Swanson (Ref. 4) indicate that losses in telemetry performance due to quantization are approximately 0.04 dB ± 0.02 dB for 4-bit quantization. More accurate quantizers would reduce this error by approximately a factor of four for each additional bit of quantization. The next significant loss source is error in the combiner weights, but this can be kept under 0.01 dB. This indicates that a system using 8-bit quantization could easily achieve performance within 0.05 dB of ideal, over a wide range of input signal and noise levels.

With coarse (4-bit) symbol quantization, the SNR of the combined symbols, in the sense of the ratio of mean-squared signal level to noise variance, is not a good measure of telemetry system performance. However, it can be accurately predicted and measured, so it is a good indication of proper operation of the SSC. Using software combining of 4-bit quantized symbols, this demonstration achieved a measured loss in symbol SNR of 0.23 dB ± 0.13 dB, which was within the expected tolerance of the calculated loss of 0.14 dB ± 0.02 dB.

For the maximum data rate at Voyager Neptune encounter, symbol stream combining requires two orders of magnitude less data than does baseband combining, in a near-real-time implementation. Performance of the SSC is at least as good as that of baseband combining. This work has been instrumental in developing the current implementation plan to use symbol stream combining for near-real-time combining of the Very Large Array (VLA), in New Mexico, with the Goldstone array, at Neptune encounter.

References

1. Hurd, W. J., Pollara, F., Russell, M. D., Siev, B., and Winter, P. U., "Intercontinental Antenna Arraying by Symbol Stream Combining at ICE Giacobini-Zinner Encounter," *TDA Progress Report 42-84*, pp. 220–228. Jet Propulsion Laboratory, Pasadena, California, Feb. 15, 1986.

2. Hurd, W. J., and Aguirre, S., "A Method to Dramatically Improve Subcarrier Tracking," *TDA Progress Report 42-86*, Jet Propulsion Laboratory, Pasadena, California, Aug. 15, 1986.

3. Vo, Q., "Signal-to-Noise Ratio and Combiner Weight Estimation for Symbol Stream Combining," *TDA Progress Report 42-76*, pp. 86–98. Jet Propulsion Laboratory, Pasadena, California, Feb. 15, 1984.

4. Pollara, F., and Swanson, L., "Effects of Quantization on Symbol Stream Combining in a Convolutionally Coded System," *TDA Progress Report 42-84*, pp. 82–87. Jet Propulsion Laboratory, Pasadena, California, Feb. 15, 1986.

5. Vilnrotter, V. A., and Rodemich, E. R., "Table Look-Up Estimation of SNR for Quantized Symbols." To be published in *TDA Progress Report 42-87*, Jet Propulsion Laboratory, Pasadena, California, Nov. 15, 1986.

6. Hurd, W. J., Reder, L. J., and Russell, M. D., "Symbol-Stream Combiner: Description and Demonstration Plans," *TDA Progress Report 42-78*, pp. 115–121. Jet Propulsion Laboratory, Pasadena, California, Aug. 15, 1984.

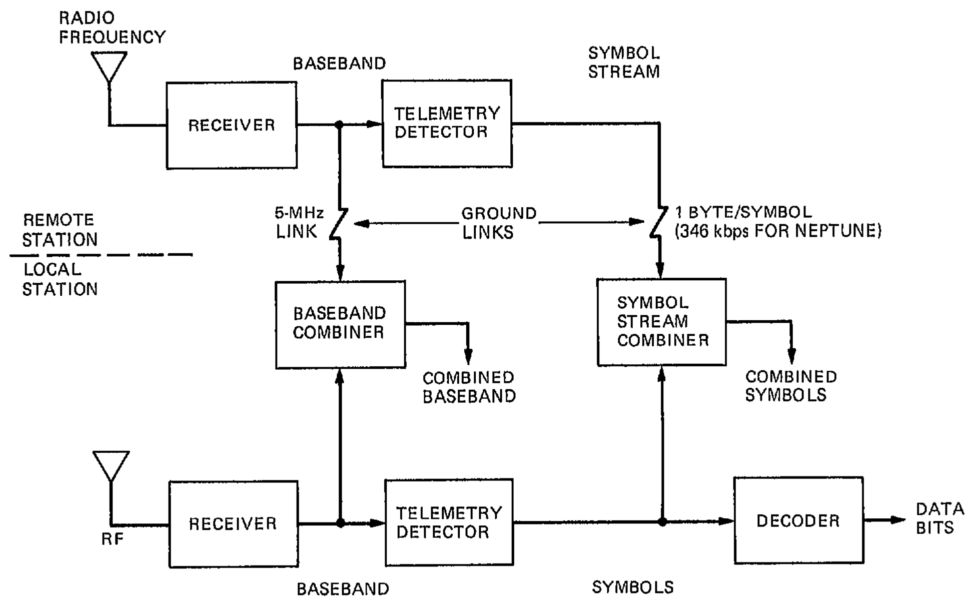

Fig. 1. Symbol stream combining versus baseband combining

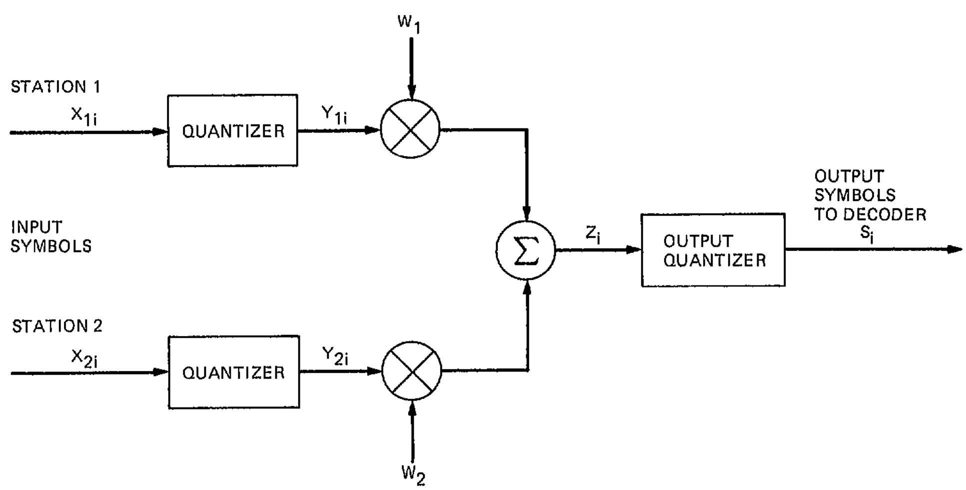

Fig. 2. Mathematics of symbol stream combining

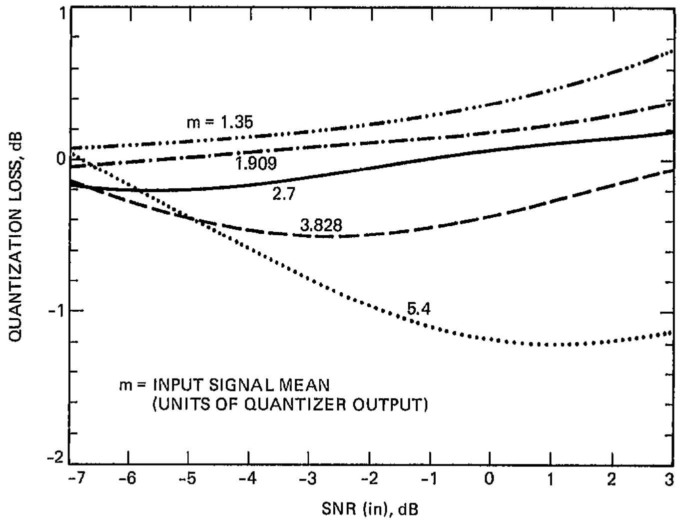

Fig. 3. Loss in SNR for four-bit quantizer

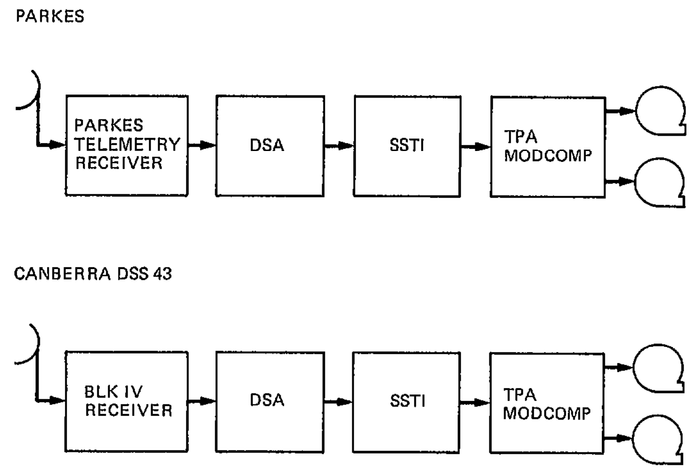

Fig. 4. Station configurations

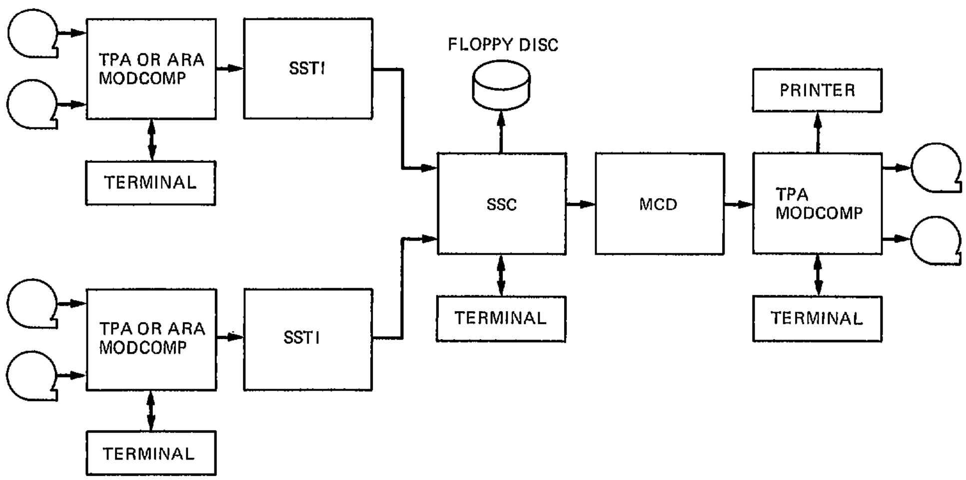

Fig. 5. Near-real-time combining and decoding configuration

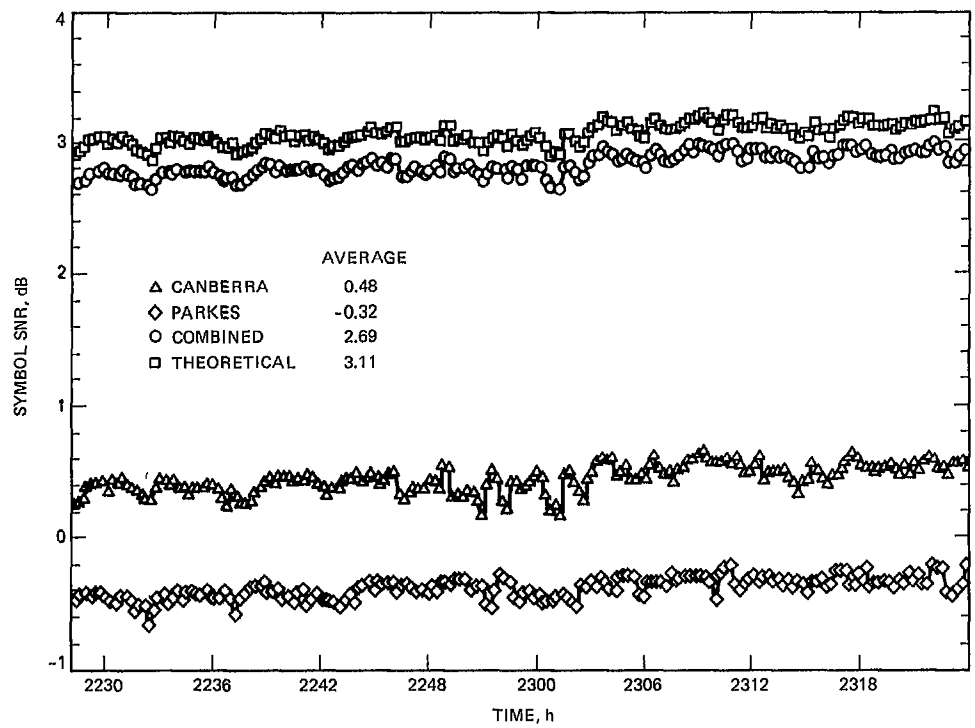

Fig. 6. Results of software combining

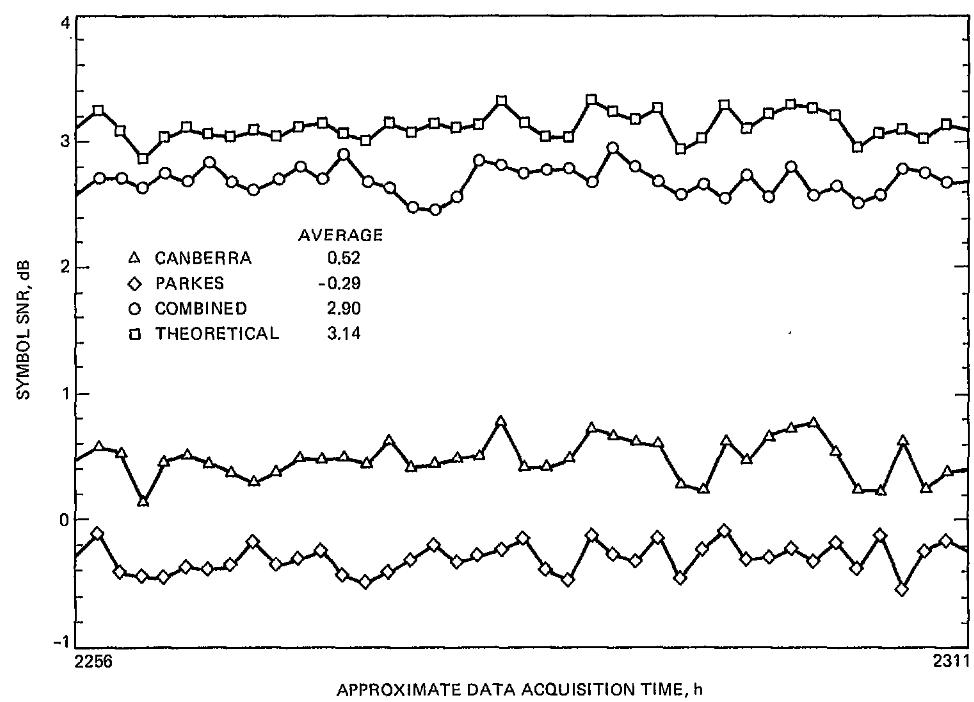

Fig. 7. Results of near-real-time combining on June 6

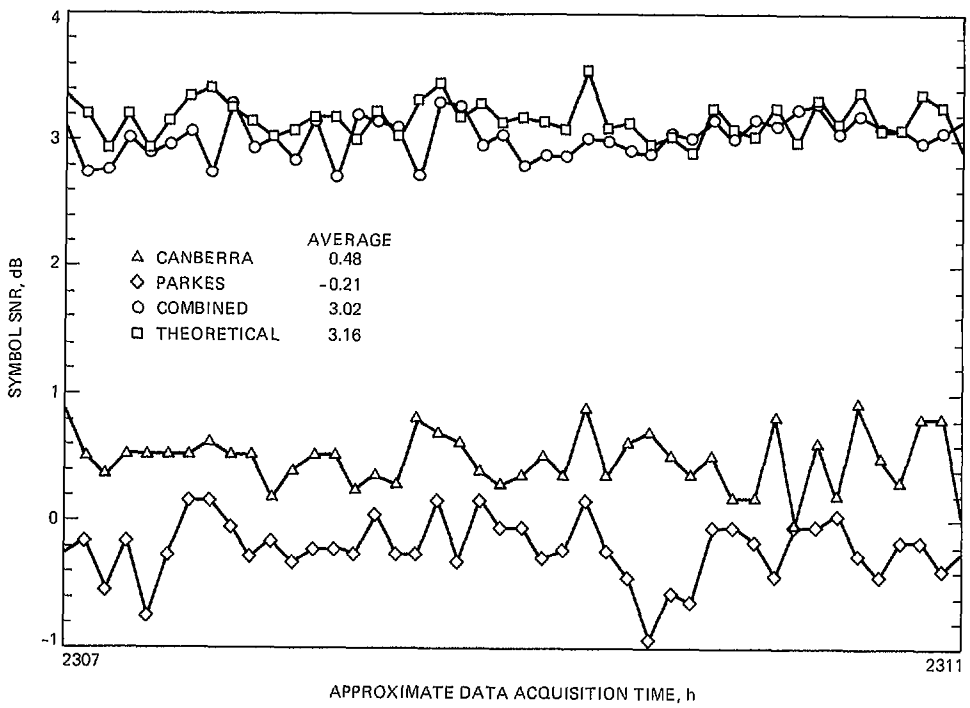

Fig. 8. Results of near-real-time combining on May 30