SIGNAL DESIGNS FOR APOLLO SCIENTIFIC DATA SYSTEMS

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Summary The Apollo lunar-exploration missions are being planned for the purpose of obtaining comprehensive scientific data. The system descriptions and key signal-design considerations for two data transmission systems – the Phase II Scientific Data System and the Particles and Fields Subsatellite – are discussed. In both cases, the designs are constrained by the requirements to (1) use the existing spacecraft systems where possible, (2) use the existing ground stations, and (3) maintain the existing Apollo communications capabilities.

Introduction The experiments proposed for the lunar-exploration phase of the Apollo Program have resulted in the addition of two data systems to the command and service module (CSM). The Phase II Scientific Data System (SDS) is to be supported by the CSM FM link on 2272.5 MHz. A subsatellite will be ejected from the CSM to provide information on the lunar gravitational field and measurements of particles and fields (P&F) in the vicinity of the moon as the subsatellite orbits the moon. The P&F subsatellite will operate on the lunar module frequencies of 2101.8 MHz earth-to-satellite and 2282.5 MHz satellite-to-earth. A mission rule has been established that, when an Apollo lunar module is active, the subsatellite transmitter will be commanded off.

The SDS was designed with two constraining requirements. The prime requirement was that no existing CSM communications capability would be deleted. The second requirement was that data be transmitted from the proposed experiments. Two possible system configurations were considered for meeting these requirements:

1) Implement a separate FM transmitter on the Apollo CSM exclusively for the scientific data.

2) Incorporate the scientific data into the present CSM FM link transmitter using time-division multiplexing (TDM).

A review of these possibilities indicated that the addition of the scientific data to the existing CSM FM link was possible and provided some attractive cost and schedule considerations. Therefore, it was decided to add a scientific data transmission mode with the following characteristics:

1) Baseband- recorded voice at 1:1 playback.
2) One real-time and one playback channel with a 5-kHz maximum frequency response.
3) One real-time and one playback channel with a 9-kHz maximum frequency response.
4) One real-time and one playback channel with 64-kbps PCM telemetry.
5) One channel of CSM- recorded 51. 2-kbps PCM telemetry.

The addition of the four analog and two PCM channels to the existing gain- and bandwidth-limited channel resulted in several interesting design problems. The predetection SNR is approximately 8. 5 db when an 85-ft Manned Space Flight Network (MSFN) station is used. The predetection bandwidths of the MSFN receivers vary from 4.3 to 5.3 MHz. In determining an acceptable signal design, the 4.3-MHz bandwidth was considered from a band-limiting and distortion standpoint, while the 5.3-MHz bandwidth presented problems in the area of FM threshold. Acceptable data are defined as follows:

1) The baseband voice channel postdetection SNR must be at least 14 db, which corresponds to a 70-percent word intelligibility.
2) The four scientific data channels must have a postdetection SNR of at least 20 db, and the subcarrier data demodulator must be operating above the FM threshold with a predetection SNR of 10 db.
3) The three telemetry channels must provide a bit error probability of no greater than 10^{-4}, which corresponds to a predetection SNR of 9 db at the input to the subcarrier data demodulator.

The P&F subsatellite is to be ejected from the CSM in lunar orbit and will transmit data for a period of approximately 1 yr. A transponder of the type designed for the MSFN test and training satellite will be used for data transmission. The P&F is gain limited because the RF subsystem originally was designed for earth-orbital use. Data requirements for the P&F are (1) 128 bps of PCM telemetry and (2) coherent Doppler measurement. The desired PCM error rate is no more than one error in 10 000bits ($P_e < 10^{-4}$). The Doppler measurements require a 12-db SNR in the carrier tracking loop.

Signal Design for the SDS Selection of the scientific data and telemetry subcarrier frequencies was based on an extension of the standard Inter-Range Instrumentation Group (IRIG) channels. The new subcarrier frequencies were chosen such that the existing CSM 165-kHz and 1.024-MHz channels could be incorporated into the total signal design. Five subcarrier frequencies of 225, 300, 400, 576, and 768 kHz were selected to occupy the band between the existing CSM 165-kHz and 1.024-MHz channels. The 225-kHz frequency was determined by multiplying the 165-kHz frequency by a factor of 1.37. This value is approximately the same multiplying factor used for deriving the remaining subcarrier frequencies and is similar to the multiplying factor separating the low IRIG frequencies. The 576- and 768-kHz frequencies were chosen (as opposed to 600 and 800 kHz) to eliminate possible second-harmonic interference from the 300- and 400-kHz subcarriers, respectively. In addition to avoiding the interference problem, these two frequencies have the advantage of being multiples of the 512-kHz clock in the CSM (512 x 3/2 = 768; 512 x 9/8 = 576). The S-band spectrum for the SDS frequency design is shown in figure 1.

The initial subcarrier frequency deviations ($\Delta f_1 \equiv$the frequency deviation of a subcarrier onto the carrier) were determined using a constant modulation index β criteria of $\beta = 1$ for the 165-, 225-, and 300-kHz subcarriers. A tapered deviation schedule was used for the 400-, 576-, 768-, and 1024-kHz subcarriers so that the signal design would be compatible with the CSM modulator characteristics. These values of β satisfy both the SNR and the threshold requirements for each data channel based on the classical FM discriminator mathematical model of S.). Rice.[1]

A series of SNR tests was conducted at the Manned Spacecrait Center (MSC) for the purpose of verifying the initial signal design (table I). The results of these tests indicated that the performance of the lower frequency channels was degraded because of below-threshold operation of the subcarrier data demodulators.

The degraded performance of the subcarriers was due to the low-frequency deviations of these channels and also to the excessive frequency deviations of the 768- and 1024-kHz subcarriers. These deviations had been determined analytically using the Rice[1] model for an unmodulated FM signal. The rationale was that because this equation applied to a conventional discriminator and because a phase-lock-loop FM demodulator (which has better threshold performance than a discriminator) is used in the MSFN receiving system, the output signal-to-noise curve would represent a worst-case condition. However, the measured performance is significantly degraded from the predicted results using the Rice model. This degradation is due to the multiple (seven) subcarriers affecting the phase-lock-loop performance by introducing excessive loop stress. The interchannel interference was not included in the initial signal-design performance predictions because of the unavailability of an accurate mathematical model at that time.

The results of the SNR tests indicated that empirical methods must be used to obtain a workable frequency-deviation schedule for the SDS. Therefore, a second series of SNR tests was initiated for the purpose of determining an acceptable deviation schedule. The results of these tests indicated that significant performance improvement could be obtained for the lower frequency subcarriers by increasing the frequency deviation of the degraded channels while decreasing the 1024-kHz subcarrier frequency deviation from 600 to 550 kHz.

The following conclusions were obtained as a result of the SDS simulation tests conducted in the Signal-Design Verification Laboratory at MSC:

1) The subcarrier frequency deviations listed in table II ensure satisfactory performance of the SDS under worst-case RF-level conditions.

2) A tolerance of ± 10 percent can be included with the deviations. This ± 10-percent value is not an absolute number; a ± 15-percent tolerance would probably work although the system performance would be degraded. However, a ± 20-percent tolerance will not work.

3) The FM threshold is defined for the various subcarrier channels as the input’SNR (into the first FM demodulator) at which impulses are seen in the output (subcarrier) filter at the rate of 1 impulse per sec to 1 impulse per 10 sec. There is approximately a 1-db difference in the input SNR at which these two impulse rates occur. The output data are obliterated entirely during the time of an impulse.

4) An input SNR of 10.5 db into the subcarrier data demodulator will give satisfactory performance, assuming that the subcarrier data demodulator is a threshold-extending device such as a phase-lock-loop or FM feedback (FMFB) demodulator.

5) Tolerances on the frequency deviations of the analog modulating signals onto the subcarriers are not critical. A±25-percent tolerance will provide satisfactory performance.

The theoretical required IF bandwidth for the composite signal spectrum can be determined using the minimum bandwidth rule, which states that $BW_{required} = 2(\Delta f + f_{max})$. For this particular design, the composite rss frequency deviation is approximately 1 MHz and the maximum modulation frequency f_{max} is 1.024 MHz. Therefore, the calculated required bandwidth is approximately 4.1 MHz using the minimum bandwidth equation, which indicates that the deviation schedule approaches the bandwidth capability of a minimum-bandwidth MSFN receiver. The MSFN receivers are specified to have a predetection bandwidth of 4.8 ± 0.5 MHz when operated in the FM mode.

The frequency deviations and bandwidths for the subcarrier data were determined by the requirement for simultaneous real-time and playback data capability with peak modulation frequencies of 5 and 9 kHz. The parameters were chosen so that (1) the real-time and playback channels would be adjacent and (2) the postdetection SNR performance of each subcarrier pair would be identical. The IRIG standard frequency deviation of ±7.5 percent (12.4kHz) was used for the 165-kHz subcarrier data along with a 5-kHz peak modulation frequency. The identical frequency deviation was assigned to the adjacent 225-kHz channel, which was designed as the real-time channel counterpart of the 165-kHz subcarrier. The peak modulation frequency of 5 kHz was common to both subcarriers.

The 300- and 400-kHz subcarriers were deviated 22.5 kHz (which is 7.5 percent of 300 kHz) and had a peak modulation frequency of 9 kHz. The 576- and 768-kHz telemetry subcarriers were biphase modulated with 64 kbps data, and the 1. 024-MHz telemetry subcarrier was biphase modulated with 51.2 kbps data.

The required predetection bandwidths for the four analog subcarrier demodulators were determined using the minimum-bandwidth criteria previously discussed. The calculated required predetection bandwidths are listed in table III.

The predetection bandwidths for the 576-kHz, 768-kHz, and 1.024-MHz telemetry channels were determined by the data rate and P e requirements for each channel. A postdetection $P_e \leq 10^{-4}$ and a 64-kbps data rate were required for the 576- and 768-kHz channels, and a 10^{-4} P_e and a 51.2-kbps data rate were required for the 1.024- MHz channel.

A value of 80 kHz was selected for predetection bandwidth of the 576- and.768-kHz telemetry channels to minimize the possibility of interference. This bandwidth corresponds to passing the fundamental component and approximately 85 percent of the energy for a NRZ-L code, assuming equal probability of ones and zeros.[2] The existing 150-kHz bandpass filter was retained for use with the 1.024-MHz channel.

SDS Performance Summary A detailed series of system evaluation tests was conducted at MSC for the purpose of verifying the performance of the total proposed SDS. The results of both SNR and bit-error-rate (BER) tests were used to determine the minimum-specified and expected nominal case performance of the SDS. The minimum-specified and estimated-nominal case circuit margins for an 85-ft MSFN station with the CSM at lunar distance (215 000 n. mi.) are presented in table IV.

The data shown in table IV indicate that the 768-, 576-, and 300-kHz subcarrier channels will have negative circuit margins at lunar distance for the minimum-specified case. The criterion used for acceptable performance is a 10-db predetection SNR for the analog channels and a $P_e < 10^{-4}$ for the telemetry channels.

The estimated-nominal case circuit margins indicate that all channels but the 768-kHz channel will meet the required performance criteria. The 768-kHz channel also will exhibit a positive circuit margin when a 10^{-3} P_e is used.

Signal Design for the P&F Subsatellite With the restriction that the P&F subsatellite be compatible with existing Apollo S-band ground stations, the choices of modulation techniques are somewhat limited for both the downlink and the uplink. Because of the rigidity of the Apollo command link, the design of the subsatellite uplink must closely parallel that of the Apollo system. However, because a substantial performance margin exists on this link, constraining the signal design presents no special problems.

The downlink, with its limited effective radiated power (ERP), requires nearly optimum use of all available power to establish reliable communications. Here the choice of signal design is critical to a successful link design.

The first proposed modulation scheme involved f requency- shift keying (FSK) a PCM data stream onto a 3.9-kHz sine wave subcarrier. The modulated subcarrier is phase modulated onto the S-band carrier. This modulation scheme is denoted by the symbol PCM/FSK/PM.

The PCM/FSK/PM scheme appeared undesirable because of possible interference with the carrier acquisition as a result of the closeness of the 3.9-kHz subcarrier to the carrier. Furthermore, the PCM/FSK/PM scheme requires a higher receiver signal-to-noise spectral-density ratio than does a similar biphase-modulated system. In an effort to minimize the required signal-to-noise density ratio, and, in effect, the required spacecraft ERP, several methods of implementing a biphase-modulation scheme (PCM/PM/PM) were investigated.

Because one ground rule for the system design requires a minimum impact on the existing ground-station facilities, the obvious choice for a subcarrier frequency is the 1.024 MHz of the Apollo telemetry subcarrier. Use of this subcarrier would require no ground-station modification. However, hardware designers indicated that implementing this high a frequency would require the use of high-speed logic that would strain the already tight primary power budget in the spacecraft. Thus, no further consideration was given to use of the Apollo telemetry subcarrier frequency.

In considering the support requirements for the several scientific experiments or programs being planned, it became apparent that a definite need existed for a variable-frequency biphase subcarrier demodulator at the MSFN sites. Engineers at the Goddard

Space Flight Center (GSFC) had been considering such a device for some time. It was decided, after discussions with cognizant GSFC engineers, to pursue the subsatellite signal design based on the availability of the variable-frequency biphase demodulator. The remaining task then was to select a suitable frequency for the subcarrier.

Some general criteria were identified for selection of the subcarrier frequency. As mentioned previously, the frequency should be low enough to preclude the necessity for using high-speed logic in the spacecraft design. It is also highly desirable to select a frequency from which the 128-bps clock could be derived, using a binary counter. A third consideration involves the IF bandwidth of the MSFN S-band receivers. The receiver uses a limiter-wideband/phase-detector combination for subcarrier detection, which, because of the limiter suppression, can degrade performance by as much as 1.04 db if the IF SNR is less than -3.47 db. Thus, it is important to minimize the IF bandwidth. In the Apollo configuration, the IF bandwidth is 3.3 MHz. At the expected received power levels from the subsatellite, the full 1.04-db performance degradation would be experienced using this bandwidth. An alternate filter of 60 kHz (-1 db) is being implemented in the MSFN receivers to accommodate the Apollo lunar-surface experiments package (ALSEP). Using this filter will eliminate limiter suppression at the 85-ft sites and reduce it by one-half at the 30-ft sites. Thus, selection of a subcarrier frequency that is compatible with a 60-kHz IF bandwidth is desirable.

A final consideration in selecting the frequency is to move the subcarrier outside the range of the approximately 12-kHz Doppler uncertainty of the carrier. This consideration will help minimize carrier-acquisition problems at the ground stations. A frequency that meets all these criteria is 32. 768 kHz, which is the value selected for the subsatellite data subcarrier.

The other major concern in the signal design was an uncertainty about the use of a square wave rather than a sine wave subcarrier. The effect of using a square wave subcarrier on ground-station receiver performance was unknown. Cursory analysis indicated no significant difference in link performance using either of the subcarriers. However, because a significant simplification in spacecraft hardware implementation exists with the square wave, a detailed study of the effects of using a square wave subcarrier was undertaken.

The analysis performed on the proposed communications link was directed toward answering the following questions:

1) Is there an inherent power advantage in using a square wave rather than a sine wave subcarrier ?

2) Considering both the square wave and the sine wave subcarriers, is there an optimum choice of modulation indices that will minimize the required spacecraft ERP?

3) Will the power spectral distribution, as a result of using a square wave subcarrier, adversely affect the performance of the telemetry receivers ?

The results of this analysis are summarized below. A more detailed presentation is given in reference 3.

From a power standpoint, the primary difference in the calculations for a square wave or a sine wave subcarrier is in calculating the power distribution. If the total received RF power is P_T then the subcarrier power P_S is given by $P_S = P_T M_{LS}$ and the carrier power P_C is given by $P_C = P_T M_{LC}$ where the terms M_{LS} and M_{LC} are the modulation losses of the subcarrier and carrier, respectively, and are functions of the subcarrier modulation index. For the sine wave subcarrier, $M_{LS} = 2J_1^2$ (m) and $M_{LC} = J_0^2(m)$, where the J_i are Bessel functions of the first kind and m is the subcarrier modulation index. For the square wave subcarrier, $M_{LS} = 8/\pi^2 \sin^2(m)$ and $M_{LC} = \cos^2(m)$. These functions are plotted in figure 2. A cursory look at these plots indicates that, for a given modulation index, the square wave puts more power in the subcarrier and the sine wave puts more power in the carrier. One might speculate that, because SNR requirements ar e generally less severe for carrier tracking than for data demodulation, the square wave should be favored. However, the proposed 1.0-radian square wave subcarrier modulation index should be considered. For this case, M_{LC} is -5.5 db and M_{LS} is -2.4 db. If a sine wave subcarrier is used with a 1.36-radian modulation index (certainly, 1.36 radians is a reasonable value), M_{LS} remains at -2.4 db but M_{LC} becomes -4.7 db. Thus, 0.8 db has been added to the carrier power with no reduction in subcarrier power. It is apparent, then, that the square wave subcarrier cannot be chosen on the basis of power distribution in the link.

Although the sine wave appears to provide slightly better power distribution, the difference is not significant enough to rule out the square wave, which has decided hardware-implementation advantages. Furthermore, from the referenced analysis[3] and several quick-look tests, it has been determined that the spectrum is essentially the same for both the sine wave and the square wave in the subcarrier predetection bandwidth and that use of the square wave does not adversely affect the S-band receiver performance. Therefore, the square wave subcarrier will be implemented.

P&F Subsatellite Communications Performance Summary With the subsatellite communication system thus defined, it is possible to calculate the predicted performance for a typical mission. One method of predicting performance is based on circuit margin calculations. Some minimum performance criteria are Established for each channel in the system. For the subsatellite downlink, a maximum P_e of 10^{-4} is specified for the telemetry channel. This translates to a requirement for a 31.6-db/Hz signal-to-noise density ratio at the receiver output. The channel circuit margin then is defined as the difference between the required ratio and the predicted ratio. For the carrier, a 12-db SNR in the carrier tracking loop bandwidth is required. Thus, the circuit margin is a measure of how near the system comes to meeting the specified requirements.

A summary of circuit margins for the subsatellite uplink is given in table V for operation with ground stations equipped with 30-ft antennas (with cooled parametric amplifiers) and with 85-ft antennas. A summary of the downlink margins is given in table VI. In both tables, minimum-specified or worst-case parameter values were used in making the calculations. As indicated in the tables, uplink performance is expected to be good for both 30- and 85-ft stations. Downlink performance is expected to be good at the 85-ft sites; however, the downlink performance at the 30-ft sites is expected to be marginal.

References

1. S. O. Rice, “Noise in FM Receivers,” Proc. , Symposium on Time Series Analysis, M. Rosenblatt, ed. , John Wiley & Sons, Inc., New York, N. Y., pp. 375-424; 1963.

2. B. H. Batson, “Transmission Characteristics of Split-phase PCM Codes,” NASA MSC Tele/Communications Div. Rept. EE69-2003(U); November 25, 1969.

3. L. A. Lorio, “Communications Study for the Particles and Fields Lunar Subsatellite,” TRW Systems Group Rept. No. 11176-H546-RO-00 (NAS 9-8166), Houston, Tex.; May 21, 1970.

TABLE I - INITIAL SIGNAL-DESIGN PARAMETERS

Subcarrier frequency, f_{sc}, kHz	$^a\Delta f$, kHz	Subcarrier predetection bandwidth, kHz	Maximum modulating frequency	Test receiver carrier demodulation predetection noise bandwidth, MHz
165	165	34.75	5.0 kHz	4.4
225	225	34.75	5.0 kHz	4.4
300	300	63.00	9.0 kHz	4.4
400	350	63.00	9.0 kHz	4.4
576	400	80.00	64 kbps	4.4
768	500	80.00	64 kbps	4.4
1024	600	150.00	51.2 kbps	4.4

[a] Deviation of the carrier by a subcarrier.

TABLE II - FINAL SCIENTIFIC-DATA-SYSTEM SIGNAL DESIGN

Subcarrier frequency, f_{sc}, kHz	Test receiver carrier demodulation predetection noise bandwidth, MHz	$^a\Delta f_1$, kHz	$^b\beta_1$	Subcarrier predetection bandwidth, BW_{in}, kHz	$^c\Delta f_2$, kHz	$^d\beta_2$	Subcarrier postdetection bandwidth, BW_{out}, kHz
165	4.4	260	1.6	34.8	12.4	2.5	5.0
225	4.4	290	1.3	34.8	12.4	2.5	5.0
300	4.4	320	1.1	63.0	22.5	2.5	9.0
400	4.4	350	.9	63.0	22.5	2.5	9.0
576	4.4	400	.7	80.0			
768	4.4	410	.5	80.0			
1024	4.4	550	.5	150			

[a] Δf_1 = deviation of the carrier by a particular subcarrier.

[b] $\beta_1 = (\Delta f_1/f_{sc})$.

[c] Δf_2 = deviation of a subcarrier by the modulating data.

[d] $\beta_2 = (\Delta f_2/BW_{out})$.

TABLE III - CALCULATED REQUIRED PREDETECTION BANDWIDTHS

Subcarrier frequency, f_{sc}, kHz	Required predetection bandwidth,[a] kHz
165	34.75
225	34.75
300	63.00
400	63.00

[a] $BW_{required} = 2(\Delta f + f_{max})$.

TABLE IV - SCIENTIFIC-DATA-SYSTEM CIRCUIT MARGIN SUMMARY

Services	Total-received-power circuit margin, db	
	Minimum specified[a]	Estimated nominal[b]
CSM downlink FM mode 5		
Real-time SDS subcarrier:		
225 kHz	1.0	4.4
400 kHz	.0	3.7
768 kHz	-2.7	-.5
CSM downlink FM mode 6		
Real-time SDS subcarrier:		
225 kHz	1.0	4.4
400 kHz	.0	3.7
768 kHz	-2.7	-.5
Playback SDS subcarrier:		
165 kHz	1.5	4.4
300 kHz	-1.5	3.2
576 kHz	-1.2	1.5
51.2 kbps telemetry (1.024 MHz)	2.5	4.1

[a] Minimum-specified case: The subcarrier frequency deviation for each subcarrier listed was set at -10 percent of the nominal specified value; all other subcarrier frequency deviations were set at 10 percent of nominal

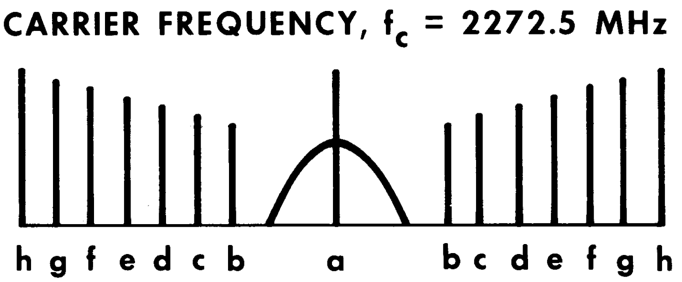
[b] Estimated-nominal case: All subcarriers were set at the nominal specified values.

TABLE V - P & F SUBSATELLITE UPLINK CIRCUIT MARGIN SUMMARY

Mode	Service	Circuit margin, db	
		85-ft station	30-ft station
1	Carrier	33.5	25.0
2	Carrier Command	18.8 17.4	11.4 8.9

TABLE VI - P & F SUBSATELLITE DOWNLINK CIRCUIT MARGIN SUMMARY

Mode	Service	Circuit margin, db	
		85-ft station	30-ft station
1	Carrier	11.8	5.6
2	Carrier Data	4.9 5.5	-1.2 -1.1



a - RECORDED CSM VOICE; FM AT BASEBAND (1:1 PLAYBACK)
b - 165-kHz DATA SUBCARRIER (1:1 PLAYBACK)
c - 225-kHz REAL-TIME DATA SUBCARRIER
d - 300-kHz DATA SUBCARRIER (1:1 PLAYBACK)
e - 400-kHz REAL-TIME DATA SUBCARRIER
f - 576-kHz 1:1 PLAYBACK OF 64-kbps PCM TELEMETRY
g - 768-kHz REAL-TIME 64-kbps PCM TELEMETRY SUBCARRIER
h - 1024-kHz 1:1 PLAYBACK OF 51.2-kbps CSM PCM TELEMETRY

Fig. 1 - S-band spectrum of Scientific-Data-System frequency design.

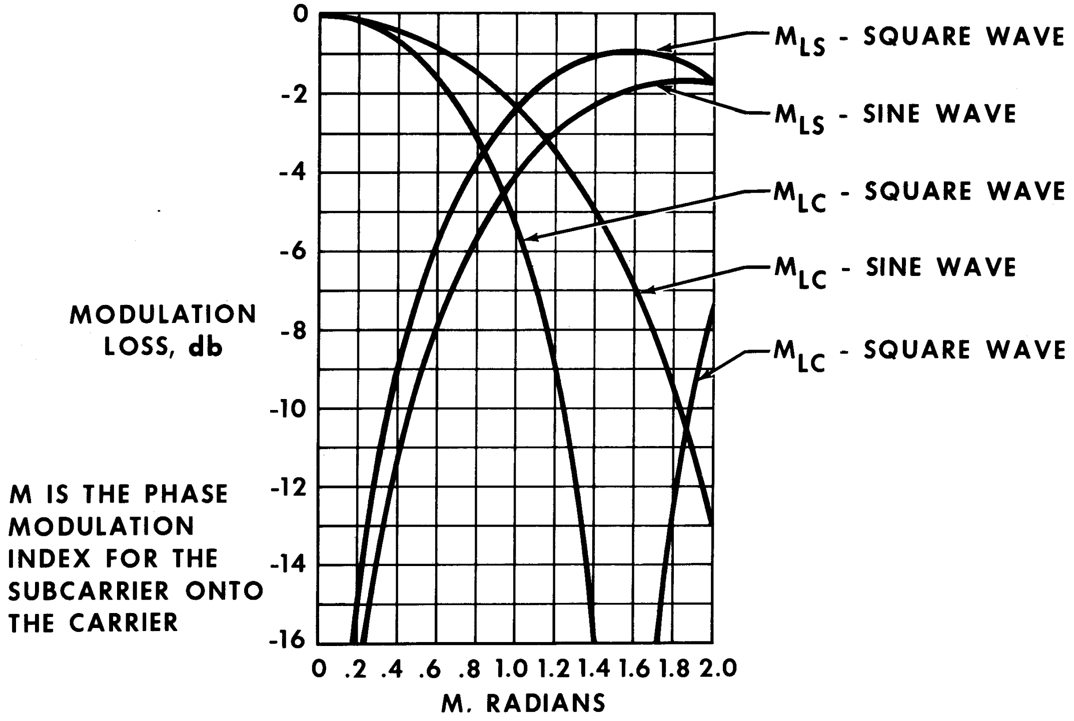


Fig. 2 - Modulation losses for sine wave and square wave subcarriers.