A COMPATIBLE DOUBLE SIDEBAND/SINGLE SIDEBAND/CONSTANT BANDWIDTH FM TELEMETRY SYSTEM FOR WIDEBAND DATA

W. O. FROST, F. H. EMENS and R. WILLIAMS
Marshall Space Flight Center
Huntsville, Alabama

SUMMARY

This paper reviews the telemetry problems involved in transmission of wideband phenomena such as shock, vibration, and acoustic measurements. Three approaches to this problem have recently received considerable attention from the telemetry community: SS/FM, DSB/FM, and constant bandwidth FM/FM. The relative capabilities and limitations of these three techniques are discussed and their S/N performance and r-f bandwidth utilization efficiency are compared. An arrangement whereby the three techniques may be flexibly intermixed on a single RF carrier is then described. Examination and consideration of the merits of this arrangement as a future standard telemetry technique is proposed.

INTRODUCTION

A critical problem which now confronts the telemetering community is the perfection of telemetry techniques to efficiently handle rapidly increasing demands for shock, vibration, and acoustic measurements. Although moderately small quantities of wideband data channels have been a typical measuring requirement for well over a decade, in recent years pressures for better methods to transmit these measurements have increased enormously. The sheer physical size of space vehicles such as Saturn certainly calls for more structural dynamics measurements, but other factors are at work as well. The astronomical cost of building a large, complex space vehicle has encouraged the compression of vehicle development programs to a minimal number of developmental flights. Four to six development launch tests are now typical for the large space vehicles, compared to 30 or so for the missile development programs of a few years ago. The dynamicist is thus impelled to measure as many points as possible on each flight, since measurements that would have been delayed until later development vehicles must now be accomplished on early flight tests. Meanwhile, the requirement for man-rating of space vehicles creates an additional critical interest in defining the vibration and acoustic environment of the vehicle as completely and as early as possible.

TELEMETRY TECHNIQUES FOR WIDEBAND DATA

Three telemetry techniques for transmission of wideband data have recently received considerable attention in the telemetry community. These are: 1) SS/FM - Single sideband suppressed carrier AM subcarriers on an FM carrier, 2) DSB/FM - Double sideband suppressed carrier AM subcarriers on an FM carrier, and 3) Constant bandwidth FM/FM - Arrangements of FM/FM channels with uniform response. Each of these techniques has certain capabilities and limitations which are pertinent to its consideration for transmission of wideband data.

SS/FM Telemetry equipment using the SS/FM technique has been developed and utilized in recent years in the Saturn and Titan III programs.[1] This early equipment was designed primarily to meet the requirements for power spectral density analysis. The phase response of individual channels and the uniformity of phase characteristics between channels were not adequate for measurements requiring waveform reproduction or cross correlation analysis. These deficiencies resulted primarily from the techniques used in implementation rather than inherent shortcomings of the SS technique.

Recent development efforts have demonstrated that the technology now exists for SS channels with flat frequency response down to 10 Hz and adequate channel-to-channel phase uniformity for cross correlation analysis. The phase vs frequency characteristic although consistent from channel-to-channel is somewhat nonlinear at low frequencies and may require phase correction networks to allow accurate waveform reconstruction.

An ideal SS channel would provide DC channel response, with a carrier component of fixed phase transmitting the DC information. However, the technology for generating such a signal does not now exist and DC response for SS/FM remains out of reach.

DSB/FM Wideband data channels with DC response and excellent phase characteristics can be provided by double sideband suppressed carrier AM subcarriers on an FM carrier. The advantages of DSB/FM over SS/FM, however, entail a factor of 2 reduction in r-f bandwidth utilization efficiency for equal S/N performance. Successful implementation of telemetry equipment using the DSB/FM technique has been demonstrated in at least one case.[2]

The discussion and comparison of DSB/FM in this paper relate to an alternate implementation, which differs in several respects from that described in reference 2. Major problems involved in design of both SS and DSB equipment are: 1) subcarrier summing, 2) automatic gain control and correction, and 3) derivation and reconstruction of carriers. These problems may be solved in an identical manner for both techniques. A straightforward approach to design of a DSB/FM link is to delete the sideband filtering from the vehicle SS/FM equipment and accomplish a minor modification in the SS demultiplexer which allows it to accommodate both SS and DSB subcarriers. The factor of 2 reduction in data bandwidth capability is then accommodated either by halving the bandwidth of individual channels or by deleting alternate channels. This design concept, which is detailed later, permits a flexible intermixing of SS and DSB subcarriers on an RF link.

Constant Bandwidth FM/FM Arrangements of FM subcarriers with uniform frequency response have been widely used in recent years in ground data acquisition systems. Evaluation of this technique for airborne and vehicle application and a comparison with proportional bandwidth FM/FM arrangements have recently been accomplished, 3 and the newly revised IRIG telemetry standards 4 now include constant bandwidth FM subcarriers. These channels provide the ultimate in data frequency and phase response. They are capable of high fidelity waveform reproduction and can provide time correlation between channels to a few microseconds. In addition, an exchange of frequency response and S/N ratio is available through selection of deviation ratio.

On the other hand, except for rather low deviation ratios, the r-f bandwidth utilization efficiency of CBW FM/FM is comparatively low. In addition, the triangular spectral characteristic of noise at the subcarrier discriminator output seriously handicaps the application of some types of analyses to data transmitted over FM subcarriers.[3]

RF BANDWIDTH UTILIZATION EFFICIENCY

The rapidly increasing usage of telemetry techniques in recent years creates serious concern about the supply of r-f spectral resources for telemetry applications. Critical limitations and restrictions on the future availability of r-f spectrum in the telemetry bands are a likely possibility. In many applications, wideband data accounts for over 90 percent of the total data bandwidth requirements. Consequently, the r-f bandwidth utilization efficiency of potential telemetry techniques warrants careful consideration. Table I compares r-f bandwidth utilization efficiency (ratio of the total summed channel bandwidths to the spectral occupancy of the r-f carrier) for the three techniques under consideration. The comparison is based on a 100 kHz baseband, a peak carrier deviation of ±125 kHz for each technique, and the commonly used approximation that the bandwidth of an FM carrier modulated by a complex signal is two times the sum of the peak carrier deviation and the highest modulating frequency.

TABLE I
COMPARISON OF RF BANDWIDTH UTILIZATION EFFICIENCY

SS/FM	-	10.7%
DSB/FM	-	5.1%
CBW FM/FM:		
$D_f = 1$	-	4.9%
$D_f = 2$	-	2.5%
$D_f = 3$	-	1.6%
$D_f = 4$	-	1.2%
$D_f = 5$	-	1.0%

NOTE: D_f is Deviation Ratio

SIGNAL-TO-NOISE PERFORMANCE

The output S/N ratio of the m th channel of an ideal SS/FM transmission link, which is operating above threshold in the presence of r-f fluctuation noise, is[5]

$$\left(\frac{S_o}{N_o}\right)_{ms} = \frac{S_c}{N_c}\left(\frac{B_c}{B_o}\right)^{1/2}\frac{f_{ds}}{f_{ss}(m)} \quad (1)$$

where S_o/N_o, is the peak data signal to rms noise ratio in the channel output bandwidth B_o resulting from an rms carrier to rms noise ratio equal to S_c/N_c in the effective i-f bandwidth B_c, f_{ds} is the full modulation peak carrier deviation allotted to the channel, and $f_{ss}(m)$ represents the baseband center frequency of the m th channel.

Equation (1) also expresses the output S/N of the mth channel of an ideal DSB/FM link. One may justify this result intuitively by comparing the operation of an SS and a DSB subcarrier channel having identical data channel bandwidth B_o and centered at equal baseband frequency f_{ss}. The two comparison channels are exposed to the same baseband noise density k, but the DSB subcarrier occupies two times the bandwidth of the SS subcarrier. Thus with equal subcarrier levels S_s the S/N ratio at the input to the channel demodulator is $S_s/k\sqrt{B_o}$ for the SS channel and $S_s/k\sqrt{B_o}$ for the DSB channel. This seems to indicate a 3db S/N advantage for the SS subcarrier. However, the DSB demodulator contributes a compensating 3db S/N gain. This gain results because each sideband of the DSB subcarrier has an amplitude $S_s/\sqrt{2}$ which adds coherently with the other sideband to give an output signal level of $2\,(S_s/\sqrt{2}) = \sqrt{2}\,S_s$ while the noise components add rms-wise. Therefore we may conclude that an SS subcarrier and a DSB subcarrier, both having equal magnitudes and equal data bandwidths and subjected to identical noise density environments, produce the same output S/N ratio. Since the carrier modulation is FM for both cases, then Eq. (1) represents the output S/N for DSB/FM as well as SS/FM.

An equivalent expression for the output S/N ratio of a constant bandwidth FM/FM channel is[1]

$$\left(\frac{S_o}{N_o}\right)_{mf} = \frac{S_c}{N_c}\left(\frac{3B_c}{2B_o}\right)^{1/2}\frac{f_{df}D_f}{f_{sf}(m)} \quad (2)$$

where f_{df} is the peak carrier deviation due to the FM subcarrier, f_{sf} (m) represents center frequency of the mth FM subcarrier, and D_f is the deviation ratio of the FM subcarrier. The other parameters are identical to those previously defined for Eq. (1).

To compare the S/N performance of SS/FM, DSB/FM, and CBW FM/FM let us consider three transmission links - one allotted to each of the three techniques. Each link transmits N channels of data of identical bandwidth and uses equal peak total carrier deviation with a linear pre-emphasis taper which is identical for each link. The rms signal level and the r-f fluctuation noise density within the receiver i-f are the same for each link, but the i-f bandwidths required by the three links are not necessarily equal. Under these conditions Figure 1 shows the signal-to-noise ratio $(S_o/N_o)_s$ of the mth SS or DSB channel relative to the output S/N of the corresponding FM channel. The curve for SS/FM, which is taken from Figure 3.6 of reference 1, corresponds to a ratio of base band channel spacing to data bandwidth of $\beta_s = 2$. The equivalent DSB/FM link requires a value of $\beta_s = 4$, which places a given channel at 2 times the baseband frequency of the corresponding mth channel on the SS/FM link. This subjects the DSB channel to an increase in noise density which accounts for the 6db difference in S/N performance. C_s is the crest factor (peak-to-rms ratio) of the data inputs and L represents load factor[1] of the composite multiplex of SS or DSB subcarriers. A typical value for C_s/L in actual operation is 4, and the likely range of variation would be from 2 to 8.

The curves of Figure 1 arenormalized to the signal-to-noise ratio, $(S_o/N_o)_f$, of the comparison CBW FM/FM link. The ratio of baseband channel spacing to peak subcarrier deviation β_f is taken to be 4, the value used for the IRIG constant bandwidth FM/FM standard. One interesting aspect of the data shown on Figure 1 is that subcarrier deviation ratio D_f does not appear in the comparison. This result can be justified by noting that the channel spacing for the FM/FM link is, $\beta_f D_f B_o$. Therefore the channel spacing required for a given data bandwidth Bo increases directly with D_f, and the advantage gained by increasing D_f is exactly offset by the greater noise density at a higher baseband position.

Incidentally, this result illustrates a relationship one may tend to neglect in application of constant bandwidth FM/FM. If the requirement is for a given number of channels of identical data bandwidth, a subcarrier deviation ratio of 1, for example, provides the same S/N performance above threshold as a deviation ratio of 2, insofar as r-f fluctuation noise is concerned, and results in a substantial reduction in r-f bandwidth. In practice, operation at reduced deviation ratio results in some increase in distortion from intermodulation and sideband attenuation, but for many applications operation at low subcarrier deviation ratios should receive serious consideration. The reader should note, however, that the result described above applies to an ensemble of identical FM data channels on a single r-f link. For FM subcarrier operation at a given baseband frequency, an exchange of bandwidth and S/N is available by selection of deviation ratio.

A HYBRID FREQUENCY DIVISION MULTIPLEX ARRANGEMENT

From the preceding discussion of SS/FM, DSB/FM and CBW FM/FM note that each technique offers attributes which are advantageous to the data user, but does not provide all of the transmission capabilities and characteristics he would prefer. For a given wideband data application, assuming equal availability of equipment, the userl s selection of telemetry technique would likely vary with specific requirements and data characteristics. If his interest was mainly power spectral density analyses (and this type of requirement typically covers more than 50 percent of the wideband data demand), his probable choice would be SS/FM in order to minimize r-f power and spectral requirements. On the other hand, if his measurements required DC response and phase correlation over a relatively wide frequency range’, he might select DSB/FM; if his major problem was medium response channels to reproduce waveforms with minimum distortion and high S/N, a constant bandwidth FM/FM link might be the better choice.

Unfortunately in the real world, the typical measuring list includes a variety of wideband data requirements and no one of the three techniques is likely to satisfy the requirements in an optimum manner. A preferred solution would provide a means whereby a choice of technique could be made for each individual measurement. This flexibility of selection is available in the hybrid frequency division multiplexer arrangement described below which allows intermixing of SS, DSB, and FM subcarriers on a single r-f carrier.

Recall that the IRIG standard for CBW FM/FM places subcarriers with ± 2 kHz deviation at baseband center frequencies which are multiples of 8 kHz beginning at 16 kHz. In addition, FM subcarriers with ± 4 kHz deviation may be inserted at multiples of 16 kHz beginning at 32 kHz. Now consider SS and DSB channels which are spaced at multiples of 4 kHz. This spacing, with a comfortable guard band allowance, permits data channel bandwidths of I kHz and 2 kHz for DSB and SS, respectively. If alternate channels are deleted, the channel spacing becomes 8 kHz which accommodates data bandwidths of 2 kHz for DSB and 4 kHz for SS. Likewise, further deletion of intermediate channels to produce a channel spacing of 16 kHz allows DSB and SS channels with data bandwidths of 4 kHz and 8 kHz, respectively. It is readily apparent that this spacing of DSB and SS channels presents the possibility for flexible intermixing of SS, DSB, and FM channels. Table II lists the data channel bandwidth options available in such a hybrid frequency multiplex arrangement.

TABLE II
DATA CHANNEL OPTIONS FOR THE HYBRID MULTIPLEX ARRANGEMENT

	Data Bandwidth (Hz)		
Channel Spacing	4kHz	8kHz	16kHz
SS	2,000	4,000	8,000
DSB	1,000	2,000	4,000
FM (D_f=1)	-	2,000	4,000
FM (D_f=2)	-	1,000	2,000
FM (D_f=3)	-	667	1,333
FM (D_f=4)	-	500	1,000
FM (D_f=5)	-	400	800

Accurate demodulation of the SS and DSB subcarriers requires a means for synchronizing the frequency and phase of carriers at the demultiplexer with corresponding carriers in the transmitting equipment. Also, the insertion of variable premodulation gain allows more efficient utilization of SS and DSB techniques, but requires the transmission of reference information to permit compensating gain adjustments to be made in the receiving equipment. Both reference information requirements can be satisfied by a primary and a secondary pilot tone transmitted with the composite frequency multiplex. The primary pilot tone serves as a frequency, phase, and gain reference. The secondary pilot tone allows the resolution of certain phase ambiguities which are inherent in the carrier reconstruction process.[1] After allowance for the reference tones a 100 kHz baseband will accommodate 23, 11, and 5 channels at a spacing of 4, 8, and 16 kHzrespectively. Some details of the vehicle and ground equipment for the hybrid multiplex arrangement are shown in Figures 2 and 3.

Figure 4 shows the exchange of channel response vs. S/N ratio which is available for a given baseband channel location of a hybrid frequency multiplex with 8 kHz channel spacing and a crest factor/load factor ratio equal to 4. For convenience in comparing the results with more familiar applications, the S/N values have been normalized to SIN ratio for a subcarrier deviation ratio of 5. The dashed portion of the SS-DSB curve represents operation which is possible only with SS at the specified channel spacing. Notice that an FM subcarrier provides better SIN than a DSB or SS subcarrier for data bandwidths less than about 900 Hz.

CONCLUSIONS

Recently, increasing demands for shock, vibration, and acoustic measurements have focused attention upon the deficiencies of present standard telemetry techniques. Further growth in these requirements likely will continue to tax the capabilities of state-of-the-art telemetry designs.

A recent survey by a group of dynamicists6 has contributed to a better understanding of the quantities and characteristics of wideband data channels required for future telemetry applications. Further comprehensive studies of data characteristics and transmission link requirements are critically needed to guide the detailed design of future telemetry equipment.

The hybrid frequency division multiplex arrangement described in this paper offers a versatile exchange of data channel frequency response for S/N ratio. It also permits efficient baseband frequency utilization where the user's requirements include a variety of wideband data. It is proposed that the merits of this arrangement be examined in connection with planning for future telemetry standards.

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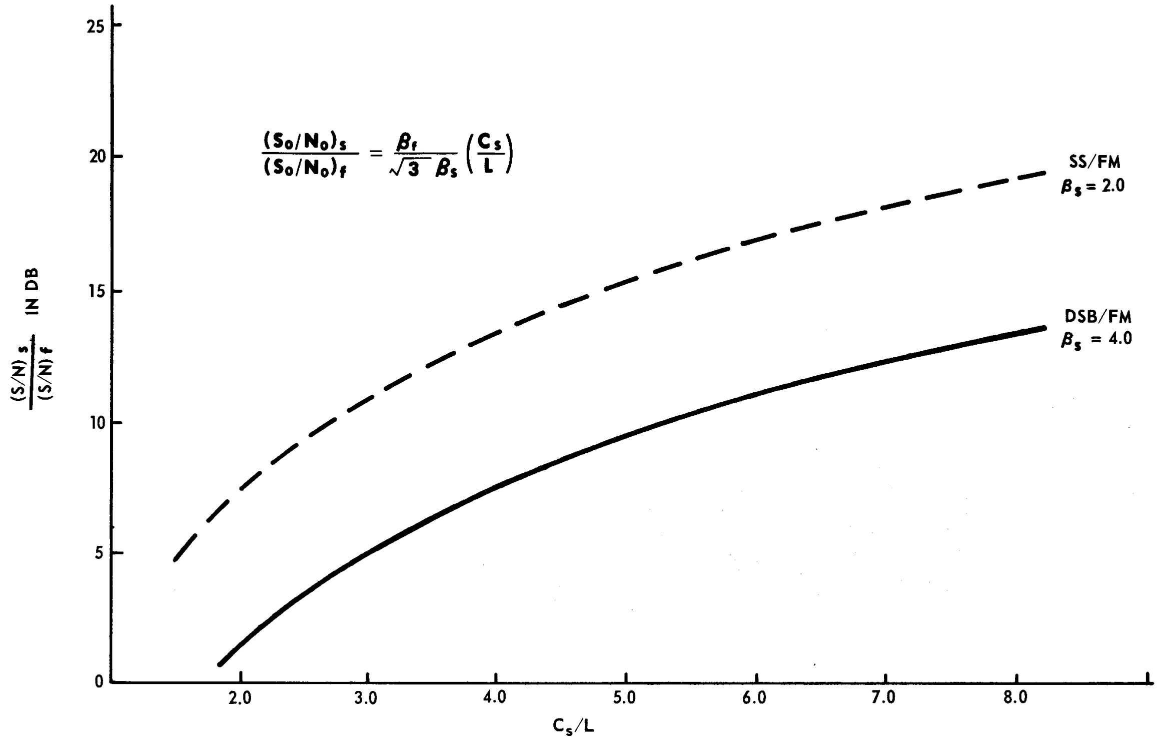

Figure 1. S/N Comparison of SS/FM, DSB/FM, and Constant Bandwidth FM/FM.

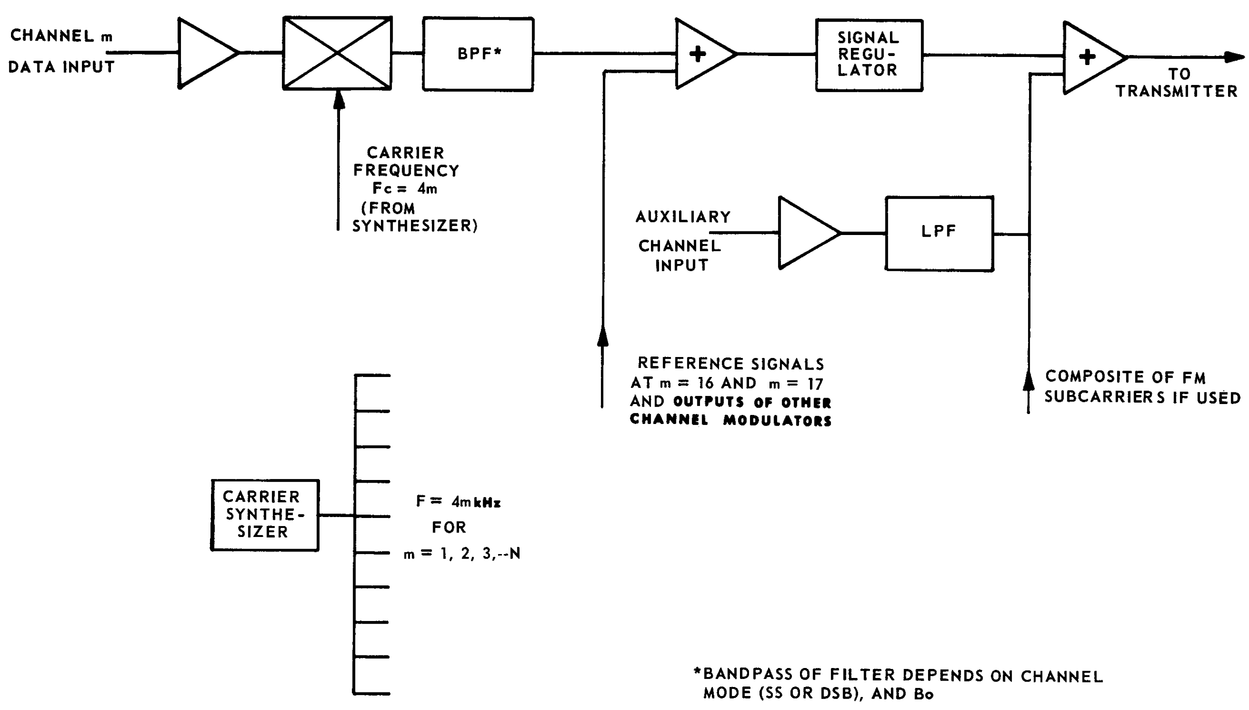

Figure 2. Channel Unit and Common Equipment for SS-DSB Airborne Multiplexer.

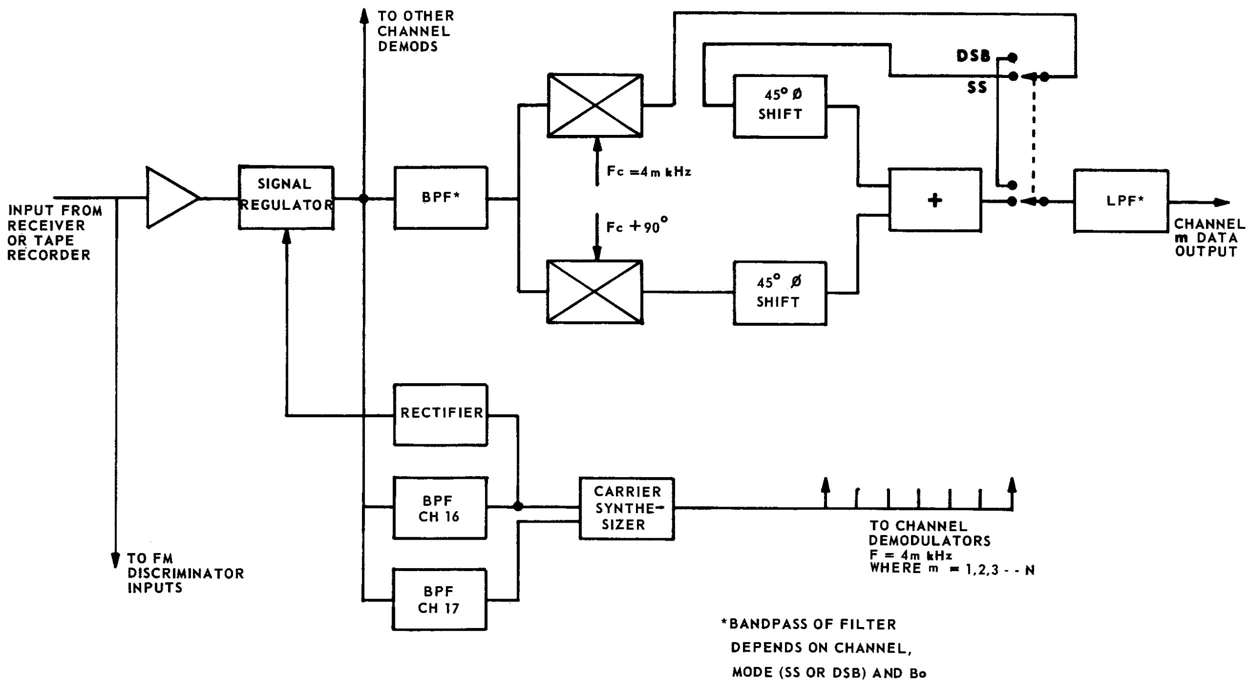

Figure 3. Channel Demodulator Unit and Common Equipment for SS-DS Ground Demultiplexer.

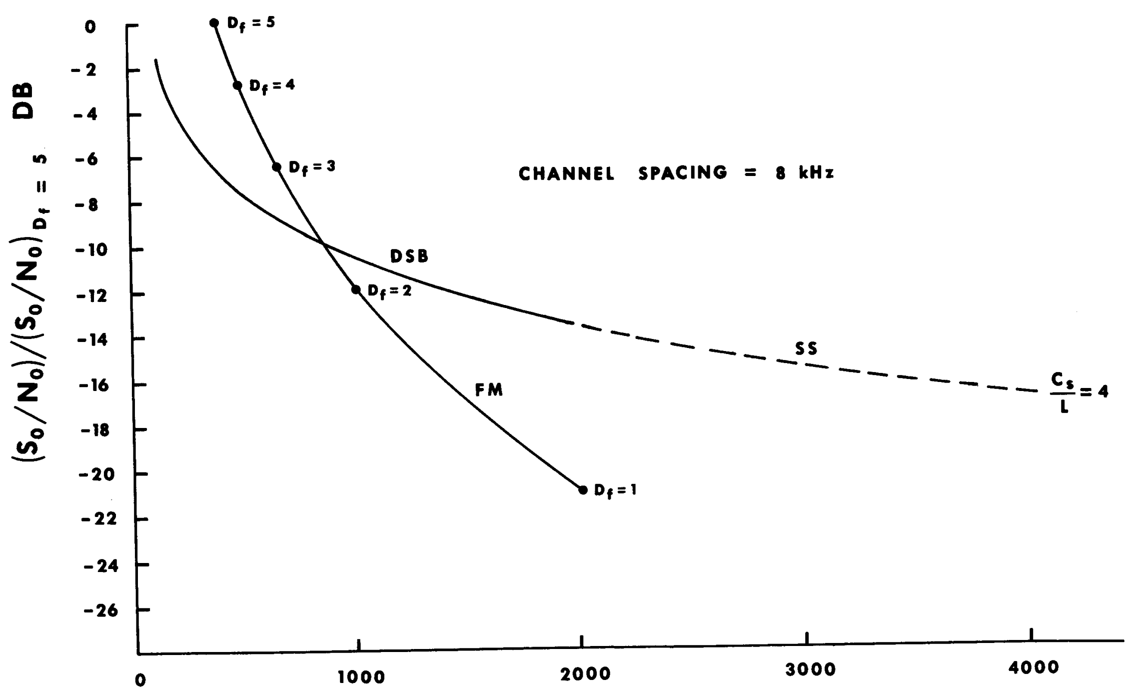

Figure 4. Channel Response vs. S/N Ratio for Given Channel Location