

# The SEASAT Synthetic Aperture Radar Data Link

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The radar-return signals from the SEASAT synthetic aperture radar (SAR) were transmitted to the ground by means of a unique analog data link. The data link translates the 19-MHz radar spectrum from 1275 MHz to a downlink frequency of 2265 MHz and encodes the radar timing signal so that it can be overlaid on the downlink-signal spectrum. Through both ground testing and in-orbit performance, the data link has been shown to provide a highly linear, coherent 20-MHz channel and time-transfer precision of better than 1 ns.

## Introduction

As was discussed in the preceding article, SEASAT contained an experimental SAR that was designed to provide all-weather imaging of both land and sea surfaces with a resolution of 25 m. As originally conceived, the wideband radar-return signal was to be digitized at the spacecraft and the data were to be transmitted using one or more NASA S-band telemetry channels. However, a study by APL revealed that, for full resolution imagery, the on-board digitizing approach consumed more transmission bandwidth than was available. APL proposed the analog data link as a bandwidth-efficient alternative.

The SAR data link takes advantage of the 19-MHz signal spectrum of SAR by neatly filling the

20-MHz telemetry channel through a simple frequency translation of the SAR output (1275 MHz) to the S-band frequency of 2265 MHz. Use of the analog data link not only avoids the need for additional bandwidth allocation but also allows use of existing NASA Spacecraft Tracking and Data Network (STDN) equipment. Following a brief description of the SAR system, the remainder of this article discusses the data link in more detail.

## The SAR System

The SAR system,<sup>1</sup> shown functionally in Fig. 1,

<sup>1</sup> SEASAT-A Synthetic Aperture Radar System Development and Technical Plan, Jet Propulsion Laboratory, Report 622-20 (1977).

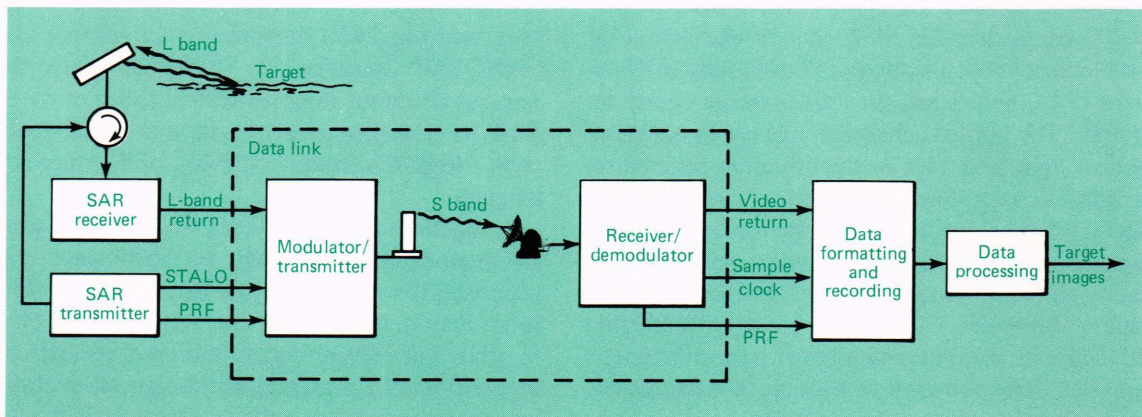


Fig. 1—SEASAT SAR system.

consists of both spaceborne and ground-based subsystems. It is completely coherent; all RF, modulation, and sampling signals are derived from the stable local oscillator (STALO) within the transmitter. Some of the pertinent characteristics of the SAR transmitter/receiver are listed in Table 1.

Table 1  
SAR TRANSMITTER/RECEIVER CHARACTERISTICS

STALO frequency ( $f_s$ )	91.059 MHz
Center frequency ( $14 f_s$ )	1274.83 MHz
Modulation	Linear FM (chirp)
Modulation deviation	$\pm 9.5$ MHz
Pulse width	34 $\mu$ s nominal
Peak power	1200 W nominal
Pulse repetition frequencies (PRF)	1464, 1540, 1581, 1647 pps (command selectable)
Receiver noise temperature	650 K
Receiver gain control	77 to 98 dB
Maximum receiver output	+13 dBm

Figure 1 shows the three elements of the SAR data link—the spaceborne modulator/transmitter assembly, the dynamic satellite-to-earth transmission path, and the receiver/demodulator equipment. The SAR return signal, obtained from the SAR receiver at L band, is the primary RF input and contains the radar echo. This signal is represented in the time domain as shown in Fig. 2. The radar echo occupies approximately half of the SAR interpulse period (IPP) and its position varies as a function of target range and the PRF being used. When the SAR transmitter is pulsed, a small portion of its power couples into the SAR receiver and results in the large leakage pulses occurring at the beginning of each IPP. The modulator/transmitter

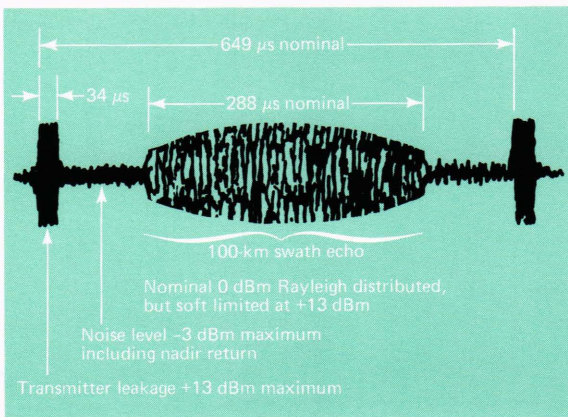


Fig. 2—SAR return signal.

is also supplied with the SAR STALO signal and the radar PRF timing pulses.

A specially designed demodulator unit, located in the ground station, provides output signals consisting of the SAR return signal translated to a video center frequency of 11.4 MHz, a sample clock at half the STALO frequency (45.53 MHz), and a PRF pulse stream that is delayed to align in time with the beginning of the echo portion of the SAR return signal (using prepass information). These signals are used by the SAR data formatting and recording (SDFR) subsystem (discussed in the following article) to digitize the echo, providing 5 bit samples at a rate of  $45.53 \times 10^6$  samples per second. Digitization, which is limited to the portion of the IPP encompassing the target echo, is initiated by the delayed PRF pulse from the demodulator. The final output from the SDFR consists of high-density digital tapes containing the video samples, status information, and Greenwich mean time. The tapes are processed off-line to produce the target images.

## Data-Link Design Considerations

Three primary system requirements contributed to the synthesis of the signal structure of the data link and to the subsequent hardware design. First, the available bandwidth, limited to a single 20-MHz-wide analog telemetry channel, had to contain not only the SAR echo signal but also the STALO phase and transmitter timing information needed for coherent processing. Second, because the relative motion between the satellite and the ground station causes variations in phase and amplitude in addition to those due to the target, it was necessary to ameliorate these effects prior to data recording. Finally, since NASA STDN stations already had a considerable investment in S-band receiving equipment, it was desirable that the data link use this equipment to the greatest extent possible.

In order to allow the three distinct pieces of SAR information to occupy the same frequency band, an orthogonal signal structure was chosen. In an orthogonal system, each piece of information is carried by a unique signal whose time waveform and frequency spectrum are distinct from the signals carrying the other information. A unique detector for each signal is used on the ground. In effect, the detector is a matched filter whose response to a nonmatched signal is very small. In the data

link, the STALO phase is transmitted as a pilot tone and is detected on the ground by using a narrow-band phase-locked loop receiver. The transmitter timing reference is carried as coherent pseudorandom noise (PRN) modulation of the pilot, and detection is accomplished by using a correlation device known as a delay-locked demodulator. Because the wideband noise-like SAR echo signal is already random, and therefore is unlike the other signals, it was left unmodified. However, in order to minimize interference with the recovery of the radar echo, the STALO and PRF signal levels were set to be nominally 20 dB below the echo.

The inclusion of a pilot carrier in the data-link signal structure offered two ancillary benefits that helped simplify the requirement for SAR-unique hardware in the ground stations. First, it allowed the use of NASA's standard phase-locked multi-function tracking receivers (MFR) with which all the stations were already equipped; second, it permitted the amplitude variations caused by relative motion between SEASAT and the ground station to be removed by the MFR's automatic gain control (AGC) circuits.

## Spacecraft Components

A functional diagram of the data-link spacecraft elements is shown in Fig. 3. Within the frequency multipliers, the STALO input signal is used to generate a coherent carrier centered in the middle of the radar spectrum. Also generated is the local oscillator signal required to translate the L-band radar output to S band. The carrier signal is phase-modulated by a 4096-bit PRN binary code that is synchronized with the radar PRF input; the code subdivides the PRF interval, nominally 649  $\mu$ s, into precise subintervals of about 160 ns and permits

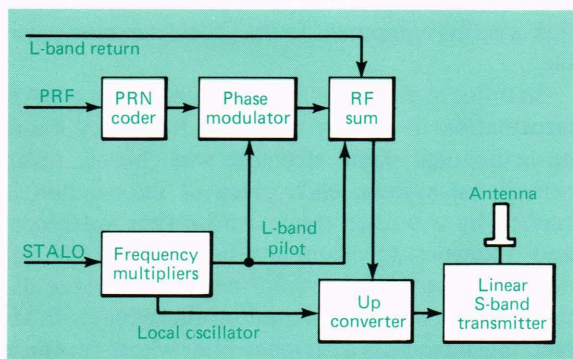


Fig. 3—Data-link spacecraft implementation.

recovery on the ground to the subnanosecond level. The modulated signal is RF-summed with the carrier and radar echo. The composite signal is translated to S band, amplified in a linear solid-state 5 W amplifier, and transmitted through a right-hand circular antenna with greater than 2.5 dB of gain at a ground station elevation angle of 20°. The data-link flight electronics package is shown in Fig. 4.

The composite transmitted spectrum, shown in Fig. 5, consists of the pilot carrier and PRN modulation signals, each fixed at +14 dBm, and the SAR echo return, which is variable. The major part of the transmitter power, under normal target situations, is taken up by the SAR echo. Since the echo is essentially wideband random noise, its density adds directly to the ground-receiver noise density and becomes the dominant noise term in the recovery of the PRF and pilot signals. This is

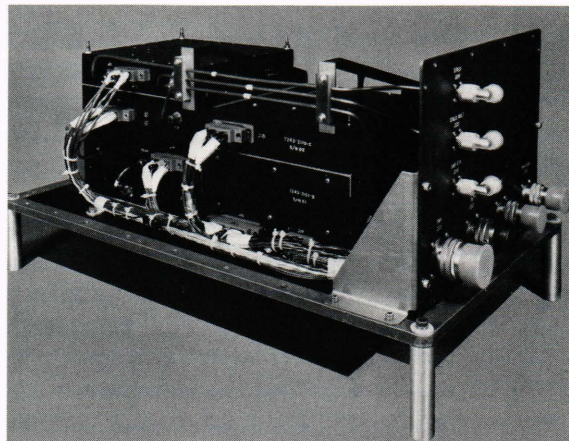


Fig. 4—Spaceborne modulator/transmitter.

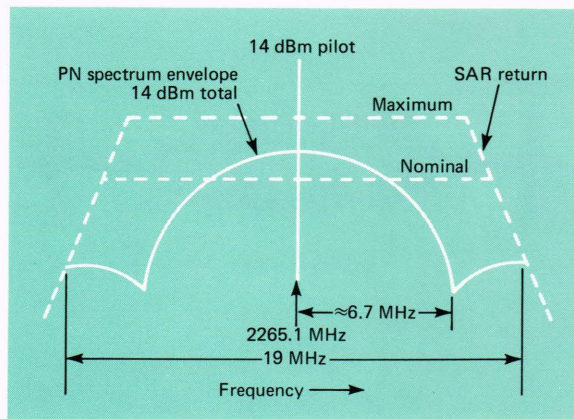


Fig. 5—Data-link transmitted spectrum.

Table 2

LINK BUDGETS FOR THE DATA-LINK SIGNAL COMPONENTS

Parameter	SAR Echo	Pilot	PRF	Units
Transmitted power	37	14	14	dBm
Spacecraft passive loss	-0.8	-0.8	-0.8	dB
Spacecraft antenna gain	3.0	3.0	3.0	dB
Space loss (20° elevation)	-164.5	-164.5	-164.5	dB
Atmospheric loss	-0.1	-0.1	-0.1	dB
Polarization loss	-0.1	-0.1	-0.1	dB
STDN antenna gain	44.0	44.0	44.0	dB
Received power (S)	-88.5	-104.5	-104.5	dBm
Receiver noise density (88 K)	-179.2	-179.2	-179.2	dBm/Hz
Total noise density	-179.2	-157.3*	-157.3*	dBm/Hz
Noise bandwidth	75.9	20.0	4.8	dB-Hz
Total noise (N)	-103.3	-137.3	-152.5	dBm
S/N for detection	21.8	32.8	48.0	dB

\*Resulting from -81.5 dBm echo, spread uniformly over 19 MHz with a 50% duty cycle.

detailed in Table 2. The PRF and pilot signals also interfere with recovery of the echo signal, but their effect at the output of the image processor is small compared to that of the SAR receiver noise.

## STDN Equipment

The total complement of receiving equipment in the STDN stations, which is "shared" by the data link, is shown in Fig. 6. The signals are intercepted by a steerable nine-meter-dish antenna and are sent to a low-noise parametric amplifier. When the dish is pointed at a 20° elevation angle, the combined antenna/preamplifier establishes a system noise temperature of 88 K. The signal is down-converted to a center frequency of 465.1 MHz by mixing with a STALO signal obtained by multiplying the station reference frequency. At this point, the three-component signal enters the multifunction receiver, which tracks the carrier and removes the downlink doppler frequency shift. Internal to the receiver, the PRN modulation and SAR signals are tapped off at a fixed center frequency of 110 MHz and sent to

the demodulator. As a consequence of the phase-locked receiver operation, these two signal components contain differential doppler shifts that must be compensated for in the demodulator by using the 132.4 MHz doppler reference signal. At the same time, the MFR also measures and corrects for variations in the level of the received carrier by automatically adjusting its gain; because these adjustments are also applied to the radar signal, complete compensation for downlink path-loss variations is achieved in real time.

## Demodulator

The demodulator<sup>2</sup> is the first ground station equipment unique to the SAR. Its function is to reconstruct the SAR echo, the STALO phase, and the transmitter timing signals in a form suitable for recording and subsequent image processing. To

<sup>2</sup>E. F. Prozeller and R. J. Heins, "A Wideband Analog Data Link for the SEASAT-A Synthetic Aperture Radar," *EASCON '78 Record*, IEEE CH 1352, pp. 111-119 (1978).

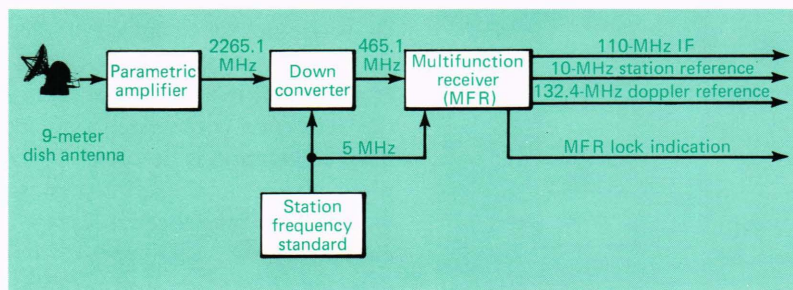


Fig. 6—STDN portion of the data-link ground system.

this end, the demodulator contains a delay-locked correlator that decodes the PRN signal to produce both output PRF pulses and a coherent sample clock. It also contains a video down converter/frequency synthesizer that provides final amplification of the SAR echo as well as coherency correction using the doppler reference from the MFR. A block diagram of the demodulator is shown in Fig. 7. The demodulator hardware is shown in Fig. 8.

**Delay-Locked Correlator**—A delay-locked correlator is a device that determines the time of arrival (TOA) of a pulsed signal by comparing the received signal with a reference that has the same known structure. Once the TOA has been determined, the correlator “tracks” the delay of the received signal by automatically adjusting the timing of the reference signal to keep the correlation at a maximum. The data-link correlator consists of the six blocks on the right side of Fig. 7. The received and the reference codes are compared in the IF correlator, which contains two matched amplitude-detection channels that provide outputs proportional to the correlation between the received code and two reference codes that have a relative delay of one chip.<sup>3</sup> The correlation detector forms the sum and difference of the two outputs; the difference signal, which varies as an odd function of the delay between the received and the reference codes,

<sup>3</sup> E. F. Prozeller, R. J. Heins, W. C. Trimble, and J. A. Trennepohl, *A Coherent Demodulator for the Data Link of the SEASAT-A Synthetic Aperture Radar*, APL/JHU CP 063 (1978).

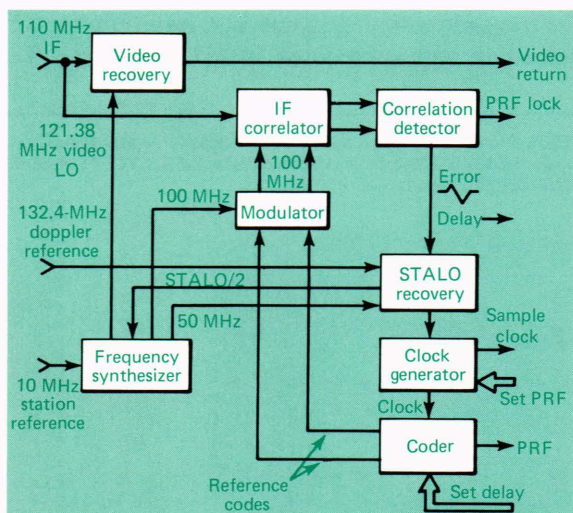


Fig. 7—Block diagram of the demodulator.

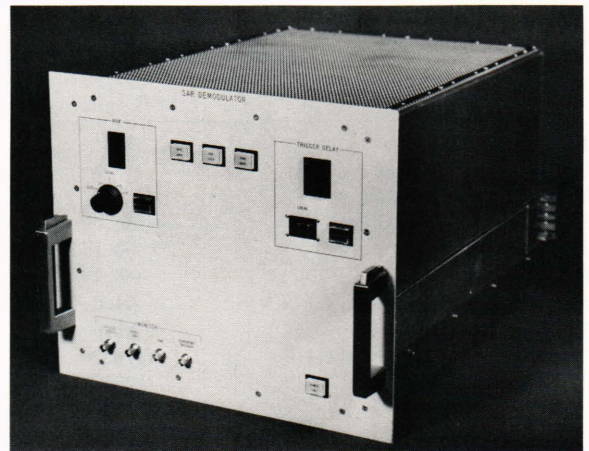


Fig. 8—Hardware of the data-link demodulator.

is integrated and is then used to control the phase of the oscillator that clocks the coder. When the codes are at maximum correlation, the difference signal is zero and the sum signal is maximum; the latter signal is used as an indication that the delay-locked correlator is in lock and that the PRF pulses, decoded in the reference coder, are coherent with the offset video output of the demodulator.

In order to achieve a time recovery jitter of less than 1 ns, the delay-locked loop must be designed to have a very narrow bandwidth. Significant dynamic-tracking biases are avoided by rate-aiding the loop with the 132.4 MHz MFR doppler-reference signal, which removes more than 99% of the code dynamics.

Before the delay-locked loop can track the received code, the phase of the demodulator's reference codes must be brought into alignment with the received code. Because of the inherent correlation properties of the codes, an error voltage will not be generated unless the absolute displacement is one chip or less. The process by which the reference codes are brought into correlation is called “acquisition.” Code acquisition starts as soon as the MFR has been phase-locked. Because the exact clock frequency required to generate the reference codes is established by the 132.4 MHz signal from the MFR and the setting of the PRF divider, the reference codes need only be shifted in time until correlation is detected. The demodulator employs a very simple serial-step acquisition strategy wherein the reference codes are advanced by one chip every two PRF periods until correlation is detected. The average acquisition time that results is less than 3 s.

**Coherency Correction**—The SAR return signal input to the demodulator is the same as that presented to the data-link input at the spacecraft except for the spectrum translation from L band to 110 MHz. The amplitude variations resulting from the dynamics of the downlink transmission path have been removed in the MFR. The MFR has also removed phase variations but only from the center of the SAR spectrum; a differential doppler effect remains. In order to reestablish the fidelity of the SAR echo and remain coherent with the sample clock and PRF timing, the original data-link doppler effect is reinserted into the local oscillator drive for the video recovery down-converter. Figure 9 shows the ground and satellite implementations for generating the 121.38-MHz video local oscillator signal. Account is taken of the scaling (established at the satellite) between the pilot and STALO frequencies (the pilot equals 199/8 times STALO) as well as the frequency offset introduced in the MFR between the pilot and the 132.4 MHz doppler reference. The net effect is that the fixed center frequency of the 110 MHz spectrum is replaced with a center frequency of one-eighth STALO and the video output becomes independent of offsets and drifts in the ground reference standard.

**Demodulator Performance Extension Features**—The demodulator PRF rates are normally under the control of other SAR-unique ground station equipment. However, the demodulator was designed with an optional mode wherein the PRF rate can be determined from the received signal by detecting the radar leakage pulses. The detection philosophy is to discern the leakage pulse from the echo return by pulse-width discrimination and from the noise by power-level discrimination. The output of the leakage pulse-detector circuit can also be used

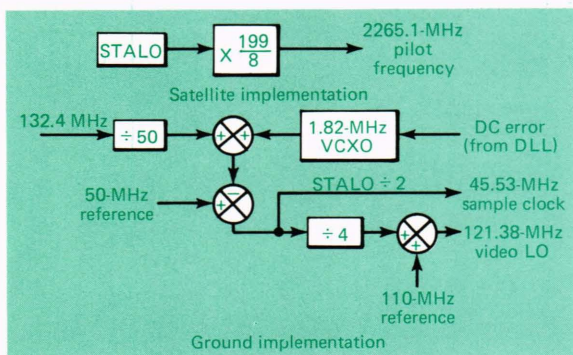


Fig. 9—Generation of the video local oscillator.

to provide an initial coarse estimate of reference code delay. When this acquisition mode is used, the PRN code is delay locked within less than 1 s after phase lock of the MFR even under the worst-case conditions if the loop is operating under high noise levels corresponding to maximum SAR echo energy.

Whenever the SAR echo level is above 0 dBm, the delay-locked loop S/N degrades, causing the time jitter of the PRF pulses to increase. This can be avoided by using the demodulator time-gate feature. When the time gate is activated, a gating pulse is generated within the demodulator and positioned, based on prepass predictions, so as to bracket the echo portion of the IPP. The gates serve to inhibit inputs to the delay-locked loop during this time, resulting in time jitter that is independent of the echo level.

## Data-Link Performance

Because of its analog nature, the data link can be thought of as an extension of the SAR on-board receiver. The perfect data link would provide a unity transfer function (i.e., what comes out is identical to what goes in); the practical data link exhibits errors resulting from such effects as limited bandwidth, electronic nonlinearities, system noise, and oscillator instabilities. Specifications for the allowable data-link errors were developed early in the program and can be grouped into two categories: those relating to the transfer function, which are measured by comparing the video output signal with the L-band input, and those relating to the recovery of the timing signals. The latter can be verified by comparing the input PRF and STALO signals with the recovered versions in the presence of a simulated radar return signal, which is the predominant source of timing jitter.

Table 3 compares the measured performance of the data-link flight unit, the STDN receiver, and the SAR demodulator connected as an end-to-end system. Design specifications are also indicated. During the tests, the antennas were replaced by a hardwired connection.

The entries listed in Table 3 show that the transfer function requirements were fully met. The gain characteristic for large inputs, which is shown in Fig. 10, can be explained as follows. Normally, a linear system driven beyond its linear range will exhibit a reduction in gain. This is not the case with the data link, because the nonlinear-

Table 3

## DATA-LINK PERFORMANCE MEASUREMENTS

Specification	Requirements	Measurements
Gain at center frequency	$0 \pm 0.5$ dB	$-0.4$ to $+0.1$ dB*
Output noise at $T = 88$ K	$\leq -17$ dBm	$< -15$ dBm at $T = 420$ K
Intermodulation (two input tones at $-3$ dBm each)	$\leq -20$ dB	$< -25$ dB
Input level for 1 dB output expansion	$\geq +3$ dBm	$\geq +3$ dBm
Amplitude versus frequency $\pm 9.5$ MHz	$\leq 2$ dB peak quadratic error	$< 0.8$ dB
Phase versus frequency $\pm 9.5$ MHz	$\leq 26^\circ$ peak cubic error	$< 10^\circ$
Phase jitter of offset video at input of 0 dBm	$\leq 10^\circ$ rms for $T = 5$ ms	$< 7^\circ$
Timing jitter of PRF at input of 0 dBm	$\leq 1$ ns for $T = 2$ s	$< 0.8$ ns at 0 dBm = 1 ns at $+4$ dBm; $\leq 0.8$ ns for time gate "on" at all input levels

\*Over the expected in-orbit thermal variation of  $-10^\circ\text{C}$  to  $+10^\circ\text{C}$ .

ity of the S-band power amplifier causes suppression of the data-link pilot signal in the presence of a larger radar echo; the AGC circuit of the STDN receiver reacts by increasing its gain to overcome the suppression, but the gain increment is also applied to the radar echo causing the expansion effect.

The phase and time-recovery performance of the data link was evaluated by driving the data link from a special signal generator built to simulate the pulsed-RF and noise characteristics of the real signal shown in Fig. 2. Figure 11 shows the PRF time-recovery performance as the echo portion of the test signal was varied in level in an attempt to simulate different cross sections of real targets. The curve labeled "time-gate off" shows that when all the energy from both the echo and leakage portions of the return signal is allowed to enter the PRF tracking loop, the timing jitter exceeds 1 ns for an echo level of about  $+4$  dBm. The second curve shows that when the time-gate feature is used, the timing jitter remains below 1 ns for all echo levels.

It is impossible to isolate definitively the in-orbit performance of the data link apart from the per-

formance of the overall SAR system, other than to observe that telemetry signals indicated totally nominal operation throughout the life of SEASAT. The extremely high quality of the SAR imagery that has been obtained indicates that the entire SAR system performed well within, if not better than expectations.

## Summary

The analog data link developed by APL represented a successful, cost-effective solution to the difficult SEASAT SAR frequency-allocation problem. The data link, consisting of both spaceborne and ground equipment, made effective use of available NASA ground station receiving equipment, mating it to a specially designed APL coherent demodulator for final signal recovery. The data link reproduced the outputs of the spacecraft SAR sensor on the ground, where they appeared very much

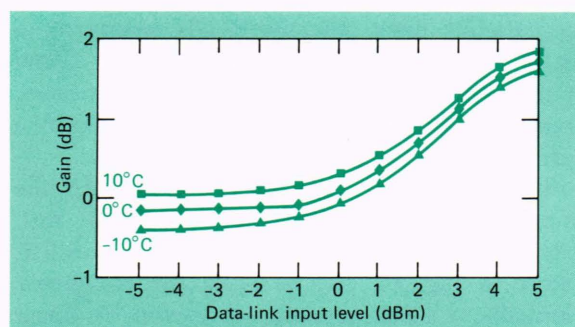


Fig. 10—Data-link gain as a function of the CW input level.

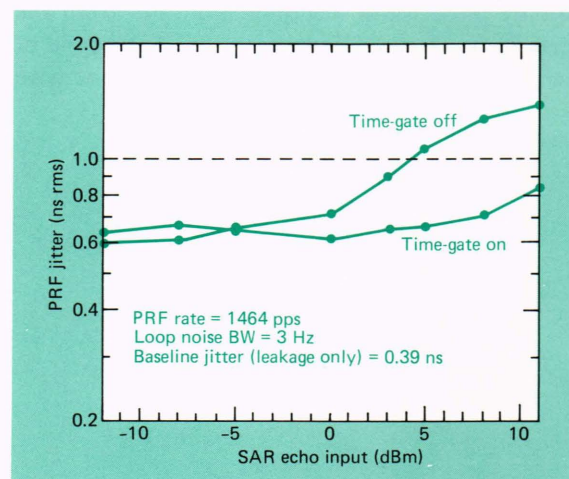


Fig. 11—PRF time-recovery jitter.

like they would as the outputs of a hypothetical spacecraft demodulator.

Before mating the data link with the SAR, very thorough end-to-end testing of the data link demonstrated performance as a subsystem well within its original requirements. The high quality of the imagery obtained from the SAR system attests to the excellent in-orbit performance of the data link as well as the other SAR subsystems.

Five demodulators were built at APL and installed in the field. Three were deployed at NASA stations in the U.S., one was installed by the Canada Centre for Remote Sensing at Shoe Cove, New-

foundland, and the other was installed by the European Space Agency at Oakhanger, England. They operated reliably throughout the life of SEASAT.

### **Acknowledgment**

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