Radio Frequency Carrier Arraying

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Carrier arraying of receiving systems provides an improvement in the signal-to-noise ratio relative to a single receiving system. Measurements using arrays of up to four receiving systems have been conducted to verify the predicted signal-to-noise ratio improvement. The measured signal-to-noise ratio improvement agrees with the predicted within 0.2 dB.

I. Introduction

The increase in the sensitivity of radio frequency reception obtained by the technique of carrier arraying has been determined in the analysis presented in Ref. 1. Measurements made to verify the predicted signal-to-noise ratio improvement obtained by carrier arraying over that of a single receiving system are described in this article. These measurements include arraying combinations of two, three, and four receivers.

DSN Block III receivers were used for these carrier array measurements. As discussed in Ref. 1, the reference receiver (receiver 1) was in the standard configuration with the first local oscillator in the phase tracking loop, as shown in Fig. 1. This local oscillator was shared by all receivers. Array receivers (2, 3, and 4) were used with the second local oscillator in the phase tracking loop. For the carrier array measurements a design bandwidth of 152 Hz was used in the reference receiver, while 1-Hz design bandwidth was used in the array receiver. This fulfilled the requirement that the bandwidth of the array receivers be much smaller than the bandwidth of the reference receiver. The RF carrier signals of the array receivers were combined with the reference receiver at IF in the summing junction of the reference receiver.

In the following material the method of calculating the predicted improvement is presented for one of the array combinations and is discussed first. This is followed by the measured signal-to-noise ratio improvement for each of the arraying combinations of two, three, and four receivers. The measured values are then compared to the predicted values.

II. Predicted Performance for Carrier Arraying

A. General

In Ref. 1 the predicted improvement performance is calculated in two steps. First, the improved performance of the reference receiver is determined, neglecting the contribution of phase noise from the array receivers. Then a correction is made to include the degradation due to the addition of phase noise from the array receivers.

Neglecting the phase noise of the array receivers, the predetection signal-to-noise ratio improvement η of the reference receiver when combined with array receivers 2, 3 and 4, using Eq. (19) of Ref. 1, is given by:

$$\eta = \frac{(1 + \beta_2\gamma_2 + \beta_3\gamma_3 + \beta_4\gamma_4)^2}{1 + \beta_2^2 + \beta_3^2 + \beta_4^2}$$

where

$\gamma_2^2, \gamma_3^2, \gamma_4^2$ = the ratio of the carrier power-to-noise spectral density of each of the array receivers 2, 3 and 4 compared to the carrier power-to-noise spectral density of the reference receiver.

$\beta_2, \beta_3, \beta_4$ = the carrier voltage of the IF signal from each of the array receivers 2, 3 and 4 compared to the carrier voltage of the IF signal of the reference receiver at the output of the summing junction.

The contribution of phase noise from the array receivers can now be included using Eq. (22) of Ref. 1. This is presented later in more detail in Section II-D of this article when a sample calculation of the carrier signal-to-noise ratio improvement resulting from arraying four receivers is discussed.

As noted above, both β's and γ's are significant parameters and must be determined for each test condition. The method of measurement and adjustment of these two parameters is discussed below.

B. Carrier Power-to-Noise Spectral Density Ratio γ^2

The absolute value of the carrier power-to-noise spectral density ratio for each receiver is not required to predict the improvement in signal-to-noise ratio that can be obtained when combining one or more array receivers with the reference receiver. It is sufficient to know the relative magnitude of carrier power and noise spectral density between each array receiver and the reference receiver. This is discussed in the following paragraphs.

To obtain the relative magnitude of carrier power, a test signal was distributed to each of the four receivers through power dividers (Fig. 2). The relative level of the signals at the output of the power dividers (P1, P2, P3 and P4) was determined by sequentially connecting the outputs of the power dividers to the reference receiver through cable C1, using the reference receiver gain control system as a carrier voltage level detector. In the MGC configuration the relative signal level measurements can be made with an accuracy of better than 0.1 dB.

To obtain the relative magnitude of the noise spectral density, measurements of the noise temperature were made on each receiver, including cables C1, C2, C3 and C4 (Fig. 2). Results of the relative signal level measurements and the noise temperature measurements are tabulated in Table 1. The carrier power-to-noise spectral density ratio γ^2 can then be obtained from the following expression:

$$\gamma_N^2 = \frac{V_N^2 \, T_{n1}}{V_1^2 \, T_{nN}}$$

where

V = the relative input signal level in volts

T_n = the input noise temperature in kelvins

1 = reference receiver

N = array receiver 2, 3 or 4

From the measurements listed in Table 1, the following are the values of γ^2 that apply to all the array measurements.

$\gamma_2^2 = 0.906$

$\gamma_3^2 = 0.961$

$\gamma_4^2 = 0.981$

C. IF Carrier Power Ratio β

Here again, the absolute levels of the IF carrier of each receiver is not required. What is needed is the ratio of the IF carrier voltage of the array receivers relative to the reference receiver when each of the array receivers is combined with the reference receiver in the summing junction. The gain control system of the reference receiver was again used to measure the increase in IF voltage when each of the array receivers was combined with the reference receiver. The accuracy of these measurements is also about 0.1 dB. These measurements are tabulated in Table 2.

D. Sample Calculation

The configuration selected for the sample calculation is the one using an array of four receivers where

$$\beta_2 = 0.75$$

$$\beta_3 = \beta_4 = 0.65$$

as identified in Table 2.

The phase noise of the reference receiver alone was measured to obtain an initial reference point. The relative receiver input signal level corresponding to this receiver phase noise measurement is obtained from Eq. (16) of Ref. 1, which gives the value of phase noise as a function of the relative signal level. Since this equation is used several times, a plot (Fig. 3) has been made. From this plot the initial reference receiver phase noise ($\sigma_{\phi n1}$) of 14.9 deg rms corresponds to a relative signal level of 12.1 dB above the reference receiver design threshold.

The predetection signal-to-noise ratio improvement of the reference receiver when summed with array receivers 2, 3 and 4, neglecting the phase noise contribution of receivers 2, 3 and 4 is

$$\eta = \frac{(1 + \beta_2\gamma_2 + \beta_3\gamma_3 + \beta_4\gamma_4)^2}{1 + \beta_2^2 + \beta_3^2 + \beta_4^2}$$

$$10 \log_{10} \eta = 5.71 \text{ dB}$$

This represents an improvement in the reference receiver predetection signal-to-noise ratio of 5.71 dB, equivalent to a relative signal level of 17.8 dB above design threshold. Again, from Fig. 3 this corresponds to reference receiver phase noises

$$\sigma_{\phi\eta 1\Sigma 1,2,3,4} = 8.00 \text{ deg rms} = 0.140 \text{ rad rms}$$

The next step is to calculate the contribution of phase noise from each of the array receivers. From the expression defining receiver phase noise as a function of relative signal level above design threshold, the phase noise of each of the array receivers can be determined knowing the relative signal level above design threshold for each of the array receivers. The relative signal level above design threshold of the array receivers differs from the reference receiver due to three factors:

(1) The ratio of design loop noise bandwidths. This factor is

$$\frac{2B_{L0} \, (\textit{reference receiver})}{2B_{L0} \, (\textit{array receiver})}$$

(2) The ratio of the carrier power-to-noise spectral γ^2

(3) The reduction in the carrier signal voltage in the array receivers due to the added noise of the first local oscillator derived from the reference receiver. From Ref. 1, this factor is

$$1 - \frac{\sigma^2_{\phi\eta 1\Sigma 1,2,3,4}}{2}$$

Adding these three factors to the value of the relative signal level above design threshold of the reference receiver (12.1 dB), the relative signal level above the design threshold for array receivers 2 becomes

$$12.1 + 10 \log_{10} \frac{2B_{L0} \, (\textit{reference})}{2B_{L0} \, (\textit{array})} + 10 \log_{10} \gamma_2^2$$

$$+ 10 \log_{10} \left[1 - \frac{\sigma^2_{\phi\eta 1\Sigma 1,2,3,4}}{2}\right]^2 = 33.4 \text{ dB}$$

From Fig. 4, this is equivalent to a contribution of phase noise from array receiver 2 of

$$\sigma_{\phi\eta 2\Sigma 1,2,3,4} = 4.32 \text{ deg rms}$$

In a similar manner, for array receivers 3 and 4

$$\sigma_{\phi\eta 3\Sigma 1,2,3,4} = 4.25 \text{ deg rms}$$

$$\sigma_{\phi\eta 4\Sigma 1,2,3,4} = 4.25 \text{ deg rms}$$

The total phase noise of the reference receiver, from Eq. (22) of Ref. 1, is

$$\sigma_{\phi\eta} = \left[\sigma^2_{\phi\eta 1\Sigma 1,2,3,4} + \left(\frac{\beta_2\sigma_{\phi\eta 2\Sigma 1,2,3,4}}{1 + \beta_2}\right)^2 + \left(\frac{\beta_3\sigma_{\phi\eta 3\Sigma 1,2,3,4}}{1 + \beta_3}\right)^2 + \left(\frac{\beta_4\sigma_{\phi\eta 4\Sigma 1,2,3,4}}{1 + \beta_4}\right)^2\right]^{1/2}$$

$$\sigma_{\phi\eta} = 8.55 \text{ deg rms}$$

From Fig. 3 this corresponds to a relative signal level above design threshold of 17.2 dB. This represents a 5.1-dB improvement over the initial reference point of 12.1 dB relative signal level above design threshold. These calculations for all the array combinations are tabulated in Table 2.

III. Measured Performance of Carrier Arraying

The most significant parameter available to measure the improvement in performance when more than one receiver is arrayed is the signal-to-noise ratio (rms phase noise) of the receiver loop output signal. Since the receiver loop output signal is used as the doppler signal, the rms phase noise of the doppler output was used to measure the receiver performance. By comparing the doppler phase noise of the reference receiver when combined with the array receivers to the doppler phase noise of the reference receiver alone, the improvement in performance can be determined directly by using the plot of receiver phase noise vs relative signal level of Fig. 5. An example using this plot is shown in Fig. 5 for the first measurement listed in Table 2, which resulted in a 2.6-dB improvement when one array receiver was combined with the reference receiver.

Measurements of radio frequency carrier signal-to-noise ratio improvements have been made by arraying combinations of two, three, and four receivers. These measurements were made with different voltage couplings β at the summing junction. These measurements are tabulated in Table 2 and do not differ by more than 0.1 dB from predicted values.

Reference

1. Brockman, M. H., "Radio Frequency Carrier Arraying for High Rate Telemetry Reception," in *The Deep Space Network Progress Report 42-45,* pp. 209-223, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1978.

Table 1. Relative input signal level and receiver noise temperature measurements

	Relative input signal level, V	T_n, K
Receiver No. 1	1.000	3170
Receiver No. 2	0.948	3147
Receiver No. 3	0.979	3161
Receiver No. 4	0.987	3147

Table 2. Carrier signal-to-noise ratio improvement due to carrier arraying of receiver systems

Receiver	β	Measured phase noise, deg rms	Carrier S/N improvement	
			Measured, dB	Calculated[a] dB
Receiver No. 1		14.9		
Receivers Nos. 1, 2	β_2 = 0.75	11.3	2.6[b]	2.6
Receiver Nos. 1, 2, 3	β_3 = 0.65	9.6	4.1	4.2
Receiver Nos. 1, 2, 3, 4	β_4 = 0.65	8.5	5.0	5.1[c]
Receiver No. 1		16.9		
Receiver Nos. 1, 2	β_2 = 0.80	12.6	2.6	2.7
Receiver Nos. 1, 2, 3	β_3 = 0.95	10.6	4.2	4.2
Receiver Nos. 1, 2, 3, 4	β_4 = 0.85	9.6	5.1	5.2
Receiver No. 1		16.9		
Receiver Nos. 1, 2	β_2 = 1.00	12.6	2.6	2.7
Receiver Nos. 1, 2, 3	β_3 = 0.95	10.6	4.2	4.2
Receiver Nos. 1, 2, 3, 4	β_4 = 1.00	9.4	5.2	5.2

[a]These calculated SNR Improvements were obtained using $\gamma_2 = 0.95$, $\gamma_3 = 0.98$, and $\gamma_4 = 0.99$.

[b]The method of determining the measured improvement in carrier SNR is shown on Fig. 5 for this one measurement.

[c]A sample calculation for this test condition is discussed in Section II-D.

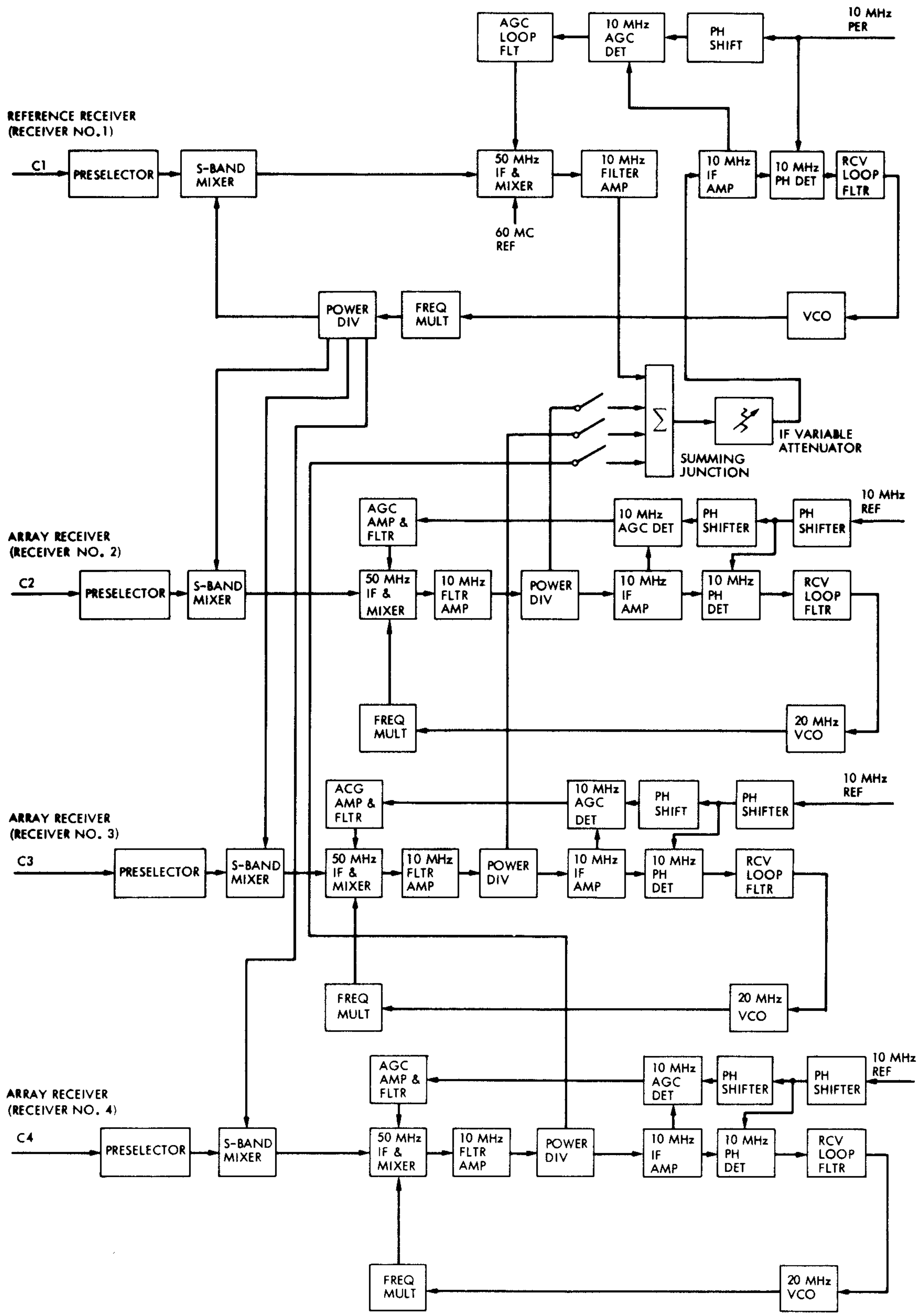


Fig. 1. Block diagram of carrier array of four receiving systems

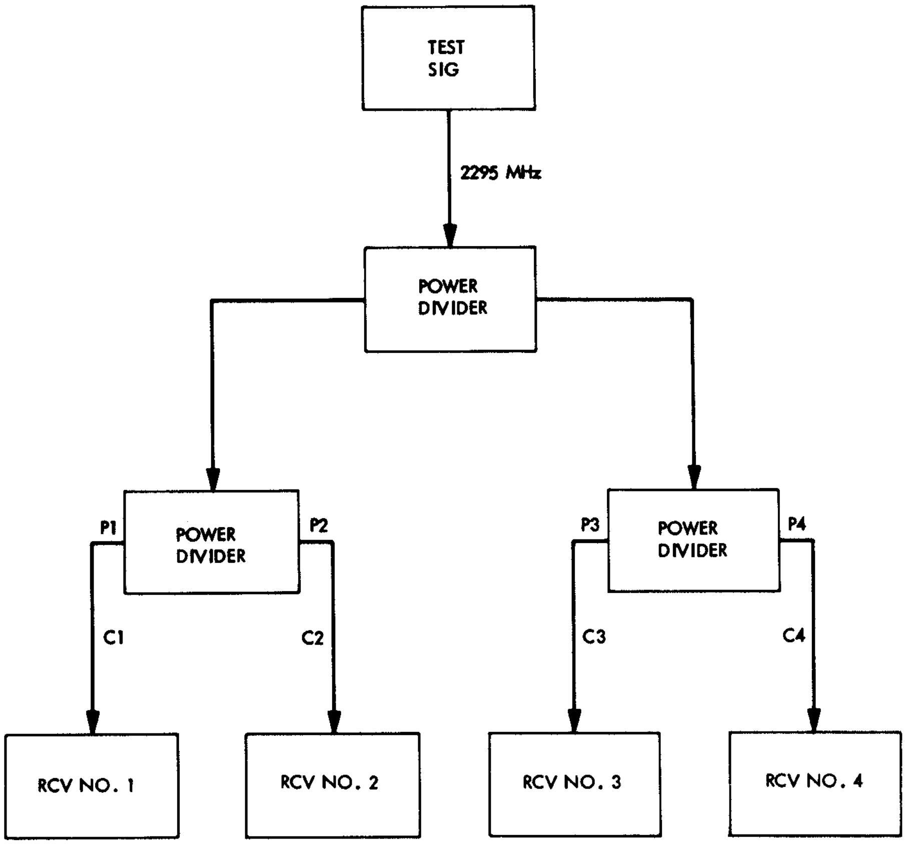
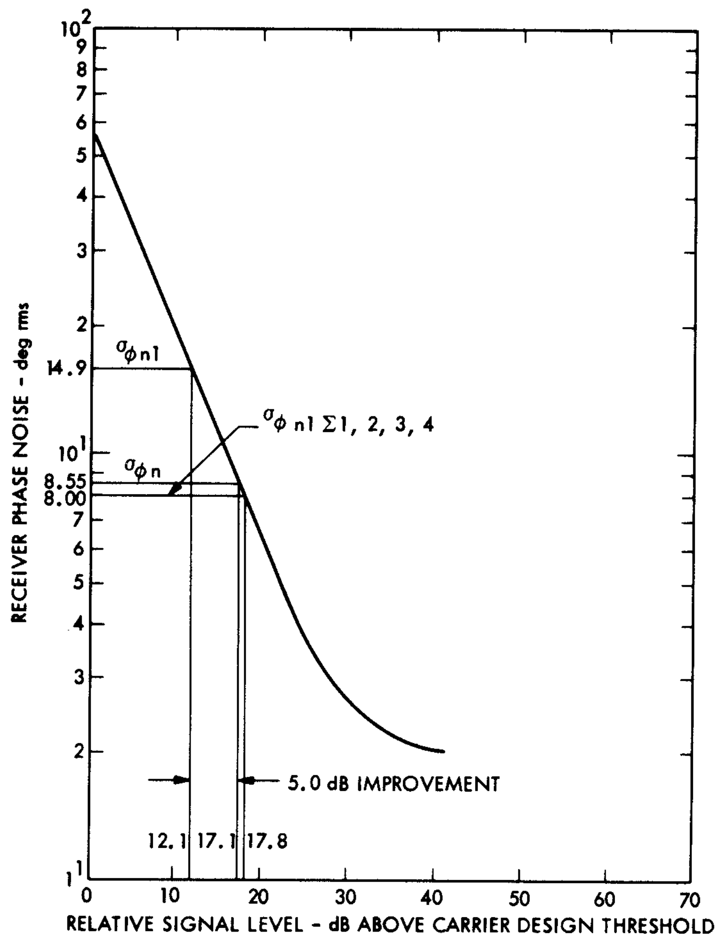


Fig. 2. Signal distribution for carrier array tests



NOTE: $\sigma_{\phi n1}$ = PHASE NOISE OF RECEIVER 1, BEFORE ARRAYED WITH RECEIVERS 2, 3, AND 4

$\sigma_{\phi n1 \Sigma 1, 2, 3, 4}$ = PHASE NOISE OF RECEIVER 1, AFTER ARRAYED WITH RECEIVERS 2, 3, AND 4 NEGLECTING THE PHASE NOISE CONTRIBUTION FROM RECEIVERS 2, 3, AND 4

$\sigma_{\phi n}$ = PHASE NOISE OF RECEIVER 1, AFTER ARRAYED WITH RECEIVERS 2, 3, AND 4 WITH THE CONTRIBUTION IN PHASE NOISE FROM RECEIVERS 2, 3, AND 4

Fig. 3. Receiver phase noise vs RF carrier level, reference receiver 1

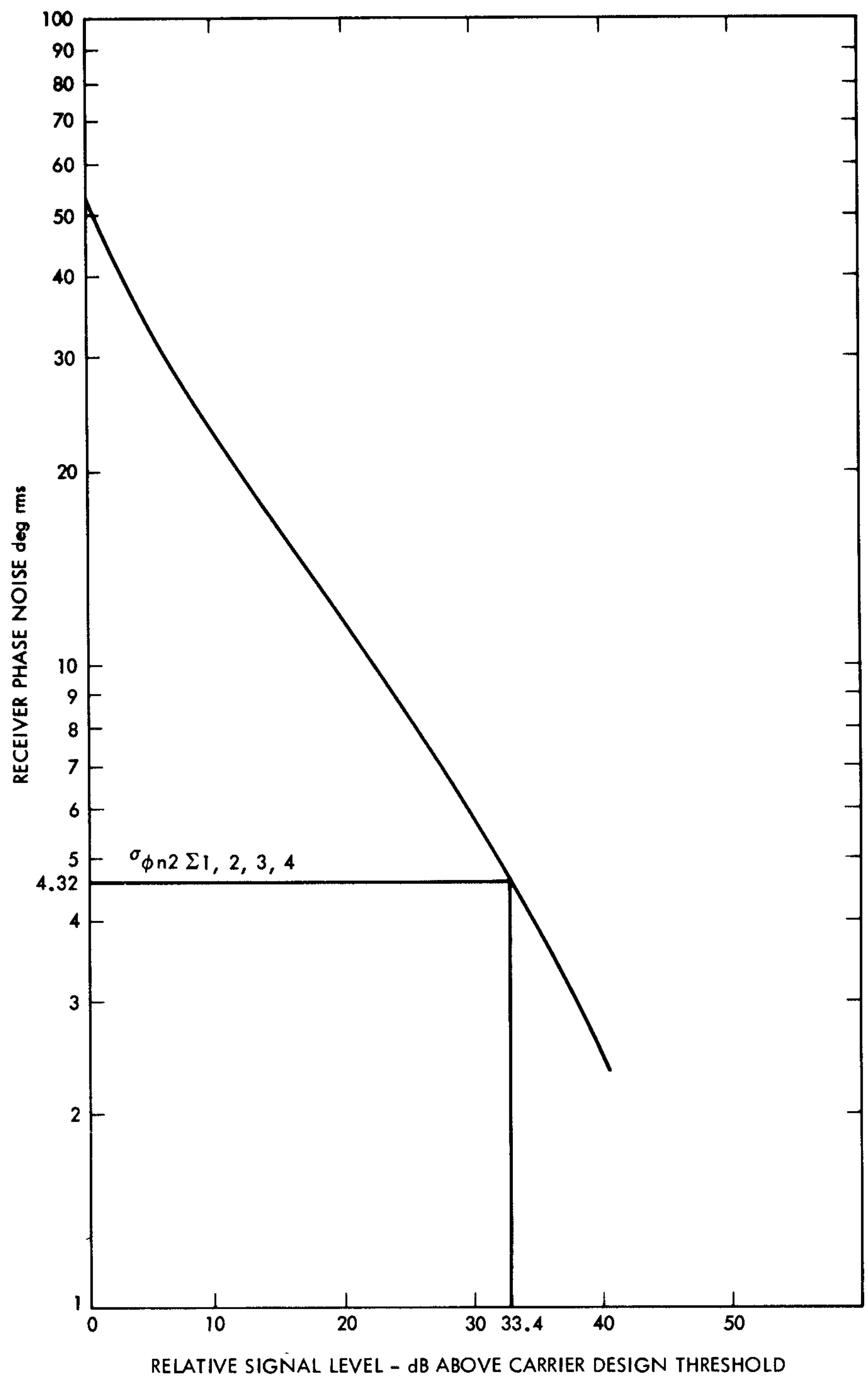


Fig. 4. Receiver phase noise vs RF carrier level, array receivers 2, 3, and 4

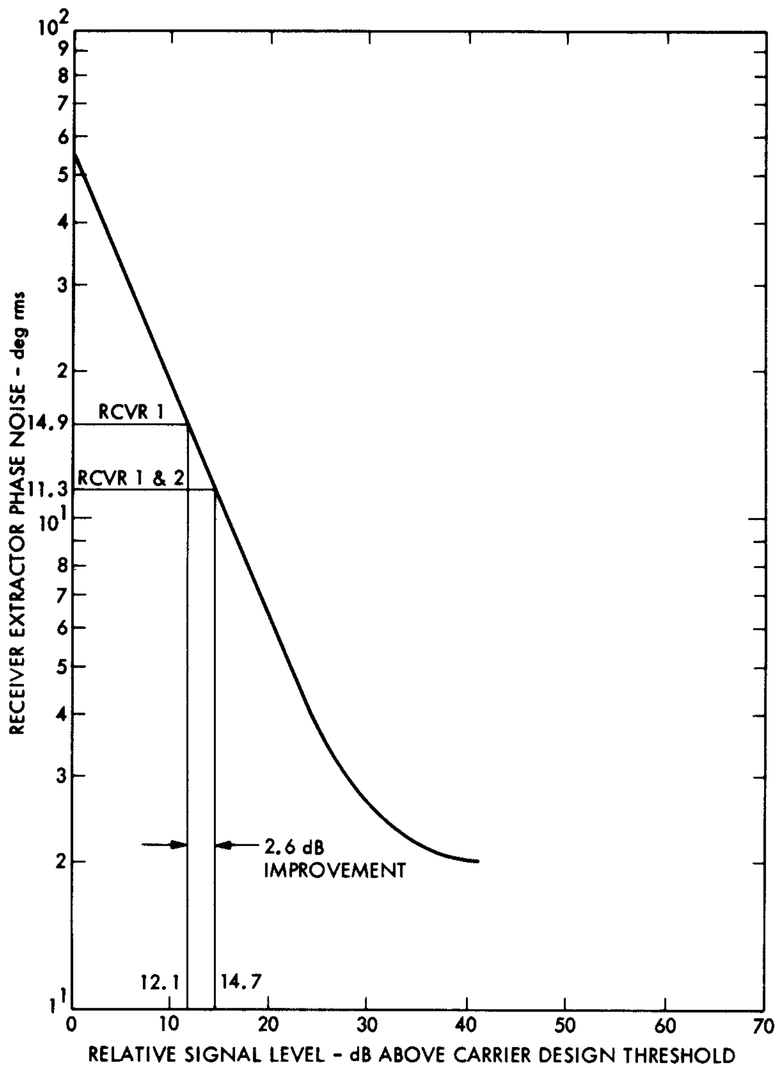


Fig. 5. Receiver phase noise vs RF carrier level, reference receiver 1