

# Prototype Real-Time Baseband Signal Combiner

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*This article describes the design and performance of a prototype real-time baseband signal combiner, used to enhance the received Voyager 2 spacecraft signals during the Jupiter flyby.*

## I. Introduction

Signal enhancement obtained by arraying the 64-meter and 34-meter antennas at each Deep Space Communications Complex (DSCC) is an operational requirement for both Voyager Saturn flybys. Arraying is performed by a Real-Time Telemetry Combiner (RTC) Subsystem located at each 64-meter site. This subsystem resynchronizes and sums the baseband signals from each antenna site. The output signal-to-noise ratio (SNR) is given by  $SNR_{RTC} = \Sigma SNR_{inputs}$  as shown graphically in Fig. 1.

This article describes the prototype Voyager RTC which is based on the theoretical work by R. Winkelstein (Ref. 1) and a successful research and development combiner demonstrated by H. Wilck (Ref. 2).

The RTC design characteristics are:

- (1) Combine baseband signals for the 64- and 34-meter antennas without degrading the optimal combined signal-to-noise ratio (SNR) by more than 0.2 dB.
- (2) Operate in an unattended mode.
- (3) Control and monitor functions performed remotely from a Data System terminal or locally via dumb terminal.
- (4) Identical hardware for both 34- and 64-meter signals, so that external delay mechanisms could be eliminated and hardware would be interchangeable.
- (5) Capable of open-loop tracking when signal is too weak to provide useful correlation feedback.
- (6) Provide for automatic signal acquisition, tracking, lost signal detection, and reacquisition.
- (7) Provide self-test, calibration, and diagnostics.
- (8) Provide for compensating relative delays of 2 to 115 microseconds.
- (9) Bandwidth to be equal to or greater than 10 megasamples per second.
- (10) Alignment tolerance plus or minus 30 nanoseconds cumulative tolerance over entire track.

Signal power degradation due to signal misalignment in the delay channels requires an alignment accuracy of 1.5 percent of a subcarrier cycle to keep source degradation less than 0.1 dB. With a maximum subcarrier rate of 500 kHz this becomes a  $\pm 30$  ns alignment tolerance. Because of the requirement that the RTC track open loop, without alignment error feedback from the correlators, the  $\pm 30$  ns tolerance must be cumulative over the entire track.

## II. Implementation

Signals from the 64-meter and 34-meter station receiver outputs pass through identical hardware delay paths in the RTC (Fig. 2). Baseband signals enter the RTC through low-pass filters (LPF) whose purpose is to prevent aliasing in the subsequent sample data process. Then an automatic gain control (AGC) normalizes the filtered inputs to a fixed power level within the range of the 8-bit analog-to-digital converters (ADC). This LPF-AGC-ADC path is implemented as a single RF printed circuit board for each input channel.

The ADC, and an 8-bit first-in first-out memory (FIFO) are driven by a separate 10-MHz phase programmable input clock for each channel. The input and output clocks are phase programmable synthesizers operating at 10 MHz. The necessary central processing unit (CPU) controlled variable delay to resynchronize the input signals is obtained by cycle (phase) slipping the input clocks relative to the common output clock. The synthesizer has 0.1 degree programmable phase resolution at 10 MHz, which corresponds to a delay line resolution of 27.8 picoseconds (far better than required).

At the output of the FIFO delay lines both signals have been resynchronized. The analog signals are then reconstructed by 8-bit digital-to-analog converters (DAC). Low-pass filters (LPF) remove the DAC clocking noise, and finally an analog summing amplifier produces the RTC combined output.

The RTC is driven by a microprocessor controller consisting of two boards, a central processing unit module and an extended memory module (XMEM). The design is an outgrowth of the system described in Ref. 3.

## III. RTC Firmware

The operating program for the RTC resides as approximately 40K bytes of resident EPROM on the CPU and XMEM modules. The program is written in Intel's PL/M language. The function of the program is to provide both normal operational and diagnostic-maintenance capabilities for the RTC system.

### A. Normal Operation

Normal operation consists of two phases; an initialization phase, and a tracking phase.

**1. Initialization.** Upon initialization, the RTC runs through a number of internal self-checks. It verifies the functioning of the station clock, checksum verifies the EPROM, initializes interfaces, parity checks the random access memory (RAM), and tests the delay line functioning and the operation of the synthesizers. If any problems are encountered, the RTC enters the diagnostic mode; otherwise operator inputs consist of a set

of pointing predicts (for calculated delay and open-loop operation) and signal characteristics (for correlator closed loop operation).

**2. Tracking.** During normal tracking the delay lines are updated at 1-second intervals for either closed-loop or open-loop operation. These updates are triggered by CPU interrupts generated by a programmable real-time clock on the CPU module. In addition to the real-time clock interrupt, six other levels of interrupt are utilized during normal operation. Three interrupts support communications, star ports A and B and the RS232C interface; and three interrupts support real-time failure diagnosis, RAM parity, and delay line problems for FIFOs.

Because all seven interrupts function asynchronously and at their own rates, common routines are re-entrant, and interrupts are disabled and re-enabled around critical calculations.

### B. Diagnostics/Maintenance Operation

The RTC program provides detailed on-line and off-line diagnostic, and maintenance features.

**1. On-line diagnostics.** During normal tracking the RTC is able to detect and locate hardware problems to the module replacement level to permit rapid and effective spares substitution.

**2. Off-line maintenance.** Although the maintenance depots have automatic test equipment (ATE) for board troubleshooting it is primarily geared to small- and medium-scale integrated circuit technology. In theory the ATE could be used on LSI boards such as in the RTC, but in practice, the amount of programming effort required could easily exceed the development effort of the original machine. Experience has shown that resident maintenance software is at present the most effective method of providing an on-site repair capability; therefore an extensive set of maintenance routines is also part of the RTC firmware. These routines allow bit level control of the RTC hardware, as well as automated testing of FIFO and correlator performance, and permit troubleshooting of the hardware in place.

## IV. RTC Testing

The RTC is designed to perform signal combining with an output SNR within 0.2 dB of theoretical as given in Fig. 1. Detailed prototype testing was done at the Compatibility Test Area (CTA-21) with field verification tests at DSS 14 (Ref. 4). Signal-to-noise ratio estimates measures from the Symbol Synchronizer Assembly (SSA) were found to be insufficiently precise to provide the 0.1 dB necessary for RTC performance

verification. Instead, telemetry symbol error rates (SER) from known data were used, and the SNR was derived by inverting the relation  $SER = 1/2 (1 - \text{Erf } \sqrt{\text{SNR}})$ . These measurements are sufficiently precise to permit 0.1-dB performance verification. Precalibration procedures before arraying (Fig. 3) use two completely redundant telemetry strings. They are provided a common simulated spacecraft test signal and their output SER and SNRs are compared. This serves to calibrate the indicated SNR with actual SNR (as determined from SER). This is important since SERs are unavailable for actual spacecraft tracks. The DSS 14 precal also determines which telemetry string is performing better. This difference is usually very small (<0.2 dB). The best telemetry string is then used for the prime data source.

The normal tracking configuration appears in Fig. 4. The 64-meter antenna telemetry string acts as backup for the RTC string. The 34-meter string is used to provide SSA SNR data only, since no useful telemetry is available at 34-meter signal levels.

## V. Voyager 2 Jupiter Encounter RTC Performance

Figures 5 and 6 display the results of measurements made during the Voyager 2 Jupiter Encounter (July 1979). Figure 5 displays SSA SNR 10-minute averages for DSS 14, DSS 12, and the RTC. Note that DSS 12 SNRs are offset by 3 dB from DSS 14 and the RTC SNRs for plot compactness. Figure 6 displays SNR differences (DSS 14 – DSS 12, RTC – DSS 14) and RTC theoretical gain. These values derived from the measurements in Fig. 5, but are displayed in a format where RTC performance is independent of output SNR. RTC theoretical gain is what would be given from Fig. 1. It is important to emphasize that Figs. 5 and 6 represent actual measurements taken under field conditions during a planetary flyby. Because this data was taken under encounter conditions, there are numerous factors which were beyond experimental control; an explanation of these factors is necessary to understand the data presented.

### A. Symbol Rate Normalization

Data was taken at several symbol rates. If the telemetry chain were perfect, the SNR change between symbol rate  $R_{sy1}$  and rate  $R_{sy2}$  would be given by

$$\frac{SNR_1}{SNR_2} = \frac{R_{sy2}}{R_{sy1}};$$

i.e., SNR dB 67.2 kbps -2.34 dB = SNR dB 115.2 kbps

Using this relation, all data was normalized to Voyager high rate of 230400 symbols per second (115.2 kbps, coded). Symbol rate SNR dependence of the telemetry showed that only the next lower rate 134400 symbols per second (67.2 kbps, coded) was usable. Even so, significant jumps (0.5 dB) are apparent at bit rate changes (telemetry string performance degrades at higher rate). This system problem was identified and solved after installation of the prototype RTC.

### B. SNR Measurements

The basic measurement was a 10-minute average of SSA SNR estimates. These values are derived from an analog power measurement (Ref. 5). Calibration curves exist, but these curves were found to be in error in the SNR range of interest for DSS 12. In fact, DSS 12 was running so close to SSA threshold that it was very difficult to keep the SSA in lock; which accounts for the sparsity of DSS 12 data points. No acceptable SSA SNR calibration procedures existed during prototype testing at symbol SNR less than -2 dB, since for single stations these signal levels are normally too low to be of any use. It is a problem unique to measurement performance when arraying to require accurate SNR measurements down to, and occasionally below, previously accepted lock thresholds. This problem has been partially solved by recalibrating the SSA so that a symbol SNR measurement as low as -5 dB is considered accurate.

## VI. Conclusion

The prototype RTC has performed to design expectations, resulting in a commitment to design operational systems to support the Voyager Saturn Encounter. An advanced research effort is underway to address solutions to operational system problems associated with real-time arraying, the results of which will be reported in future Progress Reports.

## References

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5. Lesh, J. R., "Accuracy of the Signal-to-Noise Ratio Estimator," Technical Report 32-1526, Vol X, pp. 217-232, Jet Propulsion Laboratory, Pasadena, Calif.

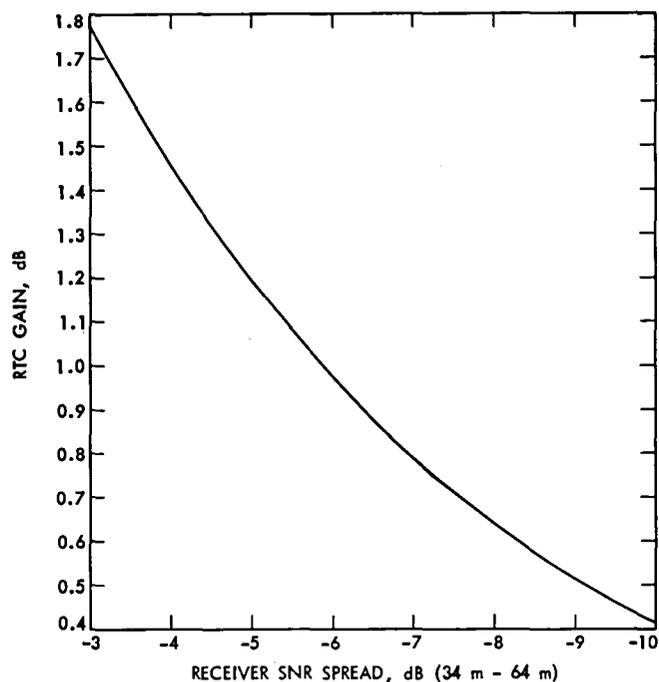


Fig. 1. RTC SNR improvement vs 34-m/64-m spread

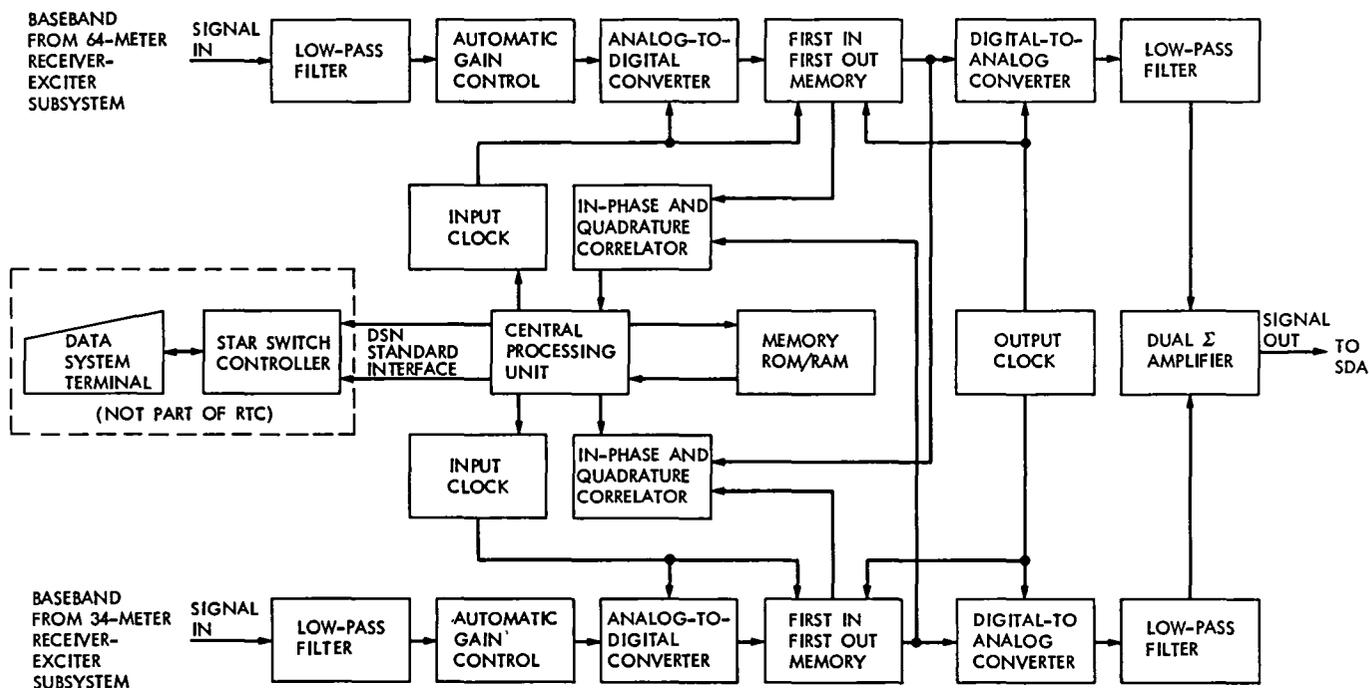


Fig. 2. RTC assembly block diagram

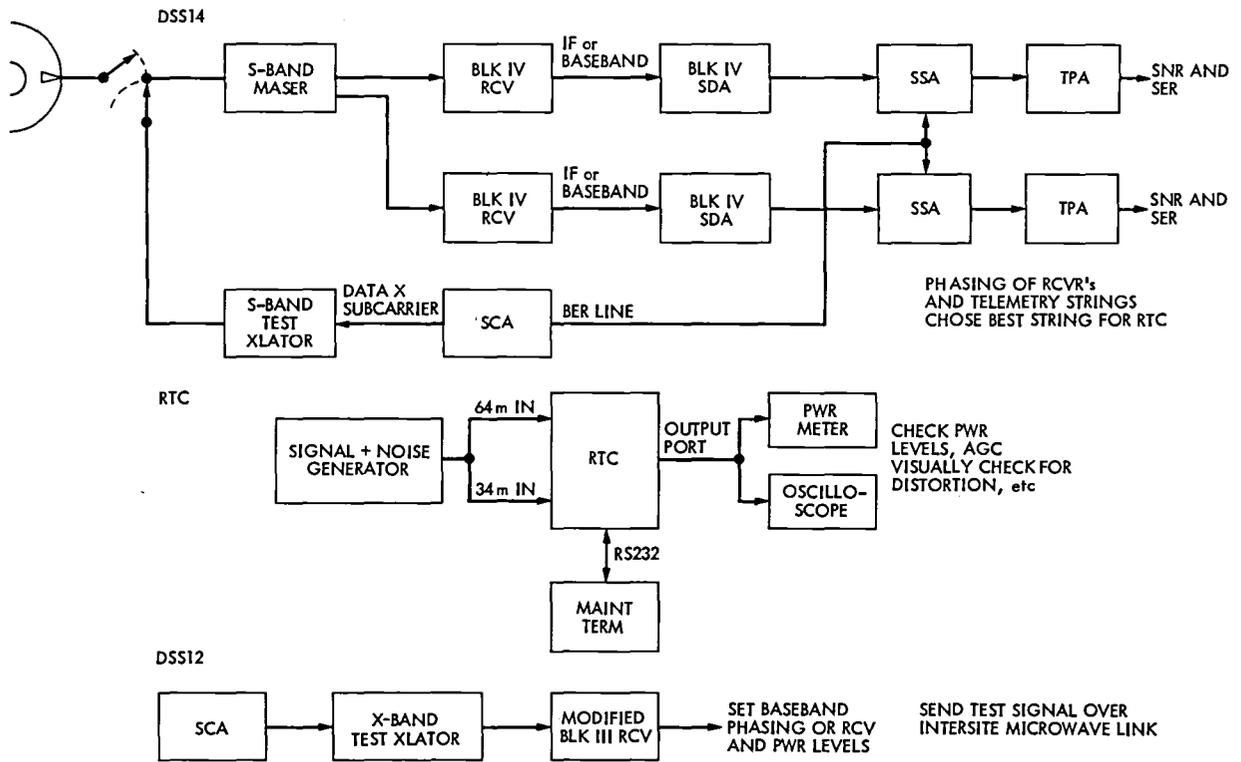


Fig. 3. Precalibration configuration

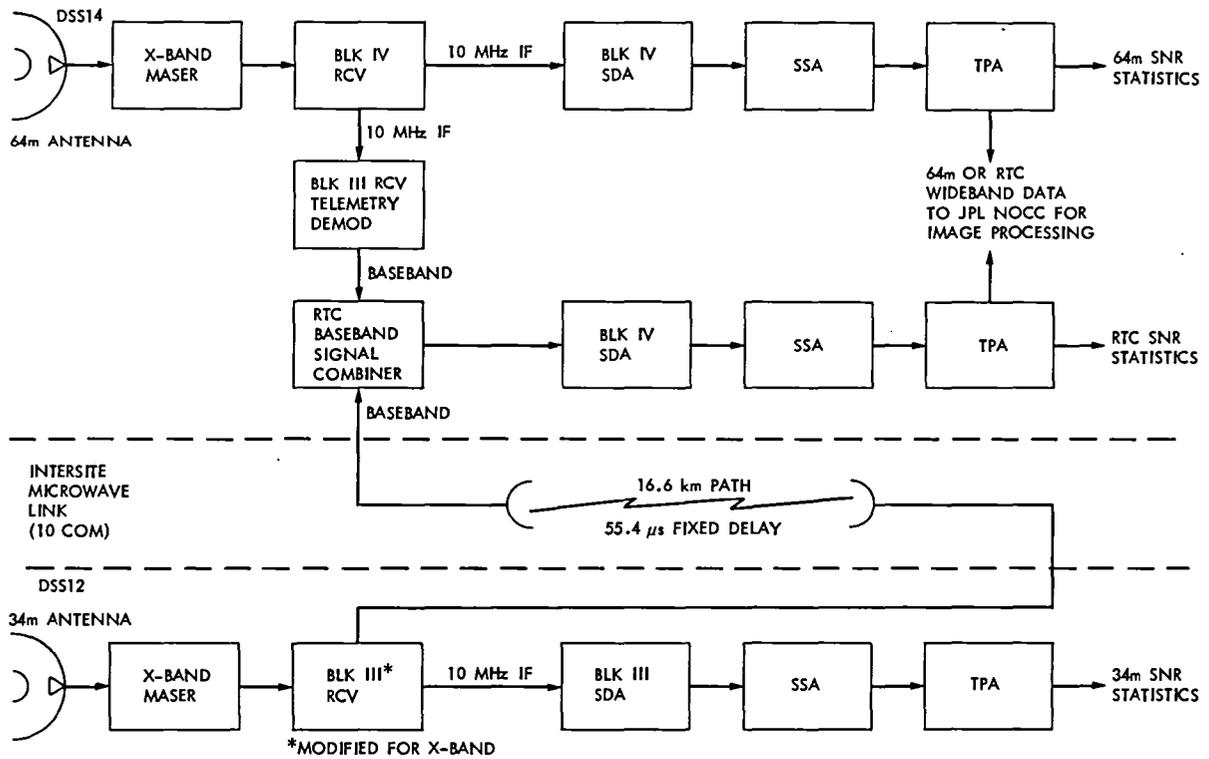


Fig. 4. Normal tracking configuration

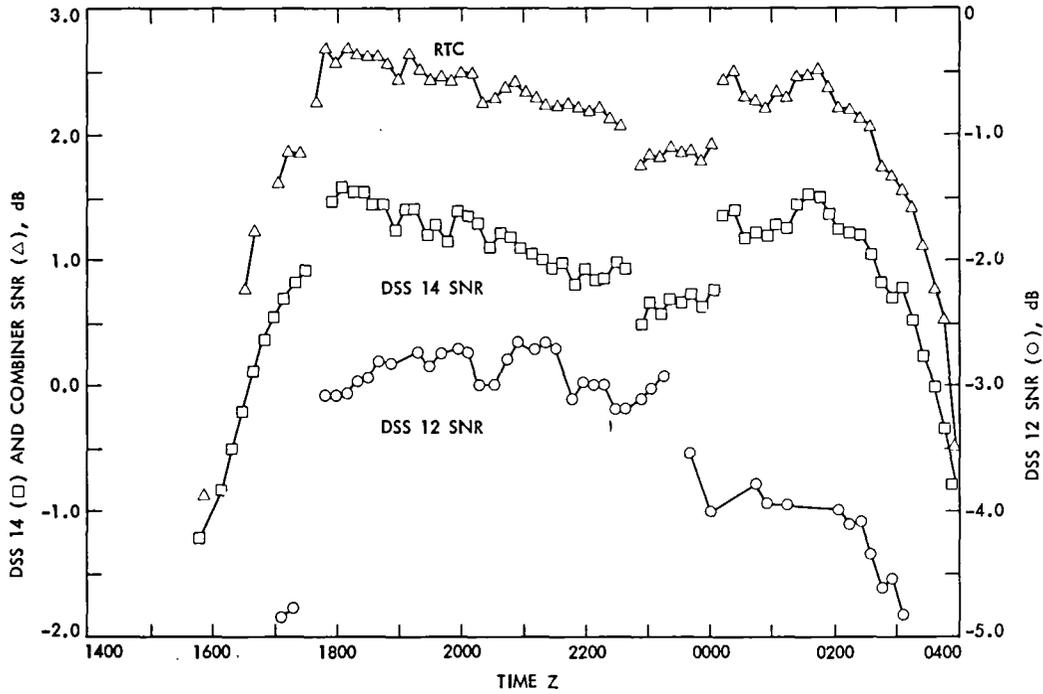


Fig. 5. RTC performance at J11, DOY 186/187, Pass 687 (SSA SNR 10-minute averages)

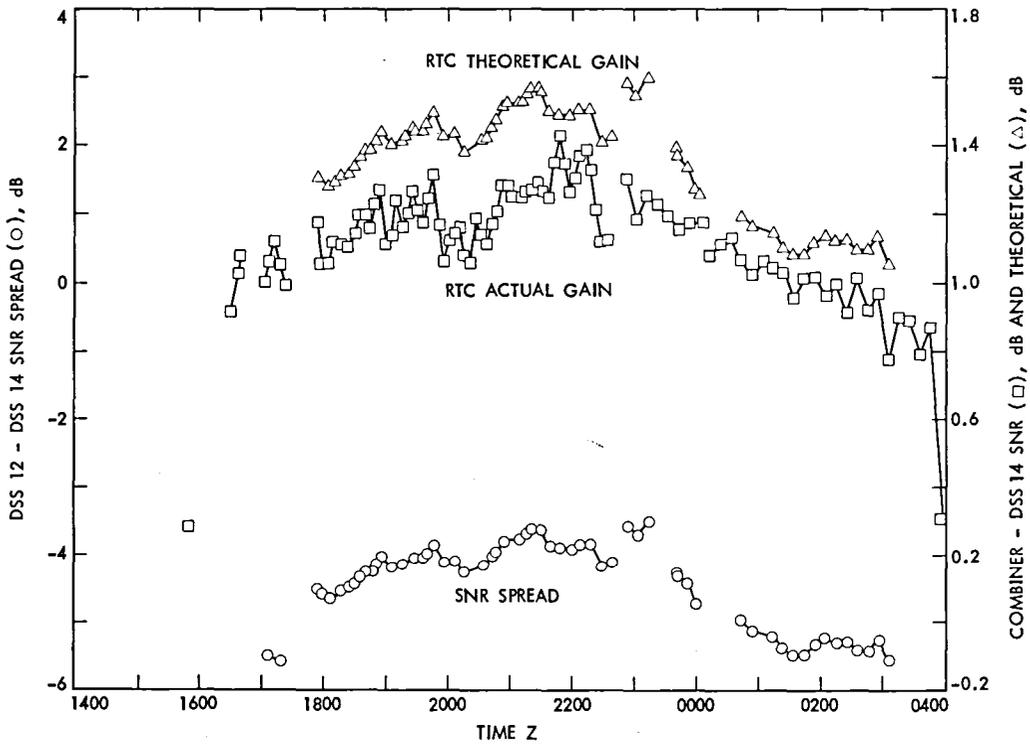


Fig. 6. RTC performance at J11, DOY 186/187, Pass 687 (SNR differences and RTC theoretical gain)