NOTCH NOISE LOADING DATA ON PRE-DETECTION RECORDING OF FM CARRIERS

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Summary In a previous paper (1) the authors reported notch noise loading tests of baseband (post-detection) tape recording showing dependency of the notch noise power ratio, NPR, on record level. The purpose of this paper is to report notch noise loading tests on pre-detection tape recording showing NPR dependence on record level, bias level, and output equalization. Both the baseband and pre-detection recording tests were made with the Hewlett-Packard Model 3950 recorder/reproducer. Generally, the pre-detection NPR were 5db or more improved over the baseband NPR. The extent of the improvement depends, in part, on the quality of the vco and discriminators utilized for the pre-detection recording as well as the carrier deviation. As the linearity of the vco and discriminator and the phase linearity of the circuits that pass the pre-detection signal are improved, the limiting factor in NPR is the noise added by the reproduce amplifier. Increasing the record level above IRIG standard produces an improvement in the output signal-to-noise ratio, NPRO, of 3 to 5 db using IRIG standard bias. Eliminating the bias and recording at the level which results in maximum output of the fundamental produced up to 8 db improvement in NPRO over IRIG.

In the course of the tests it was discovered that if harmonics are present in the recorded pre-detection signal and/or are generated in the record/reproduce process, serious intermodulation can occur unless a low-pass filter ahead of the discriminator is used.

Effect of Reproducer Equalization on NPR Data Figure 1 is a block diagram of the apparatus used to measure NPR/NPRO data for the Hewlett-Packard 3950 tape recorder/reproducer. The machine was set up in accordance with IRIG procedures. The baseband was 108 kHz with 73 kHz rms carrier deviation. The DCS model GSO-1 vco was used to generate an FM carrier at 450 kHz. The EMR model 4142 discriminator was used with ±40% bandwidth and 250 kHz video filter. Krohn-Hite Model 3103A tunable filters were used to filter out the harmonics. These filters roll off at 24 db/octave and were used in the “max flat” mode. In Table 1, filter #1 was set for 100 kHz to 600 kHz passband. Filter #2 was not in the circuit. Table 1 gives NPR data for different equalization schedules. In this table, the figure 49/65 means that with the carrier modulated, the NPR is 49 db. With modulation removed from the carrier the ratio is 65 db--this is called NPROM[1]. The 65 db is the signal-to-noise ratio in the slot with the intermodulation removed.

Line #1, back-to-back, give NPR with the vco feeding the discriminator through filter #1. Because of the direct connection, the noise floor is more than 60 db down. At high baseband frequencies, the NPR with modulation is limited mostly by non-uniform time delay (departure of phase characteristic from a linear function of frequency) due to narrow-banding the vco, bandpass filters and discriminator.[2]

Line #2 is with the HP 3950 in the loop at 60 ips. Equalization was consistent with IRIG standards and the spectral response to a white noise input of bandwidth I MHz is given in Figure 2, top trace. Note, from line 2 that the discriminator noise has risen by more than 20 db mostly due to noise in the reproducer amplifier. The bottom trace in Figure 2 is the spectrum of the noise out of the reproduce amplifier which is emphasized to make up for the loss of gain at the higher frequencies due to head-gap and tape effects. The correction is all in the reproduce amplifier because of the IRIG requirement for constant current recording.

Line #3 gives the NPR data for equalization outside the IRIG Standards. Figure 3 gives the spectrum for this case. Note that the NPRO does not change much but the intermodulation increases.

Line #4 gives the NPR with flat output amplitude gain--i.e., no gain equalization giving the spectrum of Figure 4. Note that the NPRO again does not change much but the intermodulation increases especially at the low-frequency end of the baseband. This is explained qualitatively in Appendix 1 and is due mostly to static non-linearity resulting from nonsymmetric attenuation of the side bands.

Effect of Record and Bias Levels Table 2 gives NPR data for different record and bias levels for the Hewlett-Packard 3950 tape machine. Note that increasing the record level above IRIG Standard increases NPRO at the high end of the baseband by 3 to 5 db. The reason for this is that a larger signal is reproduced from the tape whereas the noise remains constant. Because of the parabolic noise spectrum of FM, the improvement is most noticeable at the higher baseband frequencies.

By removing the bias altogether and driving the record head directly from the vco (through a flat amplifier), 5 db improvement in NPRO over IRIG record level was obtained for the 108 kHz baseband. With this baseband, 7 volts rms into the head produced maximum output. The corresponding improvement for the 204 kHz baseband was 8 db. With this baseband, 10 volts rms into the head produced maximum output.

With IRIG STD. plus 5 or 6.5 db and 7-10 volts rms direct-to-thehead record levels, there was considerable distortion introduced which generated harmonics of the carrier. If these harmonics are not shifted in phase relative to the carrier, they do not affect the discriminator output since the input to the discriminator is hard limited anyway. However, the equalizer in the output amplifier introduces non-uniform phase delay at the high-frequency end which shifts the phase of the harmonics. The result is serious degradation of the NPR particularly at the low frequency end unless a low-pass filter is used ahead of the discriminator. The harmonics in the output of the vco were reduced by a bandpass filter before tape recording. For runs #1 and #2, filter #1 was set for bandpass 100 kHz - 600 kHz and #2 filter for 10 kHz - 800 kHz. For runs #2 and #4, a Hewlett-Packard Model 467A amplifier was inserted after filter #1 to drive the record head through a 0.02μF condenser. For run #3, filters #1 and #2 were both set for 0 - 1.5 MHz. For run #4, filter #1 was set for 0 - 3 MHz and filter #2 was set for 0 - 1.5 MHz.

Discussion The tape machine and other test equipment such as vcols, amplifiers, discriminators, etc. , used for Tables 1 and 2 were more-or-less standard off-the-shelf equipment. Thus, distortion of both static and dynamic types were present to limit the NPRI due to intermodulation. By proper equipment specification, this distortion can be reduced. (In micro-wave telephone relay equipment, the distortion has been reduced several orders of magnitude compared to the data in Tables 1 and 2. However, the NPR depends on the sum of intermodulation power and noise power so that when intermodulation power is reduced, noise power controls the NPR. Thus, the NPR can never be any larger than NPRO. If B is the difference between NPRO in db and NPR in db, Figure 5 gives the correction Δdb to be added to NPR to give NPRI which is the NPR due to intermodulation alone.[(1)]

An estimate of the NPR required to support constant bandwidth FM/FM may be obtained from the following. An approximate theory relating the NPR to the output S/N of FM subcarriers gives

$$(S/N)_{FM} = 3D^3\,(NPR) \tag{1}$$

for the large carrier signal condition where

$(S/N)_{FM}$	=	signal-to-noise power ratio in an FM subcarrier output when fully modulated by a sinusoid.
D	=	subcarrier deviation ratio = $B/2F_m$ where B is the bandwidth of subcarrier selector filter and Fm is the cut-off frequency of output low-pass filter.
(NPR)	=	notch noise test NPR at frequency corresponding to the subcarrier frequency.

Thus, if D = 5, generally used with the proportional IRIG FM/FM format, the FM subcarrier improvement is 375 or 26 db. In many missions, perfectly satisfactory data would result with NPR of 20 db or less. However, the new constant bandwidth IRIG FM/FM formats are intended for vibration, acoustic, and shock data which are wide band and noise like and require wide dynamic range. In fact, based on the requirements for support of these missions, a peak-to-peak to rms noise ratio in the output of an FM subcarrier better than 46 db is necessary.(3) In terms of $(S/N)_{FM}$ in equation 1, overall performance better than 49-9 = 37 db is required. Also, on large vehicles, many wide-band data channels are often needed. To conserve the number of RF links required, it is desirable to utilize each link to the fullest extent by using low subcarrier deviation ratios - preferably around unity. For D = 1, equation 1 predicts only 5 db improvement at large signal strengths where performance is limited by intermodulation. At low signal strength (but still above carrier and subcarrier thresholds) the performance is limited by thermal noise and the corresponding formula is given by equation (2).

$$(S/N)_{FM} = 6D^3(NPR) \tag{2}$$

In order to improve low-signal strength performance, maximum carrier deviation should be used consistent with IRIG spectrum occupancy standards and allowed intermodulation. At P band, the spectrum occupancy standards restrict the modulation to about 110 kHz rms for the 100 kHz baseband.(4) We do not have data yet for L and S band.

Thus to produce 46 db peak-to-peak to rms noise ratio in the FM subcarrier output with D = 1, the NPR must be at least 46-9-5 = 32 db on the tape received by the user. If the mission tape has been dubbed once, then the noise added by the dubbing reproducer is added to the noise in the output of the user's reproducer. This leads to a goal of at least 38 to 40 db NPRO. This goal is achieved with the HP 3950 on the 108 kHz and 204 kHz baseband with 73 kHz rms modulation using IRIG record level or, better, by recording 5 db above IRIG or at 7 volts rms direct on the head with no bias. Other applications, such as hybrid multiplexing - i.e., a baseband consisting of a time division multiplex plus a frequency division multiplex - may require large NPR for efficient operation. Table 2 indicates the limiting values of NPR which can be obtained from the HP-3950 machine by recording directly on the head with no bias.

The above data appear to confirm that an NPRO of 40 db or better can be obtained. Improvement of NPRI is required to 40 db, or better, if the tape after dubbing is to deliver an NPR of 32 db or better. This can be accomplished by improving the linearity of the demodulator (the user must provide a linear FM transmitter) and the use of phase equalization (or linear phase circuits) in all circuits carrying the pre-detection waveform. This will require revisions in procurement specifications. When the static linearity and phase linearity have been improved, it may be expected that the sensitivity of NPRI to amplitude equalization, noted in Table 1, will increase in relative importance.

It must be emphasized at this point that increasing the non-linearity in the pre-detection recording process, as by recording at a level greater than IRIG Standard or by direct high-level recording without bias, tends to “freeze in” the thermal noise added ‘by the telemetry receiver RF system, plus interfering signals. For example, suppose that it is desired to use a final IF bandwidth larger than required for the modulation in order to allow for carrier frequency drift, doppler shifts, etc. , with the objective of bandpass filtering the signal at the output of the tape recorder before demodulation in order to eliminate the excess noise. This can be accomplished efficiently only if the recording process is linear. However, for a 200 kHz baseband of FM subcarriers, the IF bandwidth required for the modulation is 750 kHz or more depending on the depth of modulation and the phase linearity of the IF. Thus the additional bandwidth required for drift, etc. , is relatively small and, in this case, the non-linearity introduced to produce better NPRO is relatively unimportant.

There is a trade-off between static linearity and phase linearity. For example, if it is economical to obtain high static linearity to give high NPRI at the low-frequency end, pre-emphasis of the subcarrier amplitudes can reduce requirements on the high-frequency end where use of phase equalization circuits in the reproduce amplifier amplitude equalizers may be expensive and inconvenient. See, for example, reference 5, Figure 10.

Increase in record level above IRIG Standard level or recording at high level with no bias at all requires more gain equalization. This is illustrated by Figure 6 giving the response to white noise input with 7 volts rms on the head with no bias using equalization set under IRIG conditions. The additional equalization required increases the phase distortion unless phase equalization is used. In order to optimize the NPR from a tape recorder/reproducer it is necessary to set the bias properly and to adjust the reproduce head azimuth to produce accurate alignment with the signal on the tape to be reproduced. If either or both adjustments are incorrect, more equalization schedule is required. In addition, it is possible to produce poor NPR performance even though the equalization is consistent with IRIG Standards. For example, Figure 7 shows a spectral response characteristic consistent with IRIG but which produced NPR/NPRO of 38/38, 29/46, 19/41 and 18/22 in the 14, 34, 70, and 105 kHz notches, respectively, otherwise under the same conditions as those of Table 1. It is evident that the problem was incorrect adjustment of bias and/or azimuth which was offset by extreme equalization. More details on effects of bias and azimuth adjustment will appear in a paper submitted to the Telemetry Journal by the authors.

TABLE I
NPR Data for Hewlett-Packard Model 3950 Recorder/Reproducer

Line No.	Figure No.	Mode	NPR db Notch Frequency 14	34	70	105
1		Back-to-back	49/65	50/65	44/64	40/63
2	2	Tape	43/46	44/46	40/44	34/41
3	3	Tape	42/46	42/47	38/43	32/39
4	4	Tape	19/46	40/45	34/42	27/39

TABLE 2
NPR/NPRO AS A FUNCTION OF RECORD LEVEL AND BIAS

Line #	Run #	Mode	Record Level	Bias	Equalization	NPR/NPRO Notch Frequency 14	34	70	105	185	Tape Speed ips	Base Band kHz
1	1	Back-to Back	----	----	----	49/65	50/65	44/64	40/63	----	----	108
2	1	Tape	IRIG	IRIG	IRIG	43/46	44/46	40/44	34/41	----	60	108
3	1	Tape	IRIG +5 db	IRIG	IRIG	43/45	45/49	41/47	35/44	----	60	108
4	2	Back-to Back	----	----	----	44/65	45/66	38/66	32/67	----	----	108
5	2	Tape	7 volts rms	None	----	36/47	40/52	34/49	28/46	----	60	108
6	3	Back-to Back	----	----	----	44/64	47/67	43/67	39/67	30/63	----	204
7	3	Tape	IRIG	IRIG	IRIG	40/46	43/50	39/47	36/46	31/41	120	204
8	3	Tape	IRIG +6.5db	IRIG	IRIG	41/46	44/52	40/49	38/48	32/46	120	204
9	4	Back-to Back	10 volts rms	----	----	43/65	44/67	40/67	37/67	30/67	----	204
10	4	Tape	10 volts rms	None	IRIG	17/46	29/54	28/51	26/50	25/49	120	204

Appendix 1

Effect of Tape System Frequency Response on Intermodulation in the Pre-Detection Mode Poor gain equalization across the passband changes the carrier modulation side-band amplitudes and phases. Consider first the effect of amplitude variation. To simplify the discussion suppose that the modulation index is small so that only first order side bands need to be considered. Then the vector diagram of Figure A-1 can be used to represent the modulated carrier.

The side bands are initially 180° out of phase and of equal amplitude A_m. The vector sum of side bands and carrier is A_r. The frequency modulation of the carrier is $\theta(t)$.

Now suppose that due to poor gain equalization the two side bands are of different amplitude A_1 and A_2. The result is indicated in the vector diagram of Figure A-2. It is clear that the frequency modulation $\theta(t)$ is greater on the bottom part of the locus, than on the top. This would produce even harmonic distortion of the static type. Static distortion produces intermodulation which causes reduction of NPRI mostly at the low frequency end of the baseband.

When the pre-detection circuits produce non-uniform delay across the pre-detection passband, dynamic distortion results which reduces the NPRI mostly at the high frequency end of the baseband. Since it may be expected that the equalizer networks produce non-uniform delay across the passband, if uncompensated, a trade-off is

indicated between amplitude assymetry of the side bands and the delay distortion introduced in equalizing the amplitudes of the side bands, if uncompensated for delay. One solution is to incorporate phase compensating networks in the equalizer to give proper amplitude equalization and at the same time decrease the delay distortion to tolerable values.

References

(1) W. R. Hedeman and M. H. Nichols, “Notch Noise Loading Data on Baseband Tape Recording. 11 ITC-70 Proceedings, Page 390.

(2) A. F. Ghais, E. J. Finari and C. J. Boardman. ITC-67 Proceedings, p. 26.

(3) M. H. Nichols, ITC-67 Proceedings, p. 361.

(4) F. J. Schmitt, “Double Sideband Telemetry Study”, Lockheed Electronics Company Technical Memo. #68-1, Jan. ’68, White Sands Missile Range.

(5) F. J. Schmitt, ITC-67 Proceedings, p. 347.

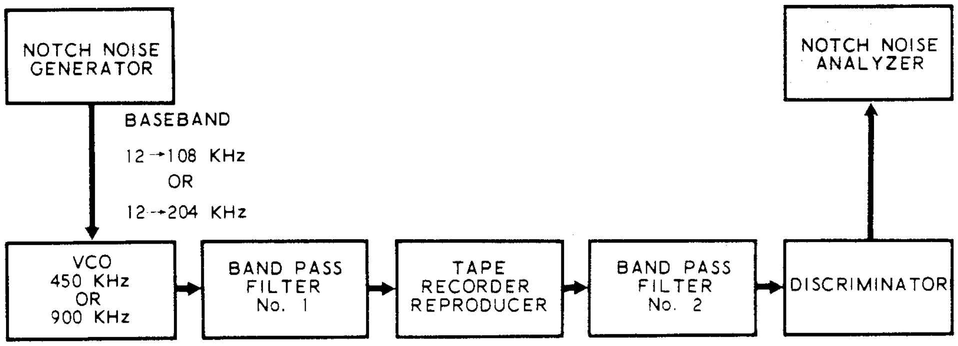

Figure 1. Block Diagram for Measuring NPR.

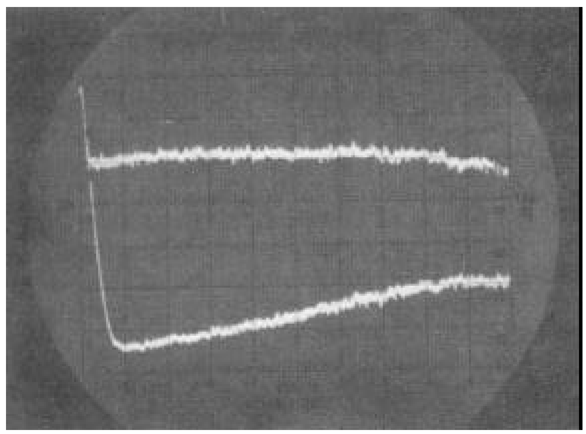

Figure 2. Spectral Response of Tape Recorder/ Reproducer corresponding to line 2 in Table 1.

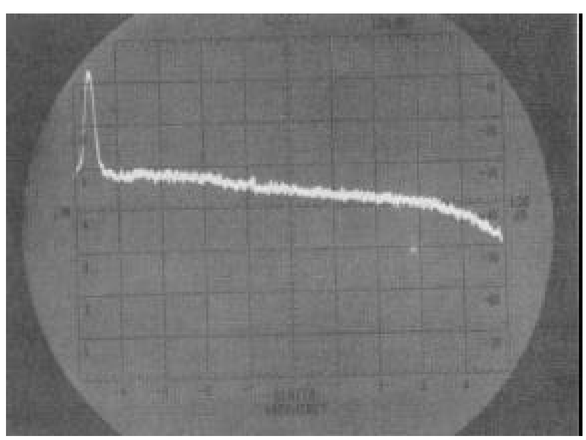

Figure 3. Spectral Response of Tape Recorder/ Reproducer corresponding to line 3 in Table 1.

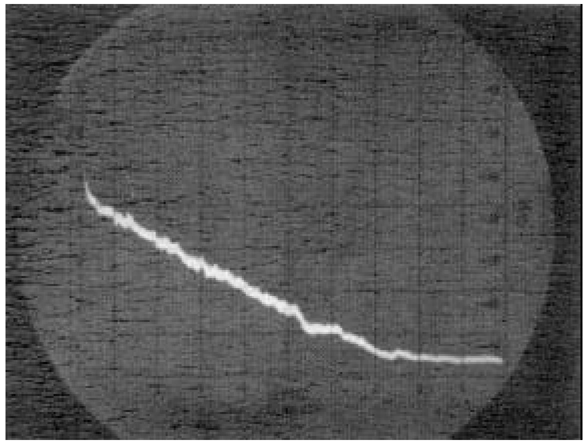

Figure 4. Spectral Response of Tape Recorder/ Reproducer corresponding to line 4 in Table 1.

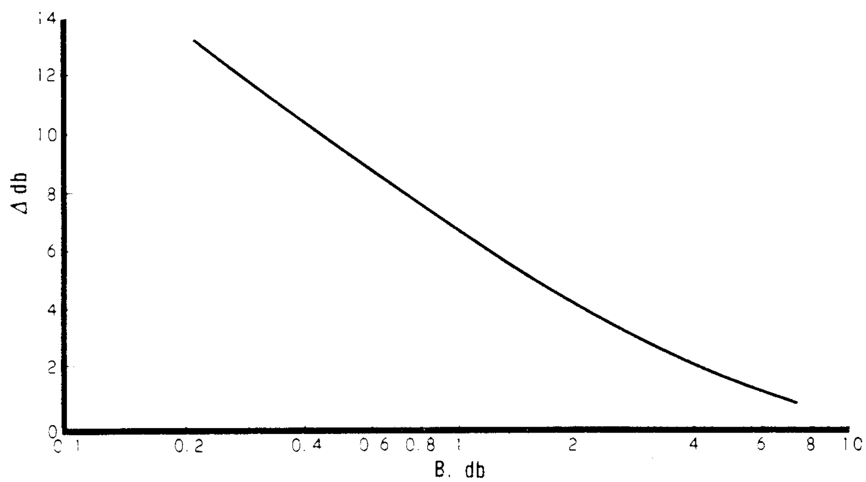

Figure 5. Calculated Curve for Converting NPR and NPRO Data to NPRI.

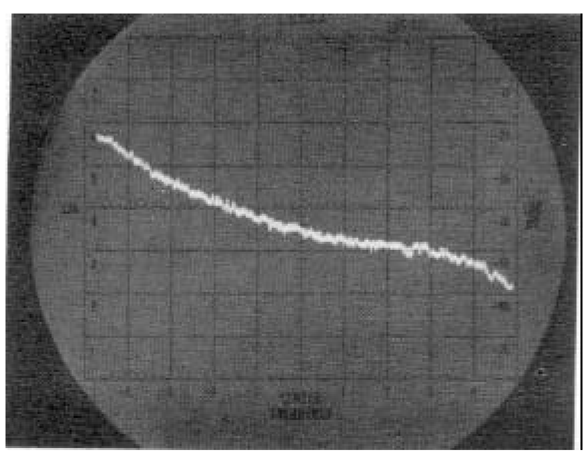

Figure 6. Spectral Response for High-Level Recording with no Bias at 120 ips. The frequency scale is 200 kHz/division. The ordinate scale is 10 dB/division.

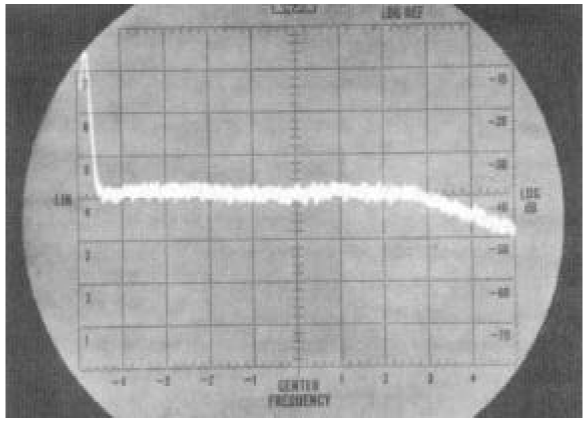

Figure 7. Spectral Response of Tape Recorder/ Reproducer with Incorrect Bias and/or Azimuth Adjustment.

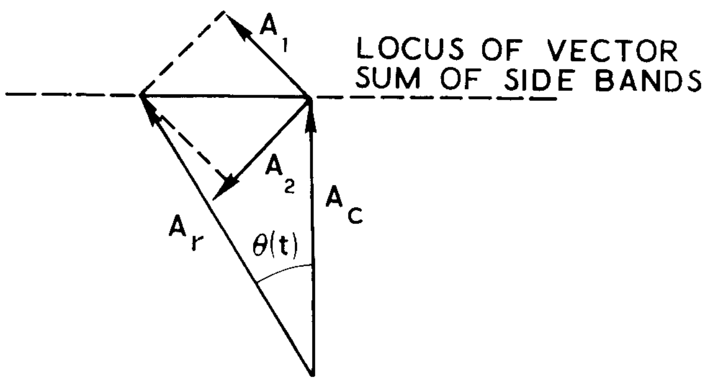

Figure A.1. Vector Diagram of FM Modulated Signla

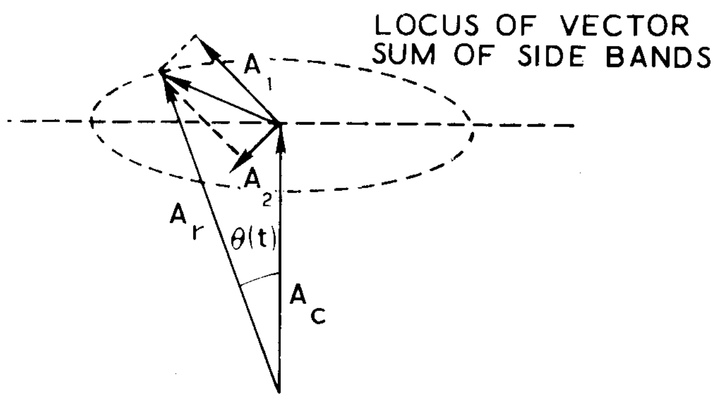

Figure A.2. Vector Diagram When A_1/A_2