SYSTEM TRANSMISSION PARAMETERS DESIGN FOR THRESHOLD PERFORMANCE

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ABSTRACT

The paper is an extension of two previous works published in the ITC 1974 and 1976 proceedings by the same author. It is the intent of this publication to summarize the two previous papers; to include corrections; to expand the explanations; and to add new material. This information has been accumulated from many system designs based on the described procedures.

It deals with a variety of transmission systems and combinations of multiplexing schemes. A number of tables and constants are provided as standards to be used in telemetry system design thereby reducing calculating time.

System engineers are given a basic step by step procedure and format for the design of any type of transmissions system. Also a computer program is now available to automatically calculate all of the parameters necessary for the system design.

The last presentation of the system design procedure dealt with the information accumulated over several years, and established the parameters from which the design equations for PCM and PAM were updated. Since that time a concentrated effort was initiated to verify the correct bandwidth equation which would be optimum for FM/FM Multi-tone Systems. Again cognizant scientists and engineers were contacted and interviewed. From past history and successes, it was well known that the bandwidth equation known as “Carson’s Rule” provided an adequate bandwidth to guarantee the system accuracies. However, it was also known that systems were in use, operating with smaller bandwidth than specified by Carson’s Rule, and also providing acceptable data accuracies. From the best information available, these systems were designed empirically with painstaking testing effort to insure their accuracy. The investigation lead to another bandwidth equation which appears to be the correct approach for providing the optimum bandwidth for Multi-Tone Systems.

There is no doubt that this is not the first application of this bandwidth equation, but this author could not find any documented information as to its use or validity when applied to multi-tone systems. This presentation has designated the new bandwidth equation as the "Multi-Tone Bandwith Equation" or "M/T B_c". The actual equation and its verification are provided later in this presentation.

A second corrective update was made in the design of the PAM/FM/FM Channel where the subcarrier design equations are established based on the same parameters as PCM. Since PCM and PAM are both pulse modulation, their design theories are similar for a subcarrier channel. In the final PAM/FM/FM analysis, a lower frequency SCO will be used as compared to that which was previously specified.

Again, the validity and verification of this update in the procedure is described later.

Finally, a third and significant addition to this presentation has been provided by Mr. Matthew Egler, of Microcom Corporation, who has written four (4) computer programs based on this procedure. Not only does this program provide the system design effort, but also provides a program for the mixing networks required for systems with PCM or PAM baseband, modulation together with a higher frequency SCO Multiplex system on the same baseband PCM/PAM/FM + FM/FM. Without this network, the baseband pulse adulation is rendered useless when coupled with an SCO Multiplex system.

A third program available on the same floppy disc, is the computation of the SCO Voltages and mixer amplifier gain necessary for modulating a transmitter with a specified modulation sensitivity in accordance with the channel deviations as computed by the System Design program.

The final program is the margin calculation based on the equations and procedure specified in Attachment E of this presentation.

Hopefully this presentation will represent the final procedures and equations. However, if any new information is accumulated based on analysis, experimentation, or field use, which has an impact on the result of this paper, a further update will be submitted to keep the methods described herein current and state-of-the-art. It is the author's contention that the capability to accurate system design lies in the use of the noise equations, and the procedures developed around those equations.

INTRODUCTION

Analytical and mathematical methods have been employed in developing a straightforward technique applicable to telemetry system design. The procedure is presented in a manner which allows the designer to identify the crucial and important parameters and calculate from closed form equations the values which are optimum for his system. Although a system may be demonstrated empirically to operate properly under laboratory conditions, a more quantitative approach is required to insure proper operation at receiver threshold conditions.

System performance at receiver threshold, signal to noise ratios at the receiver output or discriminator output, and operation under environmental conditions, are primary considerations in the design effort. The following factors are some of the fundamentals which characterize the system for threshold performance. From laboratory test results, the realistic value of $(S/N)_{in}$ or $(S/N)_c$ equal to 12db has been accepted as the accurate value. The subcarrier discriminator output signal to noise $(S/N)_d$ is 40db which allows a 1% noise contribution. $(S/N)_d$ can be selected at any desired level based on the system requirements. The accepted S/N levels are 37db or 31db for PAM decoders and 15db for PCM bit synchronizers to attain the desired accuracy. The S/N levels for PAM channels are based on the results of laboratory tests performed on the Heberling decommutator and verified by decommutator manufacturers. Many technical articles and experiments have established the S/N level for PCM systems.

With these basic design criteria established, the design objectives can be listed.

OBJECTIVES -

1) For FM/FM Multi-Tone Systems, calculate the optimum receiver bandwidth pre-emphasis characteristics and total deviation where all channels fade simultaneously at receiver threshold.
2) For PAM or PCM systems, calculate the receiver bandwidth, the total deviation, and pre-modulation filter cutoff frequency, for optimum performance at receiver threshold.
3) For any system, calculate the minimum receiver IF bandwidth which supports the modulation without contributing to distortion.
4) For any system, calculate the minimum RF power requirement which provides successful system performance.
5) Specify voltage controlled oscillator performance specifications.
6) Determine special discriminator specifications such as center frequency, bandpass and low pass filter characteristics, peak deviation requirements, and output voltage characteristics.

7) For PAM or PCM, decide on baseband or SCO channel modulation, and make the selection of SCO channel if chosen.

It should be stated that the contents of this paper and two previous papers which appeared in the 1974 and 1976 ITC proceedings are extensions of the basic noise equations as presented by Ken Uglow in 1957 and published by the I.E.E.E. Major contributions were made by Gene Law of Point Mugu in the performance of laboratory tests and suggestions, which influences the information contained in this presentation. The Glossary defines all of the terms.

GLOSSARY -

A = The sum of the ratios of the SCO channels modulation a transmitter, where the deviation of each SCO is normalized with respect to the deviation of the highest frequency SCO modulating an RF carrier.

A' = Square root of the sum of the squares of the normalized SCO peak deviation values

$$A' = \sqrt{A_1^2 + A_2^2 \ldots A_n^2}$$

B = $\frac{B_{c(cal)}}{B_{c(sel)}}$ multiplier factor

B_c = Receiver IF Bandwidth

B_{out} = Receiver Output Narrow Band Filter (3db Frequency Points), Subcarrier Discriminator Input BPF (3db Frequency Points)

$B_{c(cal)}$ = Receiver IF Bandwidth Calculated from Design Procedures.

$B_{c(sel)}$ = Receiver IF Bandwidth Selected from IRIG Standards.

C_1 = Constant, $(S/N)_{out}/(S/N)_{in}$ related to Equations 2 and 3.

C_2 = Constant, $\frac{S/N_d}{(S/N)_c\ (3/4)^{1/2}}$ as related to Equation 4.

C_{kt} = Channel Check Numbers to Insure Threshold Performance.

D = Pulse Duration in Seconds, Milliseconds, or Microseconds.

F_B = PCM System Bit Rate

F_{cr} = PAM Commutator Clock Rate

F_L = Lower Modulation Frequency (General Case)

F_m = Narrow Band Modulation Frequency (Center Frequency, Bandpass Filter Case)

F_r = Rise Time Factor $\frac{N_r}{2\pi}$ related to Frequency in kHz.

F_U = Upper Modulation Frequency

F_{ud} = Maximum data frequency response of any SCO channel. (SCD output low pass filter -3db frequency for simple modulation channels).

f_D = Carrier Peak Deviation Produced By Baseband Modulation (for PAM or PCM Baseband Modulation).

f_D' = Relative Modulation Amplitude of Baseband Modulation Signal.

f_{Df} = Final Transmitter Deviation for Baseband Modulation Resulting from $B_{c(sel)}$.

f_{dc} = RF Carrier Peak Deviation for an SCO Channel.

f_{dc}' = Relative Modulation Amplitude of an SCO Channel.

f_{dcf} = Final SCO Channel Transmitter Deviation Resulting From $B_{c(sel)}$

$f_{dc(min.)}$ = Required minimum SCO channel deviation to limit or lock subcarrier discriminator $f_{dc(min.)}$ = 5kHz.

f_{dcu} = Highest SCO Channel Transmitter Deviation.

f_{ds} = SCO Peak Deviation Due to Data Modulation.

f_s = SCO Center Frequency

f_{su} = Highest Frequency Channel in an SCO Multiplexer.

f_U = PCM or PAM Pre-Modulation Filter 3db Frequency for Baseband Modulation.

f_U' = PAM Pre-Modulation Filter 3db Frequency for PAM Multiplex Systems using (S/H) Deconmutator.

f_u = PCM or PAM Pre-Modulation Filter 3db Frequency for SCO Channel.

f_{VU} = Receiver Output LPF 3db Frequency for PAM or PCM Baseband Multiplex Systems.

f_{VU}' = Receiver Output LPF 3db Frequency for PAM Baseband Multiplex Systems Using (S/H) Decommutator.

Δf = Peak Deviation of RF Carrier by a single SCO Channel

$\Delta f'$ = Total Peak Deviation of an RF Carrier by all of the SCO channels as calculated by the square root of the sum of the squares of the individual SCO peak deviations.

K = $\frac{f_{ds}}{f_s}$ = Percentage Modulation of an SCO.

M = Modulation Index as Related to Transmitter Modulation.

N = Modulation Index As Related to SCO Modulations.

N_r = Number of Rise Times Related to Leading Edge of a Pulse and Ultimate Amplitude.

SCD = Subcarrier Discriminator

SCO = Subcarrier Oscillator

$(S/N)_c$ = Receiver Carrier to Noise Ratio, Expressed as a Voltage Ratio Related to the FM Multiplex System Equation 4.

$(S/N)_d$ = Data or Discriminator Output RMS Signal to Noise Ratio Expressed as a Voltage Ratio Related to the FM Multiplex System Equation 4.

$(S/N)_{in}$ = Receiver Carrier to Noise Ratio Expressed as a Voltage Ratio Related to the Baseband Modulation Equation 3.

$(S/N)_{out}$ = Receiver Data Output Noise Ratio Expressed as a Voltage Ratio Related to Baseband Modulation Equation 3.

T_r = Pulse Duration Related to Rise Time.

Four channel noise equations are listed from which the systems design procedures are developed. Equation 1 is the general noise equation and the subsequent three equations are special cases of the general case.

GENERAL CASE:

$$(S/N)_{out} = (S/N)_{in} \left[\frac{3B_c \cdot f_D}{2(F_U^3 - F_L^3)} \right]^{1/2} \qquad \text{EQ. (1)}$$

NARROW BAND CASE:

Primarily associated with a narrow band filter when used at the receiver output. In FM/FM Multiplex systems, the RF receiver and BPF of the SCD are the typical examples of this case and is one of the equations used in the development of the noise equation for any FM/FM channel.

$$(S/N)_{out} = (S/N)_{in} \left[\frac{B_c}{2B_{out}} \right]^{1/2} \cdot \frac{f_D}{F_m} \qquad \text{EQ. (2)}$$

LOW PASS FILTER CASE:

The equation for calculating PCM or PAM baseband modulation parameters, and also for calculating the subcarrier frequency discriminator parameters, the SCD is a second receiver in the FM/FM channel.

$$(S/N)_{out} = (S/N)_{in} \left[\frac{3B_c}{2F_U} \right]^{1/2} \cdot \frac{f_D}{F_U} \qquad \text{EQ. (3)}$$

FM/FM CHANNEL CASE:

The combination of EQ. (2) and EQ. (3), where the RF receiver and subcarrier discriminator BPF represent the narrow band case EQ. (2) and the subcarrier frequency discriminator fits the low pass filter case EQ. (3).

$$(S/N)_d = (S/N)_c \; (3/4)^{1/2} \left[\frac{B_c}{F_{ud}}\right]^{1/2} \cdot \frac{f_{dc}}{f_s} \cdot \frac{f_{ds}}{F_{ud}} \qquad \text{EQ. (4)}$$

These equations form the basis for developing the procedures and equations for optimum system design. The bandwidth terms (B_c), and the bandwidth equattion $B_c = 2\ (\Delta f + F_U)$ were given considerable discussion in the previous papers, and will be further updated in this presentation. Reviewing the four channel noise equations establishes the receiver IF bandwidth (B_c) and the deviation (f_D or f_{dc}) as the two unknowns to be calculated for their optimum values. Solving the bandwidth equation and any one of the noise equations simultaneously will result in optimum values for both terms.

BANDWIDTH AND MODULATION CONSIDERATIONS

Three bandwidth equations are applicable for transmission systems. These bandwidth equations will be described in terms of their significance to this presentation. The full bandwidth equation, well known as Carson's Rule, has been expounded in textbooks and technical papers and used in FM design practice for many years.

$$B_c = 2\ (\Delta f + F_U) \qquad \text{EQ. (5)}$$

Although this equation is not rigorously derived herein, in my 1976 paper it was compared to the power relations of the Bessel Power Sideband Function Tables, Attachment D, for modulation indices greater than one, and found to be accurate for single sinewave modulation signals. The equation's accuracy is a function of the bandwidth required to pass all power sidebands which are greater than 1% in amplitude. The single sinewave modulation bandwidth equations applies to PAM/FM systems, for reasons which are discussed later in this presentation. It is not correct for determining minimum bandwidth required for multi-tone systems.

It now becomes necessary to define the correct bandwidth equation which applies to multi-tone systems. After extensive discussions with many system engineers who had dealt with this problem, it was decided that the deviation term Δf of the bandwidth equation $B_c = 2(\Delta f + f_{su})$ should be calculated based on the square root of the sum of the squares of the individual channel peak deviations and is now designated delta f prime

$(\Delta f' = \sqrt{\Delta f_1^2 + \Delta f_2^2 \ldots \Delta f_n^2})$ where Δf sub one thru n are the peak deviations of the individual subcarrier channels). Then, the new bandwidth equations which is referred to as the multi-tone bandwidth rule M/T B_c will equal.

$$M/T\ B_c = 2(\Delta f' + f_{su})$$

To verify the validity of this new bandwidth equation, the problem was again submitted to Gene law of Point Mugu who set up various models to provide information and spectrum analyzer displays of the multi-tone systems. The amplitude of the sidebands were then measured and it was verified that for a multi-tone system, all of the sideband energy beyond the bandwidth as calculated by M/T $B_c = 2(\Delta f' + f_{su})$ was less than 1% of the total sideband energy. Based on these results, it was generally agreed that this new bandwidth equation will provide the optimum IF bandwidth for multi-tone system.

As a further note, the new bandwidth equation will satisfy Carson's Rule for a single tone modulation system where the deviation for a single tone is;

$$\Delta f' = \sqrt{\Delta f_1^2} = \Delta f_1$$

Then, for the purposes of this presentation, the multi-tone bandwidth rule will replace Carson's Rule in the calculations of bandwidth for multiplex systems. This includes FM/FM, PAM/PCM/FM/FM, and system containing PAM or PCM on baseband with SCO channels located above baseband modulation; PCM/PAM/FM + FM/FM

A second bandwidth equation applies to the FM subcarrier channels for modulation indices greater than one. An explanation for the validity using this equation is covered later under the title "Simple Modulation".

$$B_c = 2\Delta f = 2f_{ds} \qquad \text{EQ. (6)}$$

The third bandwidth equation is applicable for modulation indices of less than one, covering PCM modulating a transmitter on baseband or PCM/PAM modulating an SCO.

$$B_c = 2F_U \qquad \text{EQ. (7)}$$

The rules for selecting the appropriate bandwidth equation is based on the type of modulation signal, the frequency response requirements, and the modulation index. Modulation is classified into three types - simple, multi-tone and pulse.

SIMPLE MODULATION:

Simple Modulation is defined as a data signal which contains a fundamental frequency and its harmonics, or a variable frequency with a finite bandpass requirement. DC signals, thermocouple outputs and sine wave signals are common types of simple modulation signals.

Standard instrumentation transducers such as Piezo Electric, RTC, and Gilmore pick ups are examples of more sophisticated devices which develop simple modulation signals. It applies mainly to the subcarrier channel.

All subcarrier discriminators employ an input bandpass filter (B_{out}) where the bandwidth is based on the simple modulation case, ($B_c = 2\Delta f$). The following explanation justifies its use for subcarrier channel calculations.

At any modulation index greater than one, the Bessel function Tables indicates that limiting the bandwidth to $2\Delta f$, all sideband energy beyond the modulation peak deviation is eliminated. Further analysis shows that the energy of the sidebands extending beyond the peak deviation is equal to approximately 3% of the total spectral energy.

Subcarrier discriminators contain Bessel type input bandpass filters with a 3db bandwidth equal to $2\Delta f$. With simple type modulation applied to a SCO channel, the 3% sideband spectral energy eliminated by the subcarrier discriminator bandpass filter has the effect of a slight change in modulation index without adding distortion. The amount of degradation in frequency response as a result of the small decrease in sideband energy is equivalent to a .25db change in frequency response (dB = 20 log .97). Therefore, the subcarrier discriminator bandpass filter with bandwidth equal to $2\Delta f$ provides sufficient accuracy for any SCO channel. It is not adequate for multi-tone systems where suedo sidebands are generated and must be provided for to avoid crosstalk.

MULTI-TONE MODULATION:

A composite FM/FM mixed signal is the prime example of multi-tone modulation. In multi-tone modulation, the modulation index cannot be expressed in terms of the highest modulation signal, but must be calculated by the square root of the sum of the squares of each SCO modulating the transmitter. Also, the transmitter deviation increases in amplitude with increasing frequency SCO's to satisfy the (S/N) requirements. In many FM/FM multi-tone systems, the transmitter modulation frequency is greater than the total system deviation ($\Delta f'$). For these reasons the bandwidth equation, with terms reflecting the multi-tone system, is required. Experimental multi-tone system models have verified the following bandwidth equation where the total system deviation (Δf ') is equal to the square root of the sum of the individual channel peak deviations.

$$M/T\ B_c = 2(\Delta f' + f_{su}) \qquad \text{EQ. (5)}$$

PULSE MODULATION:

PAM or PCM channels are examples the of pulse modulation. The frequency distribution of these pulses are described by the sine x/x equation. A study of this equation indicates the presence or absence of harmonics based on the pulse width and the period. A symmetrical square wave has no even harmonics. The period to pulse duration, of a square wave indicates the harmonics which are not present. As the ratio increases, the wave form will have less and, less harmonics missing and will approach a steady state condition. The bandwidth required for this type of modulation must consider a long pulse duration condition to avoid “thresholding”.

The term “thresholding” relates to the modulation signal becoming noisy when deviating the carrier to the IF bandedge for long periods. Since the bandedges of a bandpass filter are 3db down from center frequency, the modulation signal becomes noisy at receiver threshold under band limited conditions. Threshold is directly related to modulation index and is the reason for the different bandwidth equations used in PAM and PCM channels. To avoid thresholding the channel peak deviation is never greater than 80% of the peak channel bandwidth.

An analysis of PCM modulation (NRZ) results in a modulation index of less than one, therefore the bandwidth equation which applies is:

$$B_c = 2F_U \qquad \text{EQ. (7)}$$

For PAM FM/FM, the subcarrier channel will be designed for the same modulation index as described for PCM baseband modulation. This design approach will result in an increase of transmitter deviation required by the subcarrier oscillator modulating the transmitter to provide 37db $(S/N)_d$ at the output of the SCD. Although there will be an increase in transmitter deviation, the subcarrier channel bandwidth will be minimized due to operating at a modulation index of less than one ($N < 1$). This smaller SCO bandwidth will allow the selection of a lower frequency SCO channel whose bandwidth will be:

$$B_{out} = 2F_{ud}$$

Again, the channel deviation will be as stated before since the PAM Decommutator input circuitry is equivalent to a low pass filter, whose cut-off frequency is equal to the PAM clock rate, the PAM FM/FM channel bandwidth equation normalized to the clock rate where $F_{ud} = F_{cr}$ and

$$B_{out} = 2F_{cr}$$

In systems using PAM on baseband, the modulation index will always be greater than one and therefore, the full bandwidth equation applies using terms related to PAM:

$$B_c = 2(f_D + F_{cr}) \qquad \text{EQ. (5)}$$

SUMMARIZING THE DISCUSSIONS ON BANDWIDTH AND MODULATION, THE RULES FOR SELECTING THE APPROPRIATE BANDWIDTH EQUATION ARE AS FOLLOWS:

1) For simple modulation, with modulation indices greater than one, the bandwidth equation $B_c = 2\Delta f$ applies. Simple modulation applies to sinewave signal, or transducer signals normally associated with a telemetry subcarrier data channel.
2) For multi-tone modulation, the full bandwidth equation ($B_c = 2(\Delta f' + f_{su}$) is required, where

$$\Delta f' = \sqrt{\Delta f_1^{\,2} + \Delta f_2^{\,2} \ldots \Delta f_n^{\,2}}$$

3) For PCM (NRZ) or PAM/FM/FM where the modulation index is less than one, the bandwidth equation is $B_c = F_B$ or $B_{out} = 2F_{cr}$
4) For PAM (NRZ) transmitter baseband modulation the modulation index is greater than one and the bandwidth equation $B_c = 2(f_D + F_{cr})$ applies.

TYPES OF TELEMETRY MODULATION AND APPROPRIATE DESIGN EQUATIONS:

A review of the discussions on bandwidth, modulation, and the noise equations reveal that only two unknown parameters exist for determining optimum performance. The two unknowns are the channel deviation (f_{dc} or f_D) and the receiver IF bandwidth (B_c). Optimum performance is defined as maintaining the desired data accuracy at receiver threshold, with the minimum IF bandwidth.

Referencing the two previous papers published in the ITC proceedings, updated procedures for solving the noise and bandwidth equations for a variety of telemetry systems are developed in this presentation. An elaboration of the important factors and terms in the solution is provided along with new material from more current system configurations. The new procedures will provide the required information to design any type of telemetry system for optimm performance and specify the related significant parameters. To avoid confusion, PAM and PCM will be discussed in terms of an NRZ format. The system design charts will address the design equations for NRZ format with reference to the terms required for determining the BIØ format equations.

PCM MODULATION:

Pulse Code Modulation will modulate a transmitter on baseband or modulate a subcarrier channel, depending on bit rates and system requirements. In the latter case, the SCO is treated as the transmitter and the low frequency subcarrier discriminator is considered the receiver. For any type of system using PCM modulation, the noise equation which applies is the Low Pass Filter Case (EQ3), and the bandwidth equation will be $B_c = 2F_U$. From an analysis of the input characteristics of a PCM bit synchronizer, the input is equivalent to a LPF, having a corner frequency at half the bit rate ($F_B/2$). Then from the noise equation parameters $F_U = F_B/2$ and the bandwidth equation reduces to$B_c = F_B$.

Before developing the PCM design equations, it is necessary to discuss the use and impact of premodulation filters with respect to channel accuracy, and bandwidth requirements. Also the number of poles the premodulation filter will require is dependent on the system design. laboratory experiments have clearly shown a degradation in Bit error accuracy with the use of premodulation filters. The bit error degradation occurs only at receiver threshold and is caused by the reduction in energy in the pulse resulting from the premodulation filters. Premodulation filters do have a useful function in the elimination of the sharp leading edge of the PCM pulse. They limit the transmission of the higher frequency components, thus eliminating the possibility of ringing in the system due to non-linear phase type of filter circuits. However, a non filtered PCM signal will result in the best bit error accuracy, provided the receiver IF is a linear phase type with the correct bandwidth. The receiver IF bandwidth required is independent of the pre-modulation filter cut-off frequency because it is determined from the bit synchronizer input frequency response characteristics (F_U). Since any pre-modulation filtering or receiver output video filtering will contribute to the PCM bit error accuracy, filter design compromises are presented in this paper to minimize their effects. From this discussion, it becomes apparent that as little pre-modulation filtering as possible is desired. For PCM/FM systems where PCM modulates a transmitter baseband or the PCM is applied to an SCO input, the recommendation is to use a single pole RC filter with a 3db point at one times the bit rate. This approach will provide moderate filtering to eliminate the sharp leading edges of the pulse yet have the least effect on reducing the pulse energy. Where PCM is multiplexed with SCO's and modulates a transmitter on baseband the use of 6 pole filters are necessary to minimize the channel separation between the PCM, and the SCO channels. From the normalized bessel function filters graph contained in the Appendix of this paper, the effects of various combinations of premodulation and output filters selection can be calculated

Based on the discussions and laboratory experimentation, the following system design considerations for pre-modulation filters are suggested for PCM NRZ formats.

1) PCM Modulating An SCO: PCM FM/FM

The pre-modulation and discriminator output low pass filter corner frequencies should be designed for one times the bit rate (f_u & $f_{ud} = F_B$). A single pole RC pre-modulation filter and a 4 or 6 pole bessel discrimination output low pass filter will minimize the bit error degradation of the system. It will also result in the correct discriminator output low pass filter for adequate subcarrier frequency filtering.

2) Multiplex Systems with PCM and SCO's Modulating a Transmitter on Baseband: PCM/FM + FM/FM

The pre-modulation cutoff frequency will be of utmost importance since it will ultimately decide the frequencies of the SCO Channels. The following criteria is recomended for selecting the cutoff frequencies of the pre-modulation and receiver output filters associated with the channel. Both filters shall be at least 6 pole bessel types low pass filter set at $.7F_B$. The combined filter characteristics is the best compromise to minimize the bit error and provide the optimum selection of system components.

3) PCM Modulating the Transmitter on Baseband:

The system is similar to the PCM subcarrier channel except there are no restrictions on the receiver video filter, as compared to the subcarrier discriminator case. The premodulation filter and the receiver output video cut-off frequencies are selected to limit the bit errors. The recommendations for the pre-modulation filter cut-off point is $f_U = F_B$ and the receiver video output filter is adjusted for $f_{VU} = 2F_B$.

This information pertaining to the selection of the pre-modulation filter and all other filters will be summarized in the system design charts.

From the previous discussions, PCM is pulse type modulation at a modulation index of less than one. The low pass filter case of the noise equations applies with a bandwidth equation $B_c = F_B$.

LOW PASS FILTER CASE - Equations related to PCM NRZ baseband moduation including the SCO channels.

$$(S/N)_{out} = (S/N)_{in} \left[\frac{3B_c}{2F_U}\right]^{1/2} \cdot \frac{f_D}{F_U} \qquad \text{EQ. (3)}$$

The following are the known parameters.

$F_U = ½F_B$

$(S/N)_{out}$ = 15db (5.62 volt ratio)

$(S/N)_{in}$ = 12db (3.98 volt ratio)

$$C_1 = \frac{(S/N)_{out}}{(S/N)_{in}}$$

Pre-Modulation and Receiver Video Filters

$f_U = F_B$ (Single Pole RC)

$f_{VU} = 2F_B$ (Receiver Output Video Filter)

Pre-Modulation and Receiver Output Filter for PCM Multiplexed with SCO's on Baseband:

$f_U = .7F_B$ (6 Pole Bessel Type)

$f_{VU} = .7F_B$ (6 Pole Bessel 'Iype)

Pre-Modulation and Discriminator Output Low Pass Filter for SCO Channel:

$f_u = F_B$ (Single Pole RC)

$f_{ud} = F_B$ (4 or 6 Pole Bessel Type)

Receiver or SCD Bandwidth Equation

B_c or $B_{out} = F_B = 2F_U$ EQ (3A)

$$F_D = (2/3)^{1/2} C_1 \frac{(F_U)^{3/2}}{(B_c)^{1/2}} \qquad \text{EQ. (3B)}$$

Substituting EQ. 3A into EQ. 3B and solve for modulation index where $M = f_D/F_U$

$$M^2 = \frac{C_1^{\,3}}{3} \qquad \text{EQ. (3C)}$$

Substitute appropriate S/N ratios into EQ. 3C and determine the modulation index of the PCM Channel for baseband modulation or modulating an SCO.

$$C_1 = \frac{5.62}{3.98} = 1.41$$

$$M^2 \text{ or } N^2 = \frac{(1.41)^2}{3}$$

$$M \text{ or } N = .82$$

The peak deviation f_D or f_{dc} is computed from the modulation index equation where:

$$M = \frac{f_D}{F_U} \quad \text{or } N = \frac{f_{ds}}{F_{ud}} \quad \text{where } F_U \text{ or } F_{ud} = \tfrac{1}{2}F_B$$

$$f_D \text{ or } f_{ds} = .82 \; \frac{F_B}{2} = .41F_B \qquad \text{EQ. (3D)}$$

Note: The deviation parameter as developed from the noise equations can be compared to deviation of $.35F_B$ developed by other methods. Both deviations provide similar results, and only in the most severe bandwidth limited cases did the deviation equation $f_D = .35F_B$ show any advantage.

The relative deviation amplitude equation of a PCM modulation channel is:

$$f_D' = (2/3)^{1/2} C_1 \left[\frac{F_B}{2}\right]^{3/2} \qquad \text{EQ. (3E)}$$

This relative amplitude equation is used when solving for the parameters of a multiplex system containing more than one modulation disciplines.

Since the modulation index equation of the PCM channel is less than one, the same noise and bandwidth equations apply to the design and selection of an SCO Channel modulated by a PCM signal, therefore, the same equations previously developed apply except for some difference parameter designations. (B_c becomes B_{out} and M is designated N). Both the PCM baseband modulation and the SCO PCM modu ation type channels will be addressed in the system design chart.

Another consideration is the affects of IFM on PCM baseband modulation. One of the principle advantages of PCM modulation is the small transmitter deviation required to maintain the bit error accuracy. However, sufficient transmitter deviation is also required to overcome any system IFM resulting from the mechanical environments such as vibration and shock. The final system deviation from a PCM channel modulating a transmitter on baseband should be adjusted (if necessary) to minimize the effects of the IFM. IFM occurs when the transmitter components are disturbed due to shock or vibration causing a modulation signal unrelated to the PCM modulation signal. The analysis for developing the levels of IFM affecting PCM are beyond the scope of this paper. However, based on reported results from experiments and users, the following suggestion is provided. A safe level for PCM baseband modulation, with IFM interference from vibration or shock shall be as follows:

> The ratio of the PCM deviation, to the transmitter IFM specification under shock and vibration will be 4 to 1.

In designing a PCM/FM/FM Channels, the above discussion does not apply, since an SCO is virtually IFM free. The System Design Chart will cover the suggested ratio of PCM deviation to IFM interference in the appropriate part of the procedure.

PAM MODULATION:

The same noise equations and procedures apply to PAM as were developed for PCM. The following information describes the bandwidth equation, pre-modulation filter and the channel parameters, as related to PAM modulation. Also discussed will be the different results in the pre-modulation filter parameter values for the two types of PAM decommutators which are presently in use (INT) Integration Type and (S/H) Sample and Hold Type. In some system designs the S/H Decornmutator will be specified because of its characteristics which can result in closer channel separation for PAM Baseband multiplex systems.

The characteristics of the PAM Decommutator will determine the values of F_U and $(S/N)_{out}$. From experiments at Point Mugu, the input characteristic of the Heberling

Decommutator is equivalent to a LPF with a frequency cutoff at one times the PAM Commutator clock rate. All other PAM Decommutators exhibit the same input characteristics. Also, from experimentation on the Heberling PAM Decommutator, the signal level at the receiver output $(S/N)_{out}$ should be designated at 37db. An additional 3db is contributed by the output data channel filter with a 3db point at twice the data rate. Then a total of 40db at the PAM Decommutator Data Channel output, results in a 1% noise contribution to the overall channel data error analysis. If a 2% noise system is acceptable, the $(S/N)_{out}$ reduces from 37db to 31db. This same analysis applies for the S/H type Decommutators. The advantage of a lesser accuracy system is the reduction in required system bandwidth. Since the Decommutator input characteristics dictate the frequency of the F_U parameters in the noise equation, the pre-modulation and receiver output LPF are religated to limiting the transmission response and the receiver output noise. Again, it is stated that pre-modulation and receiver output filters will contribute some error to the system accuracy. The pre-modulation filter does become significant in the design of baseband multiplex system to insure closer channel separation, and will require 6 Pole Bessel Type filters. For single channels PAM baseband systems, the single pole RC pre-modulation filters are sufficient.

The procedure for determining the various pre-modulation and receiver output filter cutoff points (f_U and f_{VU}) can be described by the following discussion.

From the wave forms of the NRZ PAM Pulse (Figures 1A and 1B) the rise time and frequency response of the pre-modulation and receiver output LPF can be analyzed for the Integration Type (INT) and Sample and Hold Type (S/H) Decommutators.

An integration type PAM Decommutator, Figure 1A, samples the signal during the middle 50% of the channel pulse. The sample window is integrated and the channel output is a function of the amplitude of the integrated sampling window. A pre-modulation filter conditioning the pulse as shown in Figure 1A, will limit the frequency response and will have minor effects on the system accuracy, because nothing occurs in time until the beginning of the sampling window. It is important that the ultimate amplitude is reached in sufficient time, to avoid errors in the sample window.

From Figures 1A and 1B, it is obvious that any encroachment into the sampling areas will have less effect on the integration type decommutator due to its much larger sampling window, than would be experienced in the S/H type decommutator.

For this reason, when designing the filters for a PAM system using an integration type decommutator, both the premodulation and receiver output LPF 3db frequency points will be based on the pulse rise time eualling one fourth thepulse duration. ($T_r = D/4$) (Figure 4).

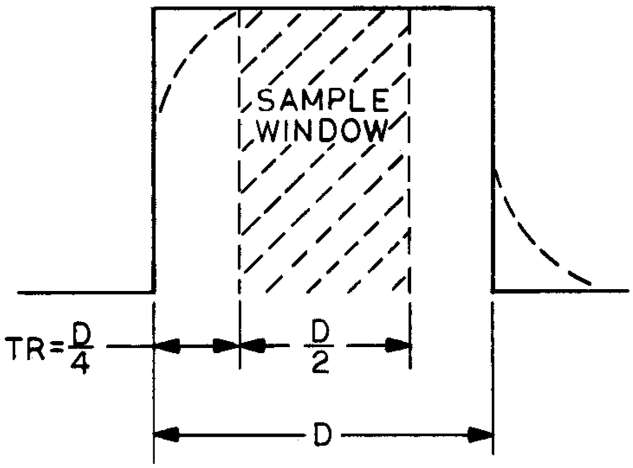


Figure 1A
<u>Integration Type Decom</u>
(INT)

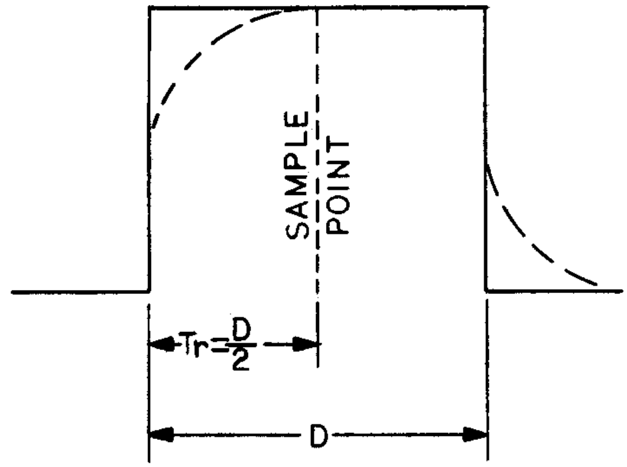


Figure 1B
<u>Sample & Hold Type Decom</u>
(S/H)

In analyzing the effects of filtering as related to the S/H type decommutators, the cascading of the pre-modulation and receiver output low pass filters will affect the ultimate amplitude of the pulse to a much greater extent. For this reason, the frequency cutoff points of the pre-modulation and receiver output low pass filters are extended so that the combined attenuator of the filters at the sampling point will be a maximum of 3db down. The sample and hold type decommutator (Figure 1B) samples a narrow pulse at ½D. Experiments were performed on the sample and hold type (EMR 515) decommutator to determine the performance characteristics. Using a linear phase 6 pole Bessel filter, it was shown that a PAM signal conditioner at ½D, while operating at receiver threshold $(S/N)_{in}$ = l2db, resulted in no crosstalk between channels and a 40db signal to noise ratio at the output of the PAM data channels. A rise time of less than ½D did not improve performance, and a rise time beyond the ½D point resulted in crosstalk. As the system $(S/N)_{in}$ dropped below threshold the PAM data channel noise increased until the PAM decommutator lost lock.

These discussions on PAM signal conditioning will result in separate equations for determining the system filter cutoff points of the Integration Type Decommutator as compared to the S/H type decommutator.

The rise times and corresponding frequency responses are calculated in the following manner for a single pole RC pre-modulation filter. The number of rise times related to any point on the rise time curve is given by:

$$N_r = -\ln(1-p) \qquad \text{EQ. (8)}$$

N_r = Number of Rise Times

p = The Proportion of the Ultimate Level Desired

$\ln$ = Natural Log Operator

The number of rise times is related to frequency response in terms of radians. Dividing the number of rise times, N_r by 2π radians, converts N_r to a frequency response term (F_r) related to the pulse rise time. By dividing the rise time factor F_r by T_r , the point where the sampling window begins is designated in terms of frequency. The following table is based on EQ. (8) to show the number of rise times and the factor (F_r) for determining the frequency response necessary to satisfy various ultimate amplitudes of a single pole RC filter.

Table 1

RISE TIME FACTORS F_r

p (% of Ultimate Amplitude)	N = (# of Rise Times)	$F_r = \frac{N_r}{2\pi}$
99.8%	6.28	1.000
99%	4.60	.733
98%	3.91	.623

In many telemetry systems, four or six pole Bessel type pre-modulation filters are specified for their response and attenuation characteristics. The mathematical derivation of the equations for 4 or 6 pole filters, Attachments B1 and B2, to determine the number of rise times N_r for different ultimate amplitudes is beyond the scope of this paper. However, from experimental results the factors, F_r determined for a single pole RC filter, with respect to 98 to 99.8% amplitudes are sufficiently accurate when applied to both the 4 and 6 pole Bessel filters.

Careful consideration is necessary in selecting the rise time factor F_r for PAM modulation. This selection affects the amount of error introduced into the channeirby the pre-modulation filter. It is obvious from Figure 1 that any infringement into the sample window results in error. For the purposes of this paper, and the development of procedure which follows, the best compromise in terms of the rise time factor, F_r is 98% or .623.

Thus, the selection of the rise time factor F_r and pre-modulation filter response must be made by the system engineer with a view toward minimizing the effects on data accuracy. Understanding the characteristics of the modulation signal, the system parameters, and having the equations required to make the appropriate selections and calculations will result in the optimum system design. The frequency response for the different types of decommutators is computed by the equations:

Integration Type Decommutators	Sample and Hold Type Decommutators
$f_U = \frac{F_r}{\frac{1}{4}D} = 2.5F_{cr}$	$f_U = \frac{F_r}{\frac{1}{2}D} = 1.25F_{cr}$

f_U = 3db Frequency Response Point

F_r = Rise Time Factor = .623 for 98% Ultimate Amplitude

D = Pulse Duration = $1/F_{cr}$

For S/H type decommutators, the 3db points of the pre-modulation and receiver output low pass filters are extended based on the following discussions. If both the pre-modulation and receiver output LPF are designed for the cut-off point f_U as previously specified, then the combination of both filters would result in the response curve being down 6db instead of 3db at the point of interest. To avoid this problem, a suitable compromise is to extend the cutoff frequency so that each filter is 1.5db down at f_U instead of 3db down. Bessel type filters are used for pulse type modulation to avoid ringing. Referring to the 4 and 6 pole normalized curves, Attachments B1 and B2, the attenuation is 1.5db down at .7 times the 3db cutoff point. To extend the cutoff frequency of the filters, the calculated value of f_U must be divided by 0.7. The new value (f_U ') for pre-modulation and receiver output low pass filters 3db points, where using a S/H type decommutator will be:

$$f_U' = \frac{f_U}{.7} = \frac{1.25F_{cr}}{.7} = 1.78F_{cr}$$

Summarizing the discussions on pre-modulation and receiver output IPF filters, for PAM single channel baseband modulation the premodulation filters will be a single pole RC set at $f_U = 2.5F_{cr}$ and the receiver output video filter should be set at $2f_U = 5F_{cr}$.

For subcarrier channels both the premodulation and the SCD output LPF are designed for the same cutoff frequency for either the integration or S/H type of decommutators.

f_u and $F_{ud} = 2.5F_{cr}$

The premodulation SCO filter will be a single pole RC and the SCD output LPF will be 4 or 6 pole Bessel type.

For systems where PAM is multiplexed with SCO's both modulating the transmitter on baseband, and using an integration type decommutator, the PAM channel filters (f_U and f_{VU}) will equal $2.5F_{cr}$ and each filter will be at least a 6 pole Bessel type. This procedure will provide the lowest frequency SCO's which can fit the system. When using a S/H type decommutator f_U ' and f_{VU} ' will equal $1.78F_{cr}$ and each filter will be at least a 6 pole Bessel Type.

LOW PASS FILTER CASE - Equations related to PM Baseband Modulation:

$$(S/N)_{out} = (S/N)_{in} \left[\frac{3B_c}{2F_U}\right]^{1/2} \cdot \frac{f_D}{F_U} \qquad \text{EQ. (3)}$$

The following are the known parameters:

$F_U = F_{cr}$, $(S/N)_{in}$ = 12db (3.98 volt ratio)

$(S/N)_{out}$ = 37db (70.8 volt ratio) = 1% Noise or

$(S/N)_{out}$ = 31db (35.5 volt ratio) = 2% Noise

Single Channel Systems

Pre-Mod and Receiver Video Filters

$f_U = 2.5F_{cr}$ (Single Pole RC)

$f_{VU} = 5.0F_{cr}$ (Receiver Video Filter)

Multiplex Systems

Pre-Modulation and Receiver Output Filter

$f_u = 2.5F_{cr}$ (6 Pole Bessel Type)

Integration Type Decommutators

$f_{VU} = 2.5F_{cr}$ (6 Pole Bessel Type)

$f_U' = 1.78F_{cr}$ (6 Pole Bessel Type)

S/H Type Decommutators

$F_{VU}' = 1.78F_{cr}$ (6 Pole Bessel Type)

Receiver Bandwidth Equation:

$$B_c = 2\,(f_D + F_{cr}) \qquad \text{EQ. (3A)}$$

Solve Noise Equation (3) for f_D and substitute the following:

$C_l = (S/N)_{out}/(S/N)_{in}$, $FU = F_{cr}$

$$f_D = \frac{(2/3)^{\frac{1}{2}}\ C_1\ (F_{cr})^{3/2}}{(B_c)^{\frac{1}{2}}} \qquad \text{EQ. (3B)}$$

Square both side of the equation and substitute $B_c = 2(f_D + F_{cr})$

$$f_D^{\,2} = \frac{(2/3)\ C_1^{\,2}\ (F_{cr})^3}{2(f_D + F_{cr})}$$

Cross Multiply:

$$f_D^{\,3} + f_D^{\,2}\ F_{cr} = \frac{C_1^{\,2}\ F_{cr}^{\,3}}{3}$$

Divide by F_{cr} where the mod index $M = \dfrac{f_D}{F_{cr}}$

$$M^3 + M^2 = \frac{C_1^{\,2}}{3} \qquad \text{EQ (3CC)}$$

Solve mod index equation for $(S/N)_{out}$ = 37db and $(S/N)_{in}$ = 12db (1% Noise data channel)

$$C_1 = \frac{70.79}{3.98} \text{ volt ratio} = 17.79$$

$$M^3 + M^2 = \frac{(17.79)^2}{3} = 105.47$$

$$M = 4.44$$

Solve mod index equation for f_D and BW equation for B_c .

$$f_D = MF_{cr}$$

$$f_D = 4.4F_{cr} \quad \text{EQ. (3DD)}$$

$$B_c = 2(f_D + F_{cr}$$

$$= 2(4.4F_{cr} + F_{cr})$$

$$= 10.8F_{cr}$$

The same parameters calculated for $(S/N)_{out}$ = 31db and $(S/N)_{in}$ = l2db (2% Noise Data Channel) are:

$$M = 2.7$$

$$f_D = 2.7F_{cr}$$

$$B_c = 7.4F_{cr}$$

Where the system will be configured with PAM on baseband multiplexed with SCO’s, the relative amplitude equation is:

$$f_D' = (2/3)^{1/2} \; C_l \, (F_{cr})^{3/2} \quad \text{EQ. (3EE)}$$

Equations Related to PAM Modulating an SCO:

The procedure for PAM/FM/FM where PAM modulates an SCO, results in equations which are the same as a PCM FM/FM channel. The channel will operate at N = .82 because $F_{ud} = F_{cr}$ and $(S/N)_d$ is selected at l5db. Operating the SCO in this way will require a subcarrier discriminator input signal above threshold, but the trade offs of the signal to noise ratios and modulation index will result in the selection of the lowest SCO channel frequency and a minimum receiver IF bandwidth.

For selecting an SCO for a PAM modulating signal, the known facts are as follows:

$$(S/N)_d = 37\text{db}$$

Based on the PCM baseband calculations, we know the modulation index will be:

$$N = .82$$

Then, the required subcarrier channel bandwidth for a channel whose modulation index is less than one is:

$$B_{out} = 2F_{ud}$$

From the previous discussions, F_{ud} is dictated by the PAM decommutator characteristics where:

$$F_{ud} = F_{cr}$$

And the subcarrier deviation will be calculated from the modulation index equation:

$$N = \frac{f_{ds}}{F_{cr}}$$

$$\therefore f_{ds} = N f_{cr} = .82F_{cr}$$

The SCO peak deviation will be 82% of the channel peak SCD bandwidth which will satisfy the requirements of thresholding as described in the PCM discussions.

The bandwidth equation will be:

$$B_{out} = 2F_{cr}$$

Where $F_{cr} = F_{ud}$

substituting the bandwidth equation into the deviation solution (f_{ds}) of the noise equation result in the modulation index (N) equation:

$$f_{ds}{}^2 = \frac{2/3\ C_1{}^2\ (F_{cr})^3}{B_{out}} \quad \text{where } B_{out} = 2F_{cr}$$

$$f_{ds}{}^2 = \frac{C_1{}^2\ F_{cr}{}^2}{3}$$

Dividing by F_{cr} where $N = \frac{f_{ds}}{\frac{F_{cr}}{2}}$

$$N^2 = \frac{C_1^{\,2}}{3} \qquad \text{EQ. (3cc)}$$

Equation (3cc) can be solver for $(S/N)_{in}$ by substituting the known values of $(S/N)_{out}$ = 37db and N = .82, the result will be:

$$(S/N)_{in} = \frac{(S/N)_{out}}{3 \times (.82)^2} \qquad (S/N)_{out} = 70.74, \quad N = .82$$

$$(S/N)_{in} = \frac{70.74}{2} = 49.81 \text{ volt ratio}$$

$$(S/N)_{in} = 33.95\text{db}$$

Then for a PAM/FM/FM channel designed as described above, the subcarrier discriminator $(S/N)_{in}$ at receiver threshold $(S/N)_c$ will be 33.95db or (33.95 - 12), 21.95db above the subcarrier discriminator threshold point. The PAM Channel can also be designed for $(S/N)_d$ = 31db (2% Noise) using the same equations.

As described earlier, the premodulation filter and subcarrier discriminator output low pass filter for an SCO channel are calculated as follows:

f_u = 2. 5F_{cr} (Single Pole RC)

f_{ud} = 2.5F_{cr} (4 or 6 Pole Bessel as part of the subcarrier discriminator)

The same IFM CONSIDERATION problems exist with PAM modulating baseband as discussed in the PCM section of this paper. Sufficient deviation is necessary to overcome IFM to insure noise free data. Multiplex system with PCM on baseband are most susceptible because of the small deviation. Much less of a problem exists with PAM modulation because of the large $(S/N)_{out}$ (31 or 37db) dictating larger deviations; however the same IFM rule as stated for PCM will apply for PAM.

NARROW BAND MODULATION:

Narrow Band Modulation is governed by the Bandpass Filter Case and from Equation EQ. (2) the system design equations are developed. A doppler signal which is received with a tracking filter at the output of the receiver, is an example of narrow band modulation. The greatest use of the narrow band case and its equations, is for an FM/FM channel with a receiver and a subcarrier discriminator bandpass filter with a bandwidth equal to $2f_{ds}$.

NARROW BANDPASS FILTER CASE EQUATIONS:

$$(S/N)_{out} = (S/N)_{in} \left[\frac{B_c}{2B_{out}}\right]^{1/2} \cdot \frac{f_D}{F_m} \qquad \text{EQ. (2)}$$

$$B_c = 2\Delta f = 2f_D \qquad \text{EQ. (2A)}$$

Let $C_1 = \frac{(S/N)_{out}}{(S/N)_{in}}$ voltage ratio and solve EQ (2) for f_D

$$f_D = \frac{\sqrt{2} \cdot C_1 \cdot (B_{out})^{1/2}}{(B_c)^{1/2}} \quad F_m \qquad \text{EQ. (2B)}$$

Substitute EQ. (2A) into (2B) and where $M = \frac{f_D}{F_m}$ and solve for modulation index M.

$$M^3 = \frac{C_1^{\,2} \cdot B_{out}}{F_m} \qquad \text{EQ. (2C)}$$

The peak deviation (f_D is computed from the basic equation $M = \frac{f_D}{F_m}$ after calculating the modulation index M. EQ. (2C)

$$f_D = MF_m \qquad \text{EQ. (2D)}$$

The relative amplitude equation of a Narrow Band Modulation Channel is:

$$f_D' = 2 \cdot C_l \cdot (B_{out})^{1/2} \cdot F_m \qquad \text{EQ. (2E)}$$

FM/FM MODULATION:

The noise equations which apply to multiplex systems are a combination of the Bandpass Filter EQ. (2) and the Low Pass Filter EQ. (3) Cases. The RF receiver and the subcarrier discriminator bandpass filter represent the bandpass filter case. The subcarrier discriminator is the low pass filter case. When combining the receiver with a subcarrier discriminator, the receiver output signal to noise ratio, is the predetected signal at the output of the subcarrier discriminator bandpass filter $(S/N)_{out}$. This same (S/N) ratio is the $(S/N)_{in}$ of the subcarrier discriminator. Through substitution, the subcarrier channel noise equation is developed:

$$(S/N)_d = (S/N)_c \cdot (3/4)^{1/2} \left[\frac{B_c}{F_{ud}}\right]^{1/2} \cdot \frac{f_{dc}}{f_s} \cdot \frac{f_{ds}}{F_{ud}} \qquad \text{EQ. (4)}$$

The ratio $\frac{f_{ds}}{F_{ud}}$ is the modulation index (N) of the SCO channel. The ratio $\frac{f_{dc}}{f_s}$ is the modulation index (M) of the SCO channel modulation the transmitter.

By solving EQ. (4) for the deviation (f_{dc}) it can be seen how the 3/2 power law was developed for proportional bandwidth systems and a 6db/octave taper for constant bandwidth systems.

To maintain a constant (S/N) ratio for all the channels in a system, the deviation of proportional channels is a function of $(f_s)^{3/2}$ and for constant bandwidth channels it is a function of (f_s). The (f_{dc}) equations are employed in determining the deviation of each SCO channel and the overall transmitter pre-emphasis curve. However, in the initial design of an FM/FM system, the two unknowns are channel deviation (f_{dc}) and the optimum receiver IF bandwidth (B_c). Although the deviation varies on a per channel basis, the receiver IF bandwidth is common to all channels. Thus, the bandwidth term (B_c) can be dropped from the equation, and the relative amplitude of the channel deviation (f_{dc}) can be determined from known parameters. This equation is the key in designing the system for optimum performance, Step 3 of the System Design Chart, The (f_{dc}) equations are also necessary in Step 2 of the System Design Chart in solving for the parameters of a PCM or PAM/FM + FM/FM system.

For this reason, the relative amplitude equations, f_D ' and f_{dc} ' , for all modulation cases are listed and required in the design of FM/FM systems. Both proportional and constant bandwidth equations for f_{dc} ' are presented. Although they can be interchangeable, it is convenient to use the appropriate equation to facilitate the system design effort.

Attachment C is an f_{dc} ' table of values for standard IRIG channels with modulation indices of 2 and 5.

In the system design procedure, the values of f_{dc} ' or f_D ' are normalized with respect to the highest modulation frequencies and each channel is represented by a relative amplitude “A” one thru n. The total A prime factor (A) is developed by combining the relative amplitudes for each individual channel using the equation,

$$A' = \sqrt{A_1^2 + A_2^2 \ldots A_n^2}$$

The A' factor will represent a number related to the total deviation of a multi-tone systems. Note A_1 will always equal one since it represents the relative amplitude of the highest frequency channel.

Since an SCO multiplex system represent multi-tone modulation, the bandwidth equation MT $B_c = 2(\Delta f + f_{su})$ is necessary in the development of the design equations for an FM/FM system. Δf is the total transmitter deviation as calculated by the square root of the sum of the squares of each of the SCO’s peak transmitter deviation and f_{su} is the highest SCO center frequency in the multi-tone system.

FM/FM MODULATION EQUATIONS:

$$(S/N)_d = (S/N)_c \quad (3/4)^{\frac{1}{2}} \left[\frac{B_c}{F_{ud}}\right]^{\frac{1}{2}} \cdot \frac{f_{dc}}{f_s} \cdot \frac{f_{ds}}{F_{ud}} \qquad \text{EQ. (4)}$$

$$B_c = 2\,(\Delta f\,' = f_{su}) = 2\,(A\,'f_{dcu} + f_{su}), \qquad \text{EQ. (4A)}$$

$$\Delta f\,' = A\,'\,f_{dcu}$$

Where $A' = \sqrt{A_1^2 + A_2^2 \ldots A_n^2}$

Let $C_2 = \dfrac{(S/N)_d}{(S/N)_c \cdot (3/4)^{\frac{1}{2}}}$ voltage ratio,

$$N = \frac{f_{ds}}{F_{ud}}, \quad K = \frac{f_{ds}}{f_s}$$

Substitute C_2, N, and K into EQ. (4) and solve f_{dc} , for both proportional bandwith channels and constant bandwidth channels.

$$f_{dc_{PBW}} = \frac{C_2 \cdot (K)^{\frac{1}{2}} \cdot (f_s)^{3/2}}{(B_c)^{\frac{1}{2}} \cdot (N)^{3/2}} \quad ; \qquad \text{EQ. (4B)}$$

$$f_{dc_{CBW}} = \frac{C_2 \cdot (f_{ds})^{\frac{1}{2}} \cdot f_s}{(B_c)^{\frac{1}{2}} \cdot (N)^{3/2}} \qquad \text{EQ. (4B)}$$

Substitute EQ. (4A) $B_c = 2(A\, 'f_{dsu} + f_{su})$ into EQ. (4B) where $M = \frac{f_{dc}}{f_s}$ develop the modulation index equation (M).

$$A'M^3 + M^2 = \frac{C_2^{\ 2} \cdot K}{2(N)^3} \qquad \text{EQ. (4C)}$$

The modulation index equation is solved for the highest frequency subcarrier channel f_{su} then the deviation f_{dcu} of the highest SCO channel is

$$F_{dcu} = Mf_{su} \qquad \text{EQ. (4D)}$$

The relative amplitude equations of an SCO channel modulating a transmitter are:

$$f_{dc}{'}_{PBW} = \frac{C_2 \cdot (K)^{\frac{1}{2}} \cdot f_s^{3/2}}{(N)^{3/2}} \qquad \text{EQ. (4E)}$$

$$f_{dc}{'}_{CBW} = \frac{C_2 \cdot (f_{ds})^{\frac{1}{2}} \cdot f_s}{(N)^{3/2}} \qquad \text{EQ. (4E)}$$

More detailed derivations of the various noise equations are contained in the 1974 and 1976 papers published in the ITC preceedings. As stated before, the contents of this presentation makes necessary corrections; gives more detailed explanations; provides definite rules for making important decisions; and formulates each type of system into an independent step-by-step procedure.

DEVELOPMENT CHANNEL CHECK TABLES:

As part of the system design chart, channel check equation and tables are developed to assure subcarrier discriminator threshold performance. Compliance with the check equations eliminates the heretofore unexplained discrete channel dropouts which have plagued system engineers over the years.

In explaining the method of checking channels for the correct deviation, Tables II and III are devloped based on the Low Pass Filter Case equation as related to a subcarrier discriminator. The $(S/N)_{out}$ is tabulated for various modulation indices (N). If the subcarrier dis criminator of (FM/FM) multiplex channel represents the Low Pass Filter Case designed with an input BPF (B_{out}) equal to twice the peak deviation of the SCO, then the bandwidth equation will be $B_{out} = 2fd_{ds} = 2\Delta f$.

The modulation index equation for the subcarrier discriminator can be developed for a standard subcarrier channel using the low pass filter case of the noise equations:

Low Pass Filter Case:

$$(S/N)_{out} = (S/N)_{in} \left[\frac{3B_{out}}{2F_{ud}}\right]^{\frac{1}{2}} \quad \frac{f_{ds}}{F_{ud}} \qquad \text{EQ. (8)}$$

The following are the known parameters.

$$C_1 = \frac{(S/N)_{out}}{(S/N)_{in}}$$

$$B_{out} = 2f_{ds} \qquad \text{EQ. (8A)}$$

From Equation (8):

$$f_{ds} = (2/3)^{\frac{1}{2}} C_1 \cdot \frac{(F_{ud})^{3/2}}{(B_{out})^{\frac{1}{2}}} \qquad \text{EQ. (8B)}$$

Square both side and substitute B_{out} $2f_{ds}$

$$f_{ds}^{2} = 2/3 \cdot C_1^{2} \cdot \frac{(F_{ud})^{3}}{2f_{ds}}$$

$$f_{ds}^{3} = \frac{C_1^{2}\ (F_{ud})^{3}}{3}$$

Divide both side by F_{ud}^3 and solve for mod index where

$$N^3 = \frac{C_1^{2}}{3} \qquad \text{EQ. (8C)}$$

Let $C_1 = \frac{(S/N)_{out}}{(S/N)_{in}}$ volt ratio and substitute into EQ. (3A).

$$3N^3 = \left[\frac{(S/N)_{out}}{(S/N)_{in}}\right]^2$$

Then, for subcarrier discriminators operating at threshold $(S/N)_{in}$ = 12db; the subcarrier discriminator output noise $(S/N)_{out}$ is computed for various modulation indices, by EQ. (9).

$$(S/N)_{out} = (S/N)_{in} \sqrt{3N^3} \qquad \text{EQ. (9)}$$

Equation 9 applies for the standard subcarrier channel for any modulation index.

PCM or PAM/FM/FM are special cases of the subcarrier channel for which the modulation index is equal to .82(N), and $B_{out} = 2F_{ud}$.

$$N^2 = \frac{C_1^{2}}{3} \qquad \text{EQ. (3CC)}$$

Substitute N = .82 and $C_1 = \frac{(S/N)_{out}}{(S/N)_{in}}$ and solve for $(S/N)_{out}$

$$(S/N)_{out} = (S/N)_{in} \sqrt{2} \qquad \text{EQ. (10)}$$

Table II lists the $(S/N)_{out}$ and the related percentage of noise at the discriminator output in accordance with Equations 9, and 10.

TABLE II

SUBCARRIER DISCRIMINATOR OUTPUT
NOISE AT $(S/N)_{in}$ = l2db

	MOD INDEX N	$(S/N)_{in}$ (db)	$(S/N)_{out}$ (db)	Subcarrier Disc. Noise Output (%)
PCM/FM/FM	.82	12	15	17.7
PAM/FM/FM	.82	12	15	17.7
FM/FM	1	12	16.7	14.5
	2	12	25.8	5.13
	3	12	31.1	2.79
	4	12	34.8	1.81
	5	12	37.74	1.30
	6	12	40.0	1.0

Table III is based on determining the $(S/N)_{in}$ of the subcarrier discriminator channel necessary to maintain desired $(S/N)_{out}$. Solving the following two equations (EQ. 11 (A), and (B) provides this information.

PCM or PM FM/FM (A) FM/FM (B)

$$(S/N)_{in} = \frac{(S/N)_{out}}{\sqrt{2}} \qquad (S/N)_{in} = \frac{(S/N)_{out}}{\sqrt{3N^3}} \qquad \text{EQ. (11)}$$

From this table, the channel check factors (C_{kt}) are developed for all SCO channels.

The channel threshold check numbers, C_{kt} are calculated by comparing the computed $(S/N)_{in}$ EQ. (11) to threshold $(S/N)_{in}$ = l2db (3.98 volt ratio):

$$C_{kt} = \frac{(S/N)_{in}}{3.98} \qquad \text{EQ. (12)}$$

TABLE III

CHANNEL CHECK FACTORS (C_{kt})

Modulation	N	$(S/N)_{out(db)}$	$(S/N)_{in(db)}$	Threshold Check C_{kt}	EQ. 11
PCM on SCO $(S/N)_{out}$ = 15db	.82	15	12	1.0	A
PAM on SCO $(S/N)_{out}$ = 1%	.82	37	33.95	12.52	A
PAM on SCO $(S/N)_{out}$ = 2%	.82	31	27.95	6.27	A
SCO	2.0	40	26.2	5.13	B
SCO	3.0	40	20.9	2.79	B
SCO	4.0	40	17.2	1.81	B
SCO	5.0	40	14.3	1.30	B
SCO	6.0	40	12.0	1.0	B

For FM/FM Channels, Table III clearly shows that only at a modulation index of 6 the subcarrier discriminator will require a $(S/N)_{in}$ equal to threshold. For lower modulation indices, an input (S/N) greater than threshold is required to maintain an output S/N ratio = 40dB.

Then, for SCO data channels (f_s) at any modulation index (N), the argument of EQ. (2) shown as Equation 13 must be equal to or greater than the values listed in the last column of Table III to insure the correct performance of the SCO channel, at receiver threshold.

$$\left[\frac{B_c}{2B_{out}}\right]^{1/2} \cdot \frac{f_{dc}}{f_s} \geq C_{kt} \qquad \text{EQ. (13)}$$

Another consideration consistent with the channel check equations, is the effects of increases in IF bandwidth (B_c) and or channel deviation (f_{dc}) as related to an FM/FM channel. From the basic channel noise equation of an FM/FM channel, EQ. (4):

$$(S/N)_d = (S/N)_c \quad (3/4)^{1/2} \cdot \left[\frac{B_c}{F_{ud}}\right]^{1/2} \cdot \frac{f_{dc}}{f_s} \cdot \frac{f_{ds}}{F_{ud}}$$

Any increases in B_c or f_{dc} improve the channel noise performance. Normally, when the bandwidth selected due to available equipment is larger than calculated, the deviation of each channel is increased proportionally to fill the new bandwidth. Based on the system design results, and the desire to minimize the receiver IF bandwidth as much as possible, it may be judicious to increase the transmitter deviation of only those SCO channels which do not satisfy the channel check equations, or to increase the deviation required by PCM on baseband to overcome undesired transmitter deviation due to vibration or shock.

PROCEDURE FOR SELECTING SCO CHANNEL COMPATIBLE WITH BASEBAND MODULATION: PCM or PAM/FM + FM/FM

To complete the information required for the design of any type of telemetry system, a method is presented for selecting the first SCO channel above a PAM or PCM signal modulating a transmitter on baseband. To avoid intermodulation, the signal levels of the baseband modulation which fall into the SCO channel should be at least 40dB below the selected SCO signal level. This is based on worst case conditions of pulse modulation where the waveform is symmetrical.

A second parameter that must be considered in designing multiplex systems with PCM and PAM baseband modulation is the affects of IFM of the baseband modulation. If sufficient deviation of the baseband modulation is not provided, then the entire baseband modulation can be destroyed by the IFM. From EQ (3B) and EQ (3C) representing the deviation of a PCM or PAM channel, it is evident that the amplitude of the deviation is a direct function of C_1. Since the data channels are designed for threshold $(S/N)_{in}$ = 12db, performance, then the deviation amplitude is a direct function of the $(S/N)_{out}$. PCM data channels are designed for $(S/N)_{out}$ equal to 15db. PAM channels are designed for $(S/N)_{out}$ = 37db for 1% noise contribution and $(S/N)_{out}$ = 31db for 2% noise contribution. Because of the lower trasmitter deviations required in PCM systems and the possible effects of IFM, it is evident that the PCM system will require additional consideration in determining the PCM baseband channel deviation, and the separation between PCM baseband modulation and the first SCO channel.

To obtain the closest channel separation (in multiplex systems) between baseband PCM or PAM and the lowest frequency SCO, a PCM or PAM pre-modulation filter with 6 and 7 poles is necessary for system design.

The basic procedure for determining the separation of channels where the system has baseband modulation is as follows.

There are four (4) parameters which make up the 40db difference between baseband and SCO modulation.

1) Relative amplitude of the baseband modulation signal (f_D ') to the amplitude of the SCO channel (fdc ').

2) Harmonic content of baseband signal falling into the SCO channel. This parameter is based on the harmonic content of the unfiltered squarewave of a PAM or PCM modulation signal. Although only odd harmonics are present in a squarewave, the harmonic number will be the ratio of the selected SCO frequency to the frequency of the squarewave.

3) Pre-modulation filter attenuation as related to the normalized filter curves for 4 and 6 pole Bessel filters, Attachments B1 and B2.

4) The modulation index of the SCO channel (N), which affects the discriminator capture ratio and provide improved S/N performance.

Since the Bessel filter curves, Attachments B1 and B2, are not expressed in terms of an equation, the method for selecting the SCO channel is by trial and error.

The procedure for selecting the appropriate SCO channel compatible with baseband modulation is as follows: A standard SCO channel is selected, whose frequency, f_s is approximately 2.25 times (f_U) which is computed from the appropriate pre-modulation filter equations. The selected SCO channel must also meet the data response as specified by system design requirements.

1) Calculate relative amplitude of baseband modulation.(f_D ') using equations 3(E) and the relative amplitude of the selected SCO channel (f_{dc}) using equation 4(E), (standard values or f_{dc} ' are located in Attachment C). Their amplitude relationship is determined by thequation:

$$db_1 = 20 \text{ Log } \frac{f_D{}'}{f_{dc}{}'}$$

2) Calculate the harmonic relationship of the baseband fundamental squarewave frequency of PAM or PCM modulation, to the selected SCO channel frequency (f_s). The fundamental squarewave frequency of PCM or PAM is equal to the bit rate of PCM or the clock rate of PAM. For NRZ systems, the fundamental squarewave frequency is 1/2 the bit rate or 1/2 the clock rate. To determine the level of squarewave harmonic which falls into the passband of the SCO channel, the following equations apply.

$$db_{2\,(NRZ)} = 20 \text{ Log } \frac{F_{B/2}}{F_s} \text{ or } \frac{F_{cr/2}}{f_s}$$

3) Determine the contribution of the pre-modulation filter in attenuating the baseband modulation signal. Calculate X axis normalize number of Attachments B1 and B2 using the relationship:

$$x = \frac{f_s}{f_U \text{ or } f_U'}$$

PCM $f_U = .7F_B$

PAM $f_U = 2.5F_{cr}$

PAM $f_U' = 1.78F_{cr}$

$f_s = 2.2S$ (f_U or f_U')

From the filter curve determine the attenuation (Y) related to the calculated normalized value X.

$db_3 = Y$

4) db_4 is directly related to the modulation index (N) of the selected SCO:

$db_4 = N$

The summation of db_1 through db_4 must be equal to or greater than 40db.

$db_1 + db_2 + db_3 + db_4 \geq 40db$

If the total is larger than 40db, then the selected SCO frequency is too high and a lower frequency channel should be selected, provided it satisfies the modulation data requirements. If the total is less than 40db, then a higher SCO channel must be selected. Again, this is a trial and error method, because the pre-modulation filter curves are not presented in terms of an equation.

From past experience in designing systems with PCM baseband modulation, mixed with an SCO mux, the channel separation between the PCM channel and the first SCO will follow the requirement $f_s = 2.25f_U$. In using the recommended channel separation, the summation of db_1 through db_4 will be substantially greater than 40db. However, the final adjustment of the PCM channel deviation required for correct operation will result in a channel separation very close to 40db.

To insure sufficient PCM channel deviation as related to IFM, a final PCM channel deviation adjustment may be required. The deviation of the PCM baseband modulation will be modified to satisfy the equation $f_D = .41F_B$ or equal 4 times the transmitter IFM specification whichever is larger. As a final check for channel separation a new value for the first parameter (db_1) must be calculated using the f_{dc} and f_D final values as listed in the System Design Table. This new value of db_1 is added to the original values of db_2, db_3, db_4, and the total must still be equal to or greater than 40db. All pre-modulation and receiver output video filters shall be 6 or 7 pole Bessel type.

When designing systems with PAM baseband modulation, the results will not require any special channel deviation adjustments. This is due to the large transmitter deviations required to obtain the large $(S/N)_{out}$ values related to PAM channel design.

All of the discussions are completed and procedures for designing a data system can be expressed in the form of a design chart.

The System Design Chart as presented in this paper incorporates the work of two previous papers (Reference 1 and 2) and includes the updated information described in this text.

The established practices for selecting SCO channels from IRIG standard applies. When possible, channels having a modulation index of 5 are selected to minimize the bandwidth and total deviation. When necessary, channels with a modulation index of 2 are selected to provide higher data response.

From any system data list, the system design procedure of this presentation can provide a set of parameters for optimum performance.

The System Design Chart starts with the analysis of PAM or PCM baseband modulation. It continues into the case of multichannel systems consisting of PAM or PCM on baseband and a number of SCO channels operating somewhere above the baseband modulation. The chart is completed with the design procedures for an FM multiplex systems including channel check equations. Also included is a method and equation for performing the margin calculations, Attachment E.

SYSTEM DESIGN CHART

Step 1 Determine parameters of PCM or PAM Channels for both baseband and subcarrier channels. PCM and PAM are examples of Pulse Modulation and the channel design equations which where previously developed will be summarized in the system design chart. F_U (PCM) = $\frac{1}{2}F_B$, F_U (PAM) = F_{cr}. (NRZ Format)

Step 1 of the System Design Chart is based on NRZ modulation format. For BIØ format the equations must be developed based on $F_{U_{PCM}} = 1 \times F_B$ or $F_{U_{PAM}} = 2F_{cr}$.

A. Calculate the values of Pre-modulation filters and receiver output filters. All values are 3db frequency filter cutoff points.

● PCM Single Channel Baseband System	
Pre-Modulation Filter (Single Pole R.C.)	$f_U = 1 \times F_B$
Receiver Video Filter (Part of Receiver)	$f_{VU} = 2 \times F_B$
● PCM Baseband Multiplexed System:	
Pre-Mod Filter (6 Pole Bessel)	$f_U = .7F_B$
Receiver Output Filter (6 Pole Bessel)	$f_{VU} = .7F_B$
● PCM/FM/FM Subcarrier Channel	
Pre-Modulation Filter (Single Pole RC)	$f_u = 1 \times F_B$
Subcarrier Disc. Output LPF (6 Pole Bessel)	$f_{ud} = 1 \times F_B$
● PAM Single Channel Baseband System	
Pre-Modulation Filter (Single Pole R.C.)	$f_U = 2.5F_{cr}$
Receiver Video Filter (Part of Receiver)	$f_{VU} = 5F_{cr}$
● PAM Baseband Modulation Multiplexed System:	
Integration Type Decommutator	
Pre-Mod Filter (6 Pole Bessel)	$f_U = 2.5F_{cr}$
Receiver Output Filter (6 Pole Bessel)	$f_{VU} = 2.5F_{cr}$
Sample and Hold Type Decommutator	
Pre-Mod Filter (6 Pole Bessel)	$f_U' = 1.78F_{cr}$
Receiver Output Filter (6 Pole Bessel)	$f_{UV}' = 1.78F_{cr}$
● PAM/FM/FM Subcarrier Channel	
Pre-Modulation Filter (Single Pole R.C.)	$f_u = 2.5F_{cr}$
Subcarrier Disc. Output LPF (6 Pole Bessel)	$f_{ud} = 2.5F_{cr}$

B.	Determine the value of C_1 standard Values of C_1 at Receiver Threshold $(S/N)_{in}$ = 12db	$C_1 = \frac{(S/N)_{out}}{(S/N)_{in}}$
	● PCM Baseband Modulation (including SCO Channel $(S/N)_{out}$ = 15db	C_1 = 1.41
	● PAM Baseband Modulation	
	$(S/N)_{out}$ = 37db = 1% Noise	C_1 = 17.8
	$(S/N)_{out}$ = 31db = 2% Noise	C_1 = 8.9
C.	Calculate Modulation Index at Receiver Threshold $(S/N)_{in}$ = 12db	
	● PCM Baseband Modulation (including SCO Channel)	M^2 or $N^2 = \frac{C_1^{\;2}}{3}$
	$(S/N)_{out}$ = 15db, C_1 = 1.41	M or N = .82
	● PAM Baseband Modulation	$M^3 + M^2 = \frac{C_1^{\;2}}{3}$
	$(S/N)_{out}$ = 37db = 1% Noise	M = 4.44
	$(S/N)_{out}$ = 31db = 2% Noise	M = 2.7
	● PAM/FM/FM Subcarrier Channel	N = .82
D.	Calculate Channel Deviation, for PCM $F_U = ½F_B$. for PAM $F_U = F_{cr}$	f_D = (M or N) x F_U
	● PCM Baseband Modulation (including SCO Channel)	$f_D = .41F_B$
	● PAM Baseband Modulation	
	$(S/N)_{out}$ = 37db, 1% Noise	$f_D = 4.44F_{cr}$
	$(S/N)_{out}$ = 31db, 2% Noise	$f_D = 2.7F_{cr}$
	● PAM/FM/FM Subcarrier Channel for N = .82	$f_{ds} = .82F_{cr}$
E.	Calculate Receiver IF Bandwidth (B_c) or Subcarrier Discriminator Input BPF (B_{out}) at Receiver Threshold	
	● PCM Baseband Modulation	$B_c = 2F_U$
	$F_U = ½F_B$	$B_c = F_B$
	● PAM Baseband Modulation	$B_c = 2(f_D + F_{cr})$
	$(S/N)_{out}$ = 37db, 1% Noise	$B_c = 10.8F_{cr}$
	$(S/N)_{out}$ = 31db, 2% Noise	$B_c = 7.4F_{cr}$
	PCM/FM/FM Subcarrier Channel $f_{ds} = .41F_B$	$B_{out} = F_B$
	● PAM/FM/FM Subcarrier Channel $f_{ds} = .82F_{cr}$	$B_{out} = 2F_{cr}$

F.	Select a standard Receiver IF Bandwidth which closest fits the calculate bandwidth B_c.	$B_{c(sel)}$ = 300kHz, 500kHz, 750kHz, 1000kHz, 2000kHz, 2500kHz, 3300kHz
	● For SCO Channel, Select the Channel which fits the calculated B_c. In terms of an SCO channel, B_c is designated B_{out}.	B_{out} = selected SCO channel to fit calculated value. Tables, Attachment A.
G.	Increase deviation proportionally, if desired, to fill selected bandwidth.	
	● Multiplication Factor	$B = \frac{B_{c(sel)}}{B_{c(cal)}}$
	● Final Deviation f_{Df}	$f_{Df} = Bf_D$

For systems with PCM or PAM modulating a transmitter on baseband, Step 1 of the procedure completes the system design effott and the minimum IF bandwidth calculated is applied in the R_N equation for margin calculations Attachment E. For multichannel systems, Step 1 will provide the parameters required to select the PCM or PAM SCO Channel. PCM or PAM/FM + FM/FM

Step 2	PCM or PAM Multiplex with SCO Multiplex both modulating transmitter on baseband. Selection of SCO channels for optimum channel separation.	
A.	Calculate pre-modulation and receiver output low pass filters from Step 1 A and B and list the known parameters. $(S/N)_{in}$ = 12db	
	● PCM Multiplex Systems $(S/N)_{out}$ = 15db	$f_U = .7F_B$, $f_{VU} = .7F_B$ $C_1 = 1.41$
	● PAM Multiplex Systems:	
	Integration Type Decommutators:	f_U and $f_{VU} = 2.5F_{cr}$
	$(S/N)_{out}$ = 37db (1% Noise)	$C_1 = 17.8$
	$(S/N)_{out}$ = 31db (2% Noise)	$C_1 = 8.9$
	Sample and Hold Type Decommutators	f_U' and $f_{VU}' = 1.78F_{cr}$
	$(S/N)_{out}$ = 37db (1% Noise)	$C_1 = 17.8$
	$(S/N)_{out}$ = 31db (2% Noise)	$C_1 = 8.9$
B.	Calculate channel separation comparing the amplitude of baseband channel deviation to the first SCO deviation. Select the SCO channel which satisfies the following equation	$f_{s_1} = 2.25(f_U \text{ or } f_U')$ PCM, $f_{s_1} = 1.6F_B$ PAM (S/H), $f_{s_1} = 4.0F_{cr}$ PAM (INT), $f_{s_1} = 5.6F_{cr}$
	● PCM Channel	$f_D' = (2/3)^{1/2} C_1 \left[\frac{F_B}{2}\right]^{3/2}$
	● PAM Channel	$f_D' = (2/3)^{1/2} C_1 (F_{cr})^{3/2}$

	● SCO Channel (PBW) } Relative Amplitude Values Attachment C for Standard IRIG Channels. ● SCO Channel (CBW)	$f_{dc}'_{PBW} = \frac{C_2 (K)^{\frac{1}{2}} (f_{s_1})^{3/2}}{(N)^{3/2}}$ $f_{dc}'_{CBW} = \frac{C_2 (f_{ds})^{\frac{1}{2}} f_{s_1}}{(N)^{3/2}}$
	● Relative Amplitude	$db_1 = 20Log \frac{f_D'}{f_{dc}'}$
C.	Calculate PCM or PAM harmonic energy which interferes with the selected SCO channel.	See Step B for f_{s_1}
	● PCM Channel Relative Amplitude	$db_2 = 20 \text{ Log } \frac{F_{B/2}}{f_{s_1}}$
	● PAM Channel Relative Amplitude	$db_2 = 20 \text{ Log } \frac{F_{cr/2}}{f_{s_1}}$
D.	Determine Attenuation Contributed by Premodulation Filter as Related to the Bessel Filter Curves. Normalized X Axis Factor is:	$x = \frac{f_s}{f_u}$ or $x = \frac{f_s}{f_U'}$
	● Determine Attenuation (Y) Related to X Axis Factor from Attachments B1 and B2, 4 or 6 Pole BFC.	$db_3 = Y$
E.	Subcarrier Improvement Factor Related to Modulation Index (N) of SCO Channel f_s.	$db_4 = N$
F.	Compute Total Attenuation	$db_T = db_1 + db_2 + db_3 + db_4$
	● This is a trial and error method. If the total is more or less than 40db, the next higher or lower standard SCO channel must be tested. The lowest frequency SCO channel which meets the 40db criteria and is capable of the desired data requirements is the SCO channel to be selected.	$db_T \geq 40db$
G.	Make final deviation adjustments for PCM baseband modulation based on minimum deviation equation or minimum deviation required to overcome transmitter IFM (F_{IFM}) under environments. No final deviations adjustment is required for PAM Multiplex systems because of the large transmitter deviation required to support $(S/N)_{out}$ = 37db (1% Noise) or 31db (2% Noise).	
	● Minimum PCM deviation:	(A) $f_D = .41F_B$
	● Minimum PCM deviation to overcome Transmitter IFM.	(B) $f_D = 4F_{IFM}$
	● Recalculate db_1 based on the final adjusted PCM deviation (A) or (B) whichever is greater.	$db'_1 = 20 \text{ Log } \frac{f_D \text{ (A or B)}}{f_{s_1}}$

The final adjustment procedure is not required for PAM Multiplex Systems because of the larger transmitter deviation required to support $(S/N)_{out}$ = 37db (1% Noise) or $(S/N)_{out}$ = 31db (2% Noise)	
Final Check of Channel Separation	$db_T = db'_1 + db_2 + db_3 + db_4$
● If the final channel separation is larger or small than 40db, then the system must be tested for a higher or lower SCO channel, whichever is appropriate.	$db_T \approx 40db$

Step 3 is the procedure for the design of a multiplex system. In multiplex systems which contain PAM or PCM modulating an SCO, Step 1 is completed for the selection of the first SCO channel. (f_{s_1}). A block diagram of the system, with the appropriate known system parameters marked in each block, and the desired S/N ratios placed at the proper points, will aid in understanding the design procedure. Multiplex systems modulating a carrier are considered multi-tone modulation and always use the bandwidth equation $B_c = 2(\Delta f_s + f_{su})$. Table IV is the System Design Table recommended for posting the values computed during the design procedure.

A. Calculate relative amplitudes for subcarrier channels given by f'_{dc} and for PCM or PAM baseband modulated given by f'_D. Standard values of f_{dc} are obtained from Table Attachment C for both proportional and constant bandwidth channels.

● Calculate C_2	$C_2 = \frac{(S/N)_d}{(S/N)_c\ (3/4)^{1/2}}$ volt ratio
FM/FM Channels $(S/N)_d$ = 40db, $(S/N)_c$ = 12db	$C_2 = 29$
PCM/FM/FM Channels $(S/N)_d$ = 15db, $(S/N)_c$ = 12db	$C_2 = 1.63$
PAM/FM/FM Channels $(S/N)_d$ = 37db, $(S/N)_c$ = 12db (1% Noise)	$C_2 = 20.6$
PAM/FM/FM Channels $(S/N)_d$ = 31db, $(S/N)_c$ = 12db (2% Noise)	$C_2 = 10.3$
PCM Baseband Modulation $(S/N)_{out}$ = 15db, $(S/N)_{in}$ = 12db.	$C_1 = 1.41$
PAM Baseband Modulation $(S/N)_{out}$ = 37db, $(S/N)_{in}$ = 12db (1% Noise)	$C_1 = 17.8$
PAM Baseband Modulation $(S/N)_{out}$ = 37db, $(S/N)_{in}$ = 12db (2% Noise).	$C_1 = 8.9$
● Relative Amplitude Equations for Proportional Bandwidth SCO Channels.	$f'_{dc\,(PBW)} = \frac{C_2 \cdot (K)^{1/2} \cdot (f_s)^{3/2}}{(N)^{3/2}}$
● Relative Amplitude Equations for Constant Bandwidth SCO Channels.	$f'_{dc\,(CBW)} = \frac{C_2 \cdot (f_{ds})^{1/2} \cdot f_s}{(N)^{3/2}}$
● Relative Amplitude Equation for PCM Base band Modulation	$f'_{D\,(PCM)} = (2/3)^{1/2}\, C_1 \left(\frac{F_B}{2}\right)^{3/2}$
● Relative Amplitude Equation for PAM Baseband Modulation	$f'_{D\,(PAM)} = (2/3)^{1/2}\, C_1\, (F_{cr})^{3/2}$

SYSTEM DESIGN TABLE IV

1	2	3	4	5	6	7	8	9	10	11	12	13
SYS CHAN	IRIG CHAN.	CHAN. f_s kHz	DEV. f_{ds} kHz or %	M.I. N	f_{dc}' x 10^6 kHz	f_{dc}' NORM	f_{dc} kHz	B = ___ Bf_{dc} kHz	f_{dcf} DEV. kHz	TABLE III CHECK NO.	COMP. CHECK NO.	
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
17												
18												
19												
20												
21												
22												
						A =	Af_{dc} =		Δf =			

COMMENTS:

B.	Post f_{dc}' Values. Normalize f_{dc}' values with respect to highest frequency channel and Add Normalized Values to Determine A'.	$A' = \sqrt{A_1^2 + A_2^2 + A_3^2 \dots A_n^2}$
C.	Calculate Modulation Index of Highest SCO Channel f_{su} Modulating the Transmitter. Where C_2, K and N are The Parameters of the Highest SCO Channel.	$A'M^3 + M^2 = \frac{C_2^2 \cdot K}{2N^3}$
D.	Calculate Deviation (f_{dcu}) of Highest Subcarrier Channel and Peak Transmitter Deviation (Δf).	$f_{dcu} = Mf_{su}$, $\Delta f' = A' f_{dcu}$
E.	Calculate System Receiver Optimum IF Bandwidth.	$B_{c(cal)} = 2(\Delta f' + f_{su})$
	● Select the Standard Receiver IF Bandwidth Available Which Is Equal to Or Next Larger To the Calculated Bandwidth.	$B_{c(sel)}$ = 300kHz, 500kHz, 750kHz, 1000kHz, 1500kHz, 2000kHz, 2500kHz, 3300kHz
F.	Determine the deviations of each subcarrier channel by multiplying the normalized values of each channel by the deviation of the highest subcarrier channel calculated in Step D. Post in System Table.	$f_{dc} = f_{dcu}$ x Norm. Values
G.	Calculate B factor and adjust subcarrier deviations for final value f_{dcf}, to fill new bandwidth, using B factor.	$B = \frac{B_{c(sel)}}{B_{c(cal)}}$, $f_{dcf} = Bf_{dc}$
	● Adjust all lower frequency SCO channels for modified pre-emphasis requirements.	$f_{dc(min)} = 5\text{kHz}$
	● Adjust PCM Baseband Modulation to Meet Minimum Requirements to Satisfy Deviation Equation or IFM Equation, Whichever is Larger. $F_{(IFM)}$ = Transmitter IFM Specification.	$f_{D(PCM)} = .41F_B$ $f_{D(PCM)} = 4F_{(IFM)}$
	● No final deviation adjustment is required for PAM.	
H.	Check channels for correct (S/N) performance at receiver threshold.	
	● PAM or PCM Baseband Modulation; Check for Desired $(S/N)_{out}$. (PCM) $F_U = \frac{1}{2}F_B$, (PAM) $F_U = F_{cr}$	$(S/N)_{out} = (S/N)_{in} \left[\frac{3B_c}{2F_U}\right]^{1/2} \frac{f_D}{F_U}$
	● SCO channel Check, Refer to Table III for Standard Values of C_{kt}.	$\left[\frac{B_{c(sel)}}{2B_{out}}\right]^{1/2} \cdot \frac{f_{dc}}{f_s} \geq C_{kt}$
	● Calculate Value of C_{kt} not listed in Table III for SCO Channels.	$C_{kt} = \frac{(S/N)_{in}}{3.98}$
	PCM/FM/FM and PAM/FM/FM	$(S/N)_{in} = \frac{(S/N)_{out}}{\sqrt{2}}$
	Normally N = .82	
	FM/FM	$(S/N)_{in} = \frac{(S/N)_{out}}{\sqrt{3N^3}}$
I.	Perform Margin Calculation Using the Method Described in Attachment E. S/N = 12db	$P_t = R_N + S/N + SF + L + PL - G_R - G_T$

REFERENCES:

1. Charles Rosen, “Method for Calculating the Pre-Fsphasis Schedule for and FM/FM Telemetry System based on Optimum, Performance”, ITC Precedings Volume X 1974 Page 536.

2. Charles Rosen, “Method for Determination of System Parameters in Telemetry Baseband Modulation System”, ITC precedings Volume XII, 1976 Page 403.

3. Ken Uglow, “Noise and Bandwidth in FM/FM Telemetering” IRE transactions May 1957, Page 19.

Attachment “A” is an expansion of the IRIG Tables of subcarrier channel assignments. It is not intended to set any standards for the industry, and may not represent the actual channels assigned by IRIG in future expansion of the FM/FM System. It does present the natural progression of the standards based on IRIG established criteria.

This author does suggest a small change in the assignment of the proportional bandwidth high frequency channels. By reassigning Channel 25 to a center frequency of 525kHz instead of 560kHz, two additional SCO channels can be assigned and the frequency spectrun can remain essentially below one megahertz. SCO’s up to 1MHz are within the capabilities of most telemetry manufacturers. The new channels suggested (525kHz, 700kHz and 930kHz) will meet the guardband requirements as established for the IRIG channels and follow the progression of the mid range proportional bandwidth channels.

The constant bandwidth channels are extended using the channel spacing criteria of 4 times the peak deviation. The lowest frequency in any grouping represents an SCO where the peak deviation is 25% of the channel center frequency. The highest SCO in any grouping represents an oscillator where the peak deviation is approximately 2.0% of the channel center frequency. Both the lowest and highest channel frequency assignments in any grouping of Attachment “A” (Constant Bandwidth Channels) are based on the practical aspects of the manufacture of the SCO. The high frequency SCO performance specifications required are well within the capabilities of most telemetry manufacturers.

ATTACHMENT A
PROPORTIONAL-BANDWIDTH SUBCARRIER CHANNELS

±7.5% CHANNELS

Chan	Center Frequencies (Hz)	Lower Deviation Limit (Hz)	Note 1 Upper Deviation Limit (Hz)	Nominal Frequency Response N = 5 (Hz)	Nominal Rise Time N = 5 (ms)	Notes 1&2 Maximum Frequency Response (Hz)	Note 2 Minimum Rise Time (ms)	Note 5 Subcarrier Disc. B.W. B_{out} (Hz)
1	400	370	430	6	58	30	11.7	
2	560	518	602	8	44	42	8.33	
3	730	675	785	11	32	55	6.40	
4	960	888	1,032	14	25	72	4.86	
5	1,300	1,202	1,398	20	18	98	3.60	
6	1,700	1,572	1,828	25	14	128	2.74	
7	2,300	2,127	2,473	35	10	173	2.03	
8	3,000	2,775	3,225	45	7.8	225	1.56	
9	3,900	3,607	4,193	59	6.0	293	1.20	
10	5,400	4,995	5,805	81	4.3	405	.864	
11	7,350	6,799	7,901	110	3.2	551	.635	
12	10,500	9,712	11,288	160	2.2	788	.444	
13	14,500	13,412	15,588	220	1.6	1,088	.322	2,175
14	22,000	20,350	23,650	330	1.1	1,650	.212	3,300
15	30,000	27,750	32,250	450	.78	2,250	.156	4,500
16	40,000	37,000	43,000	600	.58	3,000	.117	6,000
17	52,500	48,562	56,438	790	.44	3,938	.089	7,876
18	70,000	64,750	75,250	1,050	.33	5,250	.067	10,500
19	93,000	86,025	99,975	1,395	.25	6,975	.050	13,950
20	124,000	114,700	133,300	1,860	.19	9,300	.038	18,600
21	165,000	152,624	177,375	2,475	.14	12,375	.029	24,750
22	225,000	208,125	241,875	3,375	.10	16,875	.021	33,750
23	300,000	277,500	322,500	4,500	.08	22,500	.016	45,000
24	400,000	370,000	430,000	6,000	.06	30,000	.012	60,000
25	560,000	518,000	602,000	8,400	.04	42,000	.008	84,000
25	525,000	485,625	564,375	7,875	.044	39,375	.009	78,760
26	690,000	638,250	741,750	10,350	.033	51,750	.007	105,000
27	930,000	860,250	999,750	13,950	.025	69,750	.005	139,500

±15% CHANNELS - NOTE 3

Chan	Center Frequencies (Hz)	Lower Deviation Limit (Hz)	Upper Deviation Limit (Hz)	Nominal Frequency Response (Hz)	Nominal Rise Time (ms)	Maximum Frequency Response (Hz)	Minimum Rise Time (ms)	B_{out} (Hz)
A	22,000	18,700	25,300	660	.53	3,300	.108	6,600
B	30,000	25,500	34,500	900	.39	4,500	.078	9,000
C	40,000	34,000	46,000	1,200	.29	6,000	.058	12,000
D	52,500	44,625	60,375	1,575	.22	7,875	.044	15,750
E	70,000	59,500	80,500	2,100	.17	10,500	.033	21,000
F	93,000	79,050	106,950	2,790	.13	13,950	.025	27,900
G	124,000	105,400	142,600	3,720	.09	18,600	.018	37,200
H	165,000	140,250	189,750	4,950	.07	24,750	.014	49,500
I	225,000	191,250	258,750	6,750	.05	33,750	.010	67,500
J	300,000	255,000	345,000	9,000	.04	45,000	.008	90,000
K	400,000	340,000	460,000	12,000	.03	60,000	.006	120,000
L	560,000	476,000	644,000	16,800	.02	84,000	.004	168,000
L	525,000	446,250	603,750	15,750	.022	78,750	.004	157,500
M	700,000	595,000	805,000	21,000	.017	105,000	.0033	210,000
N	930,000	790,500	1,069,500	27,900	.013	139,500	.0025	279,000

±30% CHANNELS - NOTE 4

Chan	Center Frequencies (Hz)	Lower Deviation Limit (Hz)	Upper Deviation Limit (Hz)	Nominal Frequency Response N = 5 (Hz)	Nominal Rise Time N = 5 (ms)	Maximum Frequency Response (Hz)	Minimum Rise Time (ms)	Subcarrier Disc. B.W. B_{out} (Hz)
AA	22,000	15,400	28,600	1,320	.265	6,600	.053	13,200
BB	30,000	21,000	39,000	1,800	.194	9,000	.038	18,000
CC	40,000	28,000	52,000	2,400	.146	12,000	.029	24,000
DD	52,500	36,750	68,250	3,150	.111	13,750	.022	27,500
EE	70,000	49,000	91,000	4,200	.083	21,000	.016	42,000
FF	93,000	65,100	120,900	5,580	.063	27,900	.012	55,800
GG	124,000	86,800	161,200	7,400	.047	37,200	.009	74,400
HH	165,000	115,500	214,500	9,900	.035	49,500	.007	99,000
II	225,000	157,500	292,500	13,500	.026	67,500	.005	135,000
JJ	300,000	210,000	390,000	18,000	.019	90,000	.004	180,000
KK	400,000	280,000	520,000	24,000	.015	120,000	.003	240,000
LL	560,000	392,000	728,000	33,600	.010	168,000	.002	336,000
LL	525,000	367,500	682,500	31,500	.011	157,500	.0022	315,000
MM	700,000	490,000	910,000	42,000	.008	210,000	.0016	420,000
NN	930,000	650,000	1,209,000	55,800	.006	279,000	.0012	558,000

1. Rounded off to nearest Hz.

2. The indicated maximum data frequency response and minimum rise time is based upon the maximum theoretical response that can be obtained in a bandwidth between the upper and lower frequency limits specified for the channels.

3. Channels A thru N may be used by omitting adjacent lettered and numbered channels. Channels 13 and A may be used together with some increase in adjacent channel interference.

4. Channels AA thru NN may be used by omitting every four adjacent double lettered and lettered channels and every three adjacent numbered channels. Channels AA thru NN may be used by omitting every three adjacent double lettered and lettered channels and every two adjacent numbered channels with some increase in adjacent channel interference.

5. Correct channel separation can be determined by adding the two bandwidths (B_{out}) of the adjacent channels and adding the result to the lower frequency channel or subtracting from the higher frequency channel.

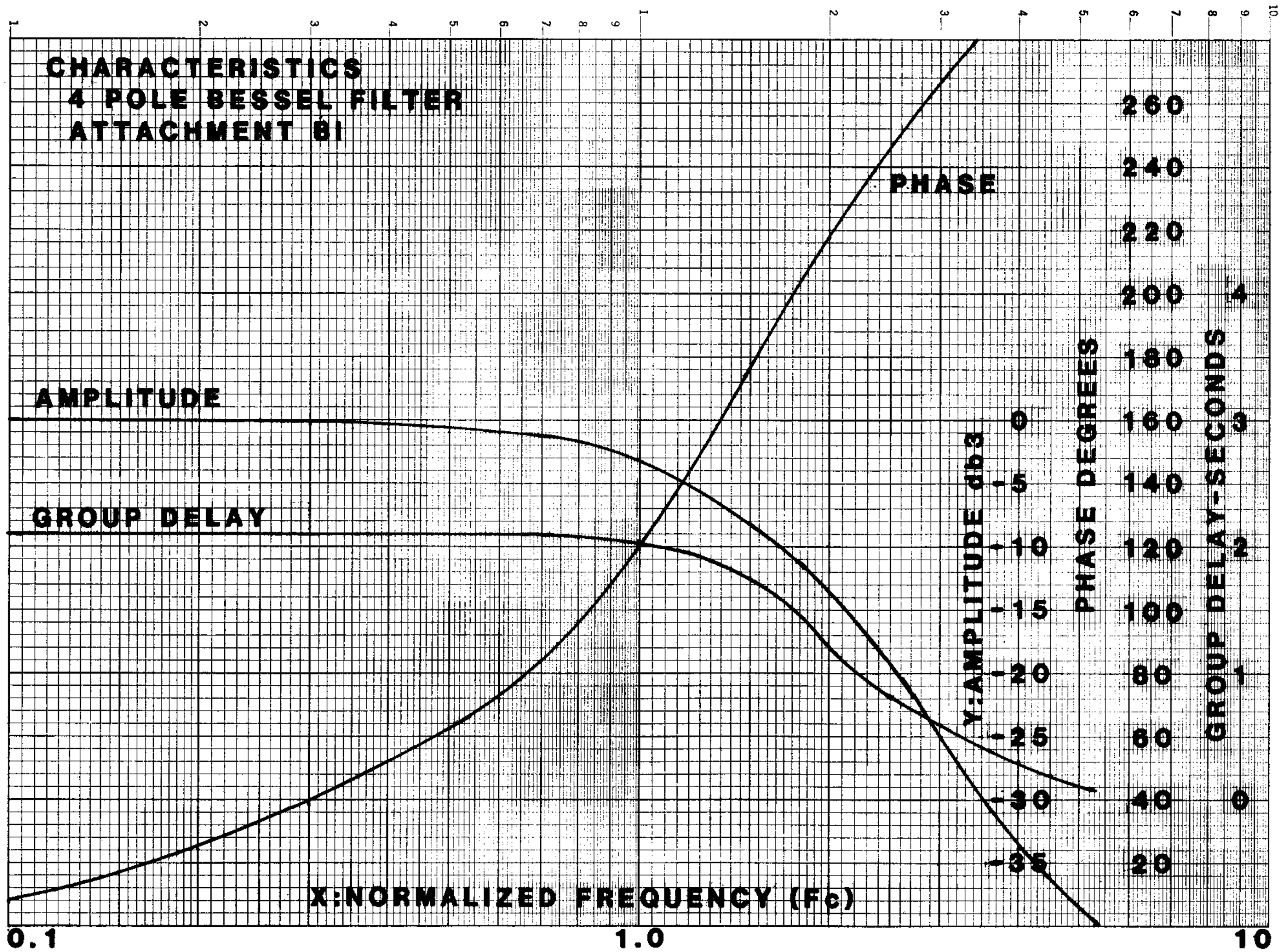
IRIG CONSTANT BANDWIDTH SUBCARRIER CHANNELS - NOTE 1

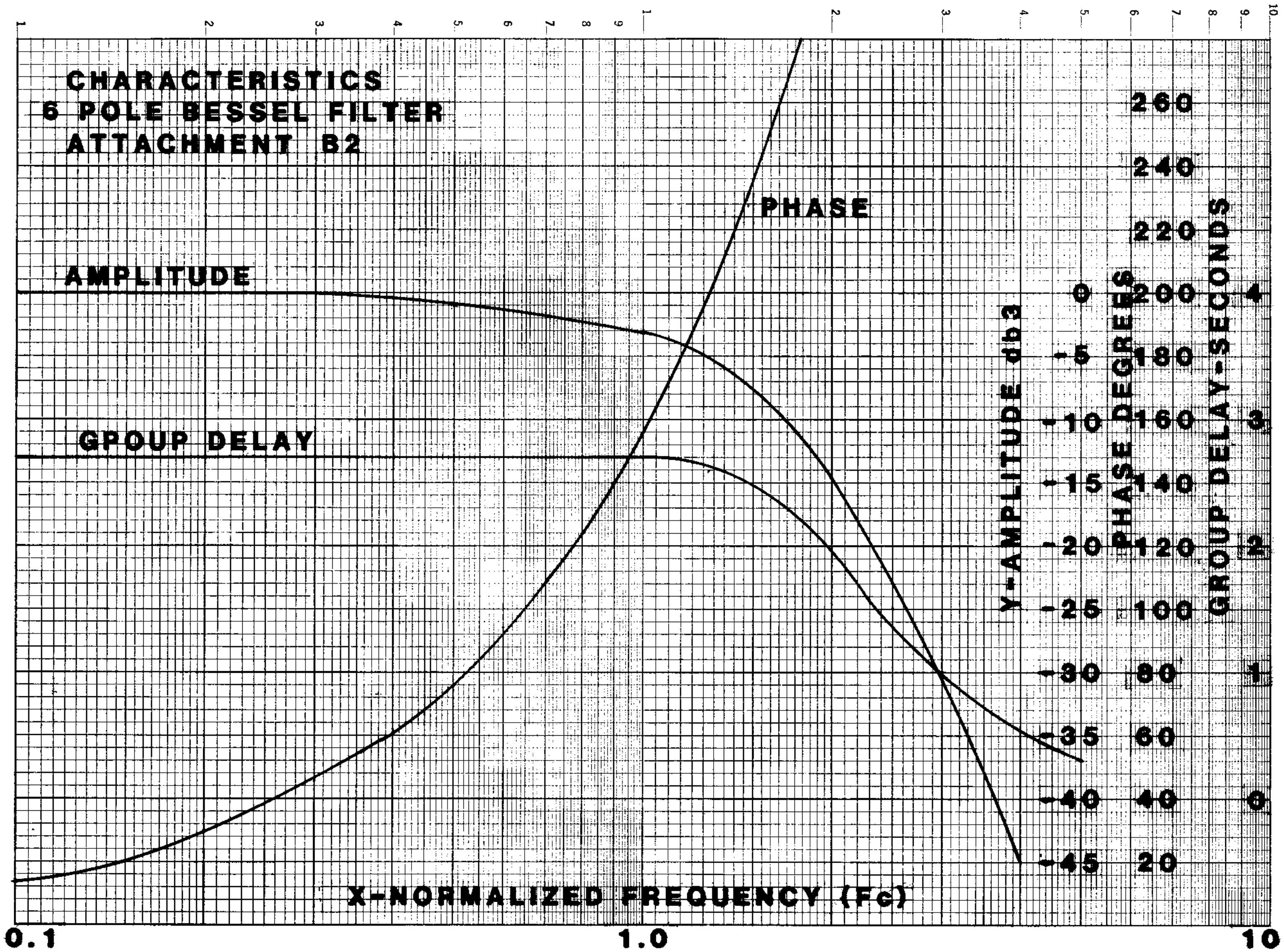
A CHANNELS		B CHANNELS		C CHANNELS		D CHANNELS		E CHANNELS	
Deviation Limits = ±2kHz Nominal Frequency Response = 0.4kHz Maximum Frequency Response = 2kHz B_{out} = 4kHz		Deviation Limits = ±4kHz Nominal Frequency Response = 0.8kHz Maximum Frequency Response = 4kHz B_{out} = 8kHz		Deviation Limits = ±8kHz Nominal Frequency Response = 1.5kHz Maximum Frequency Response = 8kHz B_{out} = 16kHz		Deviation Limits = ±16kHz Nominal Frequency Response = 3.2kHz Maximum Frequency Response = 16kHz B_{out} = 32kHz		Deviation Limits=±32kHz Nominal Freq. Res. = 6.4kHz Maximum Freq. Resp. = 32kHz B_{out} = 64kHz	
Channel	Center Frequency (kHz)	Channel	Center Frequency (kHz)	Channel	Center Frequency (kHz)	Channel	Center Frequency (kHz)	Chan.	Center Freq. (kHz)
1A	16								
2A	24								
3A	32	3B	32	3C	32				
4A	40								
5A	48	5B	48						
6A	56								
7A	64	7B	64	7C	64	7D	64		
8A	72								
9A	80	9B	80						
10A	88								
11A	96	11B	96	11C	96				
12A	104								
13A	112	13B	112						
14A	120								
15A	128	15B	128	15C	128	15D	128	15E	128
16A	136								
17A	144	17B	144						
18A	152								
19A	160	19B	160	19C	160				
20A	168								
21A	176	21B	176						
		23B	192	23C	192	23D	192		
				27C	224				
				31C	256	31D	256	31E	256
				35C	288				
				39C	320	39D	320		
				43C	352				
				47C	384	47D	384	47E	384
						55D	448		
						63D	512	63E	512
						71D	575		
						79D	640	79E	640
						87D	704		
						95D	768	95E	768
								111E	896

1. The indicated maximum frequency is based upon the maximum theoretical response that can be obtained in a bandwidth between deviation limits specified for the channel.

   The maximum frequency response represents a modulation index of 1 (N = 1).

   The IRIG standards do not recommend the use of constant bandwidth channels at a modulation index of one because of a decrease in accuracy. For this reason, most constant bandwidth multiplex systems limit the channel data response to a modulation index of two (N = 2).


CHARACTERISTICS
4 POLE BESSEL FILTER
ATTACHMENT B1
PHASE
AMPLITUDE
GROUP DELAY
Y:AMPLITUDE db3
PHASE DEGREES
GROUP DELAY-SECONDS
0
-5
-10
-15
-20
-25
-30
-35
260
240
220
200
180
160
140
120
100
80
60
40
20
4
3
2
1
0
X:NORMALIZED FREQUENCY (Fc)
0.1
1.0
10



CHARACTERISTICS
6 POLE BESSEL FILTER
ATTACHMENT B2
PHASE
AMPLITUDE
GPOUP DELAY
Y-AMPLITUDE db3
PHASE DEGREES
GROUP DELAY-SECONDS
260
240
220
0 200 4
-5 180
-10 160 3
-15 140
-20 120 2
-25 100
-30 80 1
-35 60
-40 40 0
-45 20
X-NORMALIZED FREQUENCY (Fc)
0.1
1.0
10

ATTACHMENT C
RELATIVE AMPLITUDE TABLES f_{dc}'
PROPORTIONAL (PBW) AND CONSTANT BANDWIDTH (CBW) CHANNELS

IRIG PBW CHAN.	CHANNEL CTR FREQ. f_s (Hz)	FM/FM $(S/N)_c$=12db/$(S/N)_d$=40db C_2 = 29		IRIG CBW CHAN.	CHANNEL CTR FREQ. f_s (Hz)	FM/FM $(S/N)_c$=12db/$(S/N)_d$=40db C_2 = 29	
		N = 5	N = 2			N = 5	N = 2
1	400	.006	.022	1A	16	1.86	7.4
2	560	.010	.037	2A	24	2.78	11
3	730	.013	.056	3A	32	3.71	15
4	960	.020	.083	4A	40	4.64	18
5	1300	.033	.132	5A	48	5.57	22
6	1700	.050	.197	6A	56	6.50	26
7	2300	.079	.310	7A	64	7.43	29
8	3000	.117	.461	8A	72	8.36	33
9	3900	.173	.684	9A	80	9.28	37
10	5400	.282	1.11	10A	88	10.2	40
11	7350	.448	1.77	11A	96	11.1	44
12	10500	.765	3.02	12A	104	12.1	48
13	14500	1.24	4.91	13A	112	13.0	51
14	22000	2.32	9.17	14A	120	13.9	55
15	30000	3.69	14.6	15A	128	14.9	59
16	40000	5.69	22.5	16A	136	15.8	62
17	52500	8.55	33.8	17A	144	16.7	66
18	70000	13.2	52.0	18A	152	17.6	70
19	93000	20.2	79.7	19A	160	18.6	73
20	124000	31.0	123	20A	168	19.5	77
21	165000	47.6	109	21A	176	20.4	81
22	225000	75.8	300	3B	32	5.3	21
23	300000	117	462	5B	48	7.9	31
24	400000	180	711	7B	64	10.5	42
25	525000	270	1069	9B	80	13.1	52
25	560000	298	1177	11B	96	15.8	62
26	700000	416	1645	13B	112	18.4	73
27	930000	637	2518	15B	128	21.0	83
A	22000	3.3	13.0	17B	144	22.0	93
B	30000	5.2	20.6	19B	160	26.3	104
C	40000	8.0	31.8	21B	176	28.9	114
D	52500	12	47.9	23B	192	31.5	125
E	70000	19	73.6	3C	32	7.4	29
F	93000	29	113	7C	64	14.9	59
G	124000	44	173	11C	96	22.7	88
H	165000	67	266	15C	128	29.7	117
I	225000	107	424	19C	160	37.1	147
J	300000	165	653	23C	192	44.6	176
K	400000	254	1005	27C	224	52.0	206
L	525000	382	1511	31C	256	59	235
L	560000	421	1665	35C	288	67	264
M	700000	588	2327	39C	320	74	294
N	930000	901	3563	43C	352	82	323
AA	22000	4.6	18	47C	384	89	353
BB	30000	7.4	29	7D	64	21	83
CC	40000	11	45	15D	128	42	166
DD	52500	17	68	23D	192	63	249
EE	70000	26	104	31D	256	84	329
FF	93000	40	159	39D	320	105	415
GG	124000	62	245	47D	384	126	498
HH	165000	95	377	55D	448	147	581
II	225000	152	600	63D	512	168	664
JJ	300000	234	923	71D	575	189	746
KK	400000	360	1421	79D	640	210	831
LL	525000	541	2138	87D	704	231	914
LL	560000	596	2354	95D	768	252	996
MM	700000	832	3291	15E	128	59	235
NN	930000	1275	5040	31E	256	119	470
				47E	384	178	705
				63E	512	238	940
				79E	640	297	1175
				95E	768	357	1409
				111E	896	416	1644

ATTACHMENT D

MODULATION POWER SIDEBAND TABLES

RECEIVER BANDWIDTH (B_c) VS MODULATION INDEX (M)

	M	0.5	1	2	3	4	5	6	7	8	9	10
	Carrier	88.08	58.55	5.01	6.76	15.77	3.15	2.27	9.01	2.95	0.82	6.05
	SB #1	11.74	38.74	66.52	23.0	0.87	21.46	15.31	0.01	11.01	12.03	0.38
	2	0.19	2.64	24.89	47.26	26.51	0.43	11.8	18.17	2.55	4.19	12.96
	3	-	0.08	3.32	19.11	37.01	26.62	2.64	5.58	16.95	6.55	0.68
Percentage	4	-	-	0.23	3.48	15.8	30.61	25.57	4.98	2.22	14.1	9.64
Power in	5	-	-	-	0.37	3.49	13.63	26.22	24.21	6.9	0.61	10.96
Both Side	6	-	-	-	0.03	0.48	3.53	12.08	23.01	22.79	8.35	0.04
Bands	7	-	-	-	-	0.05	0.57	3.36	10.91	20.56	21.45	9.39
	8	-	-	-	-	-	0.07	0.64	3.28	9.99	18.62	20.21
	9	-	-	-	-	-	-	0.09	0.7	3.19	9.24	17.04
	10	-	-	-	-	-	-	-	0.11	0.74	3.11	8.61
	11	-	-	-	-	-	-	-	0.01	0.13	0.77	3.03
	12	-	-	-	-	-	-	-	-	0.02	0.15	0.8
	13	-	-	-	-	-	-	-	-	-	0.02	0.17
	14	-	-	-	-	-	-	-	-	-	-	0.03
	B_c =	$2F_U$	$4F_U$	$6F_U$	$8F_U$	$10F_U$	$12F_U$	$14F_U$	$16F_U$	$18F_U$	$20F_U$	$22F_U$
	Ø Shift	28.70	57.30	114.6	171.6	229.2	287.0	343.8	401.1	485.4	515.7	573.0

NOTES:
1. $M = f/F_m$ (modulation index)
2. Ø Shift = Maximum equivalent phase shift, (M x 57.3) degrees.
3. Bandwidth $2(\Delta f + F_U)$ or $2\Delta f\ (1 + \frac{1}{M})$

F_m = Modulation frequency

F_U = Highest Modulation Frequency

Δf = Total Deviation

ATTACHMENT "E"

Radio Frequency Link Transmission Formula

$$P_t = R_N + S/N + SF + L + PL - G_R - G_T$$

All terms are power levels relative to 1mW into 50 ohms or 0dbm.

P_t = Transmitter Power (dbm)

P_T = Transmitter Power (watts) = $\dfrac{\text{Anti Log } \frac{P_t}{10}}{1000}$

R_N = Equivalent Noise Input Of Receiver

= (-174 + 10 log B + NF) dbm

B_c = Receiver I.F. Bandwidth (Hz)

NF = Receiver Noise Figure

(S/N) = $(S/N)_c$ or $(S/N)_{in}$ = 12db (threshold)

SF = Safety Factor Fade (margin) (20db for 99% signal reception reliability)

L = Miscellaneous losses (polarization, fade, cable losses, VSWR, etc; (6db suggested value)

PL = Path Loss or Attentuation

a = 37 + 20 log f + 20 log d
a = Attenuation in db
f = Frequency MHz
d = Distance in Miles

G_R = Receiving Antenna gain

G_T = Transmitting Antenna Gain

Computation of noise figure when using a pre-amplifier with a receiver:

$$NF = NF_1 + \frac{(NF_2 - 1)}{G_1} + \frac{(NF_3 - 1)}{G_1 G_2}$$

NF = Overall Noise Figure

NF_1 = Noise Figure of Pre-amplifier

NF_2 = Noise Figure of Down Converter

G_1 = Gain of pre-amplifier

NF_3 = Noise Figure of Receiver

G_2 = Gain of Down Converter

All terms for computation must be expressed in power ratios.