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SS-FM: A NEW TELEMETRY TECHNIQUE

by

Walter O. Frost

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ABSTRACT

A technique new to telemetry is discussed which promises to alleviate an enigma facing the telemetry engineer: How to adequately transmit the avalanche of vibration and other wideband data desired in the development phase of large missiles and launch vehicles. The data channels are stacked in the frequency spectrum as single sideband subcarriers which frequency modulate the RF carrier. The system design utilizes to advantage the statistical properties of vibration data to achieve maximum data transmission efficiency from the available RF carrier deviation. However, in contrast to proposed statistical predigestion techniques, the data is transmitted in raw form.

The background and philosophy of the technique is given followed by a general description of the SS-FM vehicle and ground telemetry equipment to be utilized in the Saturn vehicle program and a summary of system characteristics and performance.

The information contained in this report was presented at the Aerospace Instrumentation Symposium held at the Adolphus Hotel in Dallas, Texas, April 30 - May 4, 1961.

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INSTRUMENTATION DEVELOPMENT BRANCH
GUIDANCE AND CONTROL DIVISION

LIST OF ILLUSTRATIONS

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SUMMARY

A technique new to telemetry is discussed which promises to alleviate an enigma facing the telemetry engineer: How to adequately transmit the avalanche of vibration and other wideband data desired in the development phase of large missiles and launch vehicles. The data channels are stacked in the frequency spectrum as single sideband subcarriers which frequency modulate the RF carrier. The system design utilizes to advantage the statistical properties of vibration data to achieve maximum data transmission efficiency from the available RF carrier deviation. However, in contrast to proposed statistical predigestion techniques, the data is transmitted in raw form.

The background and philosophy of the technique is given, followed by a general description of the SS-FM vehicle and ground telemetry equipment to be utilized in the Saturn vehicle program and a summary of system characteristics and performance.

INTRODUCTION

One of the more difficult problems facing many telemetry engineers today is how to provide adequate transmission capacity for wideband data. This problem usually centers around a relatively small proportion of data channels, as far as numbers are concerned, carrying vibration data. Occasionally, other data problems such as the measurement of sound intensity enter into the picture, but more often the major culprit is vibration data. It has been stated that 10 percent of the data occupies 90 percent of the bandwidth and this is probably a fair statement of fact in many cases. A factor further complicating the situation is that the structural design people are focusing their interest higher and higher in the data frequency spectrum, as it is found that the energy content at higher vibration frequencies is not as insignificant as it was once thought to be.

The wideband data carrying capability of standard telemetry arrangements is very poor. For example the FM-FM system, most often utilized for this purpose, has one channel with a frequency response of 1050 cycles when operated at the standard subcarrier deviation ratio of 5. All other channels have progressively lower standard frequency response down to values below one dozen cycles. In fact, the total data capability of an FM-FM link, determined by summing the frequency responses of all channels is about 4700 cycles.

The basic system characteristic of significance when considering the wideband data transmission problem may be termed bandwidth efficiency; defined as the ratio, expressed in percent, of the total summed data capacity to the RF bandwidth occupied by the system. The bandwidth efficiency of a standard FM-FM system with subcarriers operating at a deviation ratio of 5, as defined in this manner, is 1.6 percent. The same system operated with deviation ratios of one (if one could tolerate the resulting cross-talk) would be approximately 8 percent. The bandwidth efficiency of a 5-bit PCM-FM system is approximately 3 percent. That of a PAM-FM system is about 3.5 percent. Some of the approaches that have been proposed and considered for the wideband data problem (and some of these have been utilized to some extent) are:

(1) Use of the FM-FM system in nonstandard arrangements with subcarrier deviation ratios down to as low as one. This approach, of course, results in loss of the wideband signal to noise improvement of the FM subcarrier and an increased cross-talk problem. In a practical arrangement, bandwidth efficiency of 3 to 5 percent can be attained in this manner.

(2) A second approach that has been proposed is use of PAM-FM. The bandwidth efficiency of this system, as previously indicated, is about 3.5 percent. Some of the problem areas here are (a) necessity of high speed multiplexing of data, (b) risk of aliasing or fold over errors, and (c) the interpolating filter problem.

(3) A third approach proposes the use of so-called predigestion techniques, in which certain data reduction functions are carried out on-board the vehicle. This technique is extremely valuable when a relatively large number of similar tests are to be performed. However, when the number of tests is small and very little is known about the exact nature of the data to be expected, use of this technique

is usually not appropriate. Another difficulty with this technique is that in case of catastrophic failure in the experiment, very little data of transient nature is obtained. Another problem is the difficulty of convincing structural design people that they are getting the information they want by this technique.

THE SS-FM TECHNIQUE

As the concept for the Saturn vehicle took form, it became apparent that the wideband data problem would be especially severe. Even the initial instrumentation studies made it clear that none of the standard telemetry techniques, or even the nonstandard techniques proposed at that time, could handle the problem satisfactorily. One of the factors that made the Saturn problem unique in this respect was the great size and complexity of the vehicle and the attendant large volume of measurements required. Of particular significance was the complexity of the power plant system, which tremendously increased the volume of measurements made. The total number of measurements on stage one alone is approximately 600 with approximately 60 of these being vibration data channels. Other considerations which made the Saturn telemetry problem unique was (1) the small number of R&D tests demanded that the maximum amount of data be gathered from each individual test, and (2) the extremely high cost of individual test vehicles made it imperative not to be skimpy with instrumentation.

Perhaps a contributing factor was the extraordinary degree to which structural design people of the Marshall group had depended upon vibration data for their design analysis in previous design experience with the Redstone, the Jupiter, and the Pershing.

For these reasons, the Marshall instrumentation group was motivated to search for new transmission techniques for wideband data. This search led to the consideration of a transmission technique used for many years in the telephone business; but which, as far as could be determined, had not before been seriously considered for telemetering. This technique consists of single sideband subcarriers modulating an FM carrier.

A literature search revealed studies reported by Landon[1] in 1948 indicating such a system possessed characteristics which should make it ideal for wideband data. Incidentally, the designation SS-FM was originated by Landon (questions have arisen on several occasions regarding the designation SS rather than SSB for single sideband).

An analytical study program was performed to determine how an SS-FM system should perform in comparison with other telemetry systems. The results of this study along with a conceptual system design was reported at a National Symposium in the Fall of 1959[2]. These studies indicated that the bandwidth efficiency of such a system should be about 15 percent, or roughly four times the value of any available technique. It indicated the system should be capable of transmitting 45 kc of data in the identical bandwidth of an FM-FM link. In fact, the bandwidth efficiency of the technique should be higher than that of any system using FM modulation of the final carrier with the exception of one. This one exception requires simultaneous record and playback capability on the vehicle and definitely appeared to be beyond the state-of-the-art at that time.

Next, it was necessary to consider the signal-noise performance of such a system. Since single sideband subcarriers do not possess wideband gain, one would logically expect that SS-FM would perform less favorably in this respect than FM-FM; probably by a factor equal to $\sqrt{3}$ times the deviation ratio, which is the wideband gain of the FM subcarrier. However, if the modulating signal of such a system is vibration data, other factors which enter the picture can more than compensate for the loss due to lack of wideband gain in the subcarrier.

These compensating factors result from a priori knowledge of the nature and characteristics of vibration data. These factors will be considered in some detail later, but first the basic modulation process of SS-FM will be discussed.

Figure 1 represents one channel of a SS-FM system. In a complete system additional channels, which are identical except for frequency location in the baseband, would be linearly summed together before being applied to the FM transmitter modulation input. Each channel undergoes a linear transposition in the frequency domain to its assigned location in the baseband. In an ideal system, the amplitude and phase characteristics of the data would not be altered in this transformation, only the frequencies would be changed. For example, channel one might modulate the transmitter directly, while channel two is transposed to 5 kc, channel three to 10 kc, etc. Now consider the composite signal amplitude that exists at the transmitter input. This signal is proportional to the RMS summation of the signal amplitudes of all data channel inputs. Since the transmitter FM deviation is proportional to the amplitude level at this point, the transmitter RMS deviation is dependent on the data amplitude levels in the channels. If the data channels are all inactive, the carrier is unmodulated.

Recognizing that this modulating signal will be vibration data, consider the nature and characteristics of vibration data. Figure 2 shows amplitude density distribution plots of vibration data gathered on the Saturn vehicle during one of its recent static test firings. Lines that are superimposed represent gaussian curves with one-sigma values identical to that of the data. It would appear from these plots that the gaussian or normal curve represents a fair estimate of the amplitude distribution characteristics of such data. Since the summation of gaussian functions is a gaussian function itself, we would expect the composite signal modulating the transmitter in an SS-FM system carrying vibration data to resemble a gaussian function.

Now, return to those compensating factors which make up for the loss of wideband subcarrier gain in comparing the SS-FM and FM-FM systems.

The peak-to-peak amplitude of the data applied to an FM subcarrier must be limited to the band edges of the subcarrier channels. That is to say, the deviation of the subcarrier frequency must be restricted to $\pm 7\frac{1}{2}$ percent or ± 15 percent of center frequency to prevent adjacent channel interference. This means that when data possesses a high peak-to-RMS ratio, the signal capacity of the channel is reduced below its capacity for a sine wave modulating signal, which has a relatively low peak-to-RMS factor of 1.41. If we assume a peak-to-RMS ratio of four, which is often used when referring to gaussian data, the reduction in RMS data capability is 2.83. For a peak factor of three, the reduction is approximately 2.1.

This inherent peak data restriction that applies to FM-FM does not exist in the SS-FM system. The signal inputs of the several channels are summed RMS-wise to form the composite signal modulating the transmitter. The data peaks of the individual channels add in a random manner resulting in an amplitude distribution of the composite signal similar to that of the data at the channel inputs and having a peak factor of approximately the same magnitude. This means that for data with gaussian type characteristics and an identical number of channels the SS-FM system will accommodate two or more times as much peak carrier deviation per channel as an FM-FM system.

An additional point should be mentioned at this time. Not only is there no inherent peak limitation on each channel in an SS-FM system, but also there is no basic RMS limitation on individual channels as such.

Rather, the limitation exists on the RMS summation of the total channels. It must be ascertained that this composite RMS summation does not cause the RMS deviation capability of the RF transmitter and its associated RF channel to be exceeded. Certainly, this criteria would need to be applied with discretion. For example, if all of the channels were inactive except the uppermost channel, which contributed all of the RF carrier deviation, we should ascertain that the significant sidebands of this channel did not fall outside the receiver IF bandwidth. This is a very important characteristic of the SS-FM system, and means of exploiting this characteristic will be pointed out later.

Another characteristic of vibration data that is of importance is the RMS amplitude as a function of time. Typically, and this applies uniquely to the missile or launch vehicle case, the outputs of the vibration pickups are relatively inactive until the firing command. At this time, the level of activity begins to rise as the combustion process builds up, and activity reaches a peak as the vehicle is about to rise from the pad. Soon after lift off, the channel activity reduces to a relatively constant level somewhat below this peak. The primary reason for maximum activity of the vibration channels at this time is excitation of the structure of the vehicle by sound reflections from ground and surrounding objects. Later during the test, after burn out a further reduction in vibration channel activity occurs during the coast phase.

Another consideration is that correlation exists between RMS variations in channel activity of the separate channels; however, this correlation is not perfect and contains a time delay. Also the human factor must be considered; the tendency of the engineer who requests a measurement to over estimate the range required. He always adds a little safety factor, the result being that the required range is over estimated many times more often than it is under estimated.

Now, since the probability that all channels will be simultaneously active to their maximum capability is very remote, if the deviation sensitivity of the system is adjusted on the basis of all channels being fully active, the full deviation capability of transmitter will never be utilized. The possibility exists, then, to determine for a specific application, something that might be called a statistical weight or loading factor which defines the expected maximum RMS combined activity of the channels. The individual carrier deviations of the channels may then be increased by this factor to make more efficient use of the available RF carrier deviation.

Examination of vibration data gathered during firings of the Redstone and Jupiter missiles indicate that a weight factor of two is suitable for missile and launch vehicle applications. This means the channel carrier deviation, determined on the basis of all channels being simultaneously fully active, may be doubled with a small probability of over deviating the RF transmitter. Of course, when operating on this basis, the possibility exists of inadvertently over deviating the transmitter. However, a limiting device which protects the transmitter from over deviation, and still does not seriously impair the data, is fairly easy to implement.

Now, consider the signal/noise performance of an SS-FM system. Let us inject into the analysis the additional factors discussed based on a priori knowledge of the nature and characteristics of the data we are dealing with.

Figure 3 compares the S/N performance of the SS-FM channels of 3 kc data bandwidth with the performance of a 70 kc FM-FM channel deviated ± 15 percent and carrying the same data. The assumptions for curve "A" are as follows:

(1) The data has a gaussian characteristic and it is desired to transmit peaks that are 4 times the RMS value.

(2) The system application permits a loading or weight factor of 2.

(3) The number of channels are identical for both systems.

(4) The RF considerations are the same. That is, peak carrier deviation, RF transmitter power, receiver bandwidth and sensitivity, and carrier frequency are all identical.

(5) No preemphasis is used for either system. The basic reason for this last assumption is that a common preemphasis setting optimum for either system would be impossible to attain. Therefore, rather than penalize either system, the assumption of no preemphasis is used.

The horizontal scale represents location of the single sideband channel in baseband frequency. The vertical scale represents the S/N advantage of a specific single sideband channel. The S/N advantage of a channel centered at 70 kc would be 2.5 db. An SS channel low in the baseband, centered say at 3 kc, has an advantage of approximately 30 db over the reference channel. Note also the 6 db per octave deterioration because of the Δnoise spectrum as baseband frequency increases.

Curve "B" represents a somewhat more conservative assumption with the loading factor equal to 1.5 instead of 2; or a data peak-to-RMS ratio of 3 instead of 4. This curve lies 3 db below curve "A."

Another improvement in S/N ratio not reflected in this graph is available in an SS-FM system. Under the assumptions that have been stated, the rated maximum carrier deviation is reached only when the combined activity of the channels is at a maximum. As discussed previously, this occurs in the case of missiles and launch vehicles one time during the test or at about lift off. For the remainder of the test, the transmitter would be deviated below its maximum value. Let us consider some methods of taking advantage of this surplus unused deviation. For example, a reduction in the scale factor of the measurements could be programed to occur; say, 20 or 30 seconds after lift off. Reduction of scale factors on all channels simultaneously may be conveniently accomplished by a step increase in gain of an amplifier preceding the FM modulator. This change of gain in effect modifies the deviation sensitivity of the transmitter. However, a more attractive possibility is to apply AGC to the amplifier preceding the modulator in such a manner that the deviation of the transmitter is kept approximately constant near its maximum permissible value. A value representing the gain of the airborne amplifier is also telemetered and used for scale correction in the ground equipment. Thus, automatic deviation control is attained, and in effect, an adaptive telemetering system results. Using this technique should result in optimum S/N performance under all channel conditions. The Saturn SS-FM system utilizes this technique and comments will be given later on how it is implemented. Just exactly how much S/N improvement may be achieved by ADC (automatic deviation control) is dependent on data channel activity conditions existing during a test. However, it is easy to imagine conditions that could result in 10 or 20 db improvement. Note that in a missile or launch vehicle, this improvement occurs during the later phases of a test when it is most needed, and is at the expense of performance during the early phase of the test when S/N ratio is plentiful.

Next, consider the implementation of an SS-FM system. As one would expect in the implementation of a new technique, many problem areas exist. As engineers who were engaged in the field ten years ago will recall, many difficult problem areas existed in implementation of early FM-FM systems. We might add that PCM people are struggling through a similar phase of development today. Let us consider some problem areas in the implementation of SS-FM.

Single sideband subcarrier multiplexers have been widely used in telephone type carrier equipment for many years. However, the size and weight inherent in this equipment prevents the use of similar designs for airborne and space vehicle applications. The typical telephone carrier terminal occupies several standard equipment racks. Much of the weight and size of telephone equipment is attributable to the band-pass filters required. These filters must be capable of discriminating between the lowest frequency of the upper sideband and the highest frequency of the lower sideband. This requires excellent skirt selectivity and a relatively large number of filter sections if the conventional LC approach is taken. In the conventional single modulation process, the frequencies of these filters are the same as the baseband frequency and extend down into the audio range. The combination of many sections and low frequencies result in considerable volume and weight in the filters.

The filter size problem may be overcome by using a double modulation process and accomplishing the filtering at a higher intermediate frequency. Using this technique, the filtering may be accomplished at a frequency where special filtering techniques such as crystal and magnetostrictive filters are practical.

Another problem area in implementing SS-FM is subcarrier frequency stability. The typical approach in telephone carrier equipment has been low frequency crystal oscillators. Crystal oscillators in the required frequency range for a single modulation technique are quite large and also unable to withstand shock and vibration. Once again the double modulation process provides a solution, because it requires an oscillator at the IF rather than the baseband frequency, where rugged crystals are difficult to attain. However, the frequency stability problem remains. The crystals could be enclosed in an oven at the expense of size and considerable power dissipation, but probably the better solution is a locked airborne and ground system which contains one crystal oscillator located in the airborne system. The airborne subcarriers in this system are synthesized from the crystal oscillator. A pilot tone is transmitted to ground and a similar synthesizing process is used to rebuild the subcarrier frequencies.

Another system problem is linearity of the modulation and demodulation process. The problem presented by the single sideband modulators is not severe. However, nonlinearity in the FM transmitter is a definite problem, the SS subcarriers possess no wideband gain; therefore, an ultra-linear characteristic in the FM transmitter is the only solution. This factor probably deteriorates the performance of the SS-FM system more than any other. The best performance that has been obtained to date with available transmitters is an intermodulation level of about 40 db - 45 db which is equivalent to 1 percent distortion.

Recording of SS-FM data presents another problem. Since the output of the FM demodulation process, the SS subcarriers, occupies the spectrum below 100 kc, they may be tape recorded direct as are FM subcarriers. However, as is well known the standard instrumentation tape recorder possesses a not so admirable amplitude characteristic and the data is deteriorated considerably by this mode of recording. In the Saturn system, we are attempting to overcome this problem by using an AGC reference on the standard FR-100 tape machine. A workable but rather unwieldy approach is demultiplexing the channels in real time and use of separate FM record tracks for the individual channels. However, it is believed the optimum solution to this problem is predetection recording.

Compatibility with present ground telemetry facilities is always a consideration with new telemetry techniques. SS-FM stands up quite well in this respect. The equipment required in addition to standard FM-FM ground equipment is the single sideband channel demodulation system. For the Saturn system, the additional ground equipment occupies about 30 inches of standard rack space.

Figure 4 is a generalized block diagram of the SS-FM system as implemented for the Saturn vehicle. The data capability of the system is fifteen channels, each having a response of approximately 30-3,000 cycles. The data and a 455 kc carrier are applied to a balanced modulator. This modulator forms a double sideband suppressed carrier signal. The upper sideband, extending from 455-458 kc, is selected by the bandpass filter, while the lower sideband is rejected. The output of the BPF is the data transposed in the frequency domain. This signal is applied to a second modulator together with a second carrier. The frequency of this second carrier is chosen to place the lower sideband at the desired frequency location in the channel baseband. The upper sideband is located at about a megacycle and is removed by a simple filter.

Note that the two modulators and the BPF needed to translate a channel of data to the baseband frequency location are identical in each of the fifteen channels. Only the frequency of the carrier into the second modulator determines baseband channel location. The vehicle system contains fifteen identical channel units. Figure 5 shows a more detailed block diagram of a channel unit.

The carriers required by the channel units are generated by the frequency synthesizer or carrier supply. The sixteen carriers are synthesized from a 910 kc crystal oscillator. A 75.83 synchronizing signal, also derived from this oscillator, is transmitted along with the data. In the demodulating equipment this 75.83 kc signal is used to resynthesize the carriers required for demodulation. This signal performs an additional function which will be described later. Figure 6 is a block diagram of the carrier supply.

The amplifier preceding the RF transmitter in figure 4 performs several functions: it sums or mixes the several channels; it filters away the upper sidebands of all the second modulators (these sidebands are in the vicinity of one megacycle); and it performs the ADC function described previously. The circuit blocks required to accomplish these functions are shown in figure 7. Note that variations in the gain of this amplifier due to the action of the ADC loop changes the received amplitude of the 75.83 kc synchronizing signal (or pilot). These amplitude variations are detected in the ground demodulation equipment and are used to reinsert the gain variations of the ADC, so that the overall system gain is constant.

Figure 8 illustrates the vehicle SS-FM system. The overall size is 10 x 10 x 9 inches. The upper portion of the assembly contains a 2 watt RF transmitter. An RF amplifier located external to this assembly raises the RF power level to 30 watts into the antenna system.

The ground demodulation equipment is illustrated in figure 9. Essentially, this equipment accomplishes the reverse frequency transpositions from those accomplished in the vehicle system. The carriers required are synthesized from an oscillator phase locked to the 75.83 synchronizing signal from the vehicle system. An amplifier preceding the phase-locked loop is AGC controlled so that the amplitude of the 75.83 signal at the output is constant; this restores the gain variations inserted by the ADC in the vehicle equipment.

Figure 10 compares the frequency response characteristics of an SS-FM channel with IRIG channels 18 and E. Note that the SS-FM channel characteristic rolls off at low frequencies, cuts off rather sharply at about 3 kc, and has a ripple in its characteristic. This ripple is due to the mechanical filters used in implementing the system.

Amplitude accuracy of the system is 5 percent; most of the error results from the filter passband ripple. The phase characteristic of mechanical filters is also very poor. However, this is of little consequence when transmitting vibration data, because evaluation consists mainly of spectrum and amplitude distribution analyses. Figure 11 shows an amplitude distribution plot of noise after transmission through the SS-FM system.

Several possibilities exist for flexible telemetry arrangements using SS-FM techniques. For example, on some of the Saturn R&D tests, SS-FM channels will be combined on the same carrier with low bit rate (25.2 kilobits per second) PCM-FM. PCM will occupy the baseband spectrum below 25 kc while approximately 10 SS channels are stacked in the 25-75 kc spectrum. Similarly, FM subcarriers and SS channels may be combined on the same carrier.

A composite telemeter in which two unlike systems are combined in the frequency domain does not suffer from many of the complexities that beset two systems combined in the time domain. After reception and carrier demodulation the two signals are separated by simple filtering techniques and routed to the respective ground stations which are identical to the arrangement for transmission on separate carriers. No synchronization between the two systems is necessary.

CONCLUSION

The SS-FM telemetry technique is being utilized on the Saturn vehicle to overcome the problem of providing adequate transmission capability for wideband data. The data channels are first stacked in the baseband frequency spectrum as single sideband subcarriers and then frequency modulate the RF transmitter. The system design uses an adaptive technique and utilizes to advantage the statistical properties of vibration data to achieve maximum data transmission efficiency from the available RF carrier deviation.

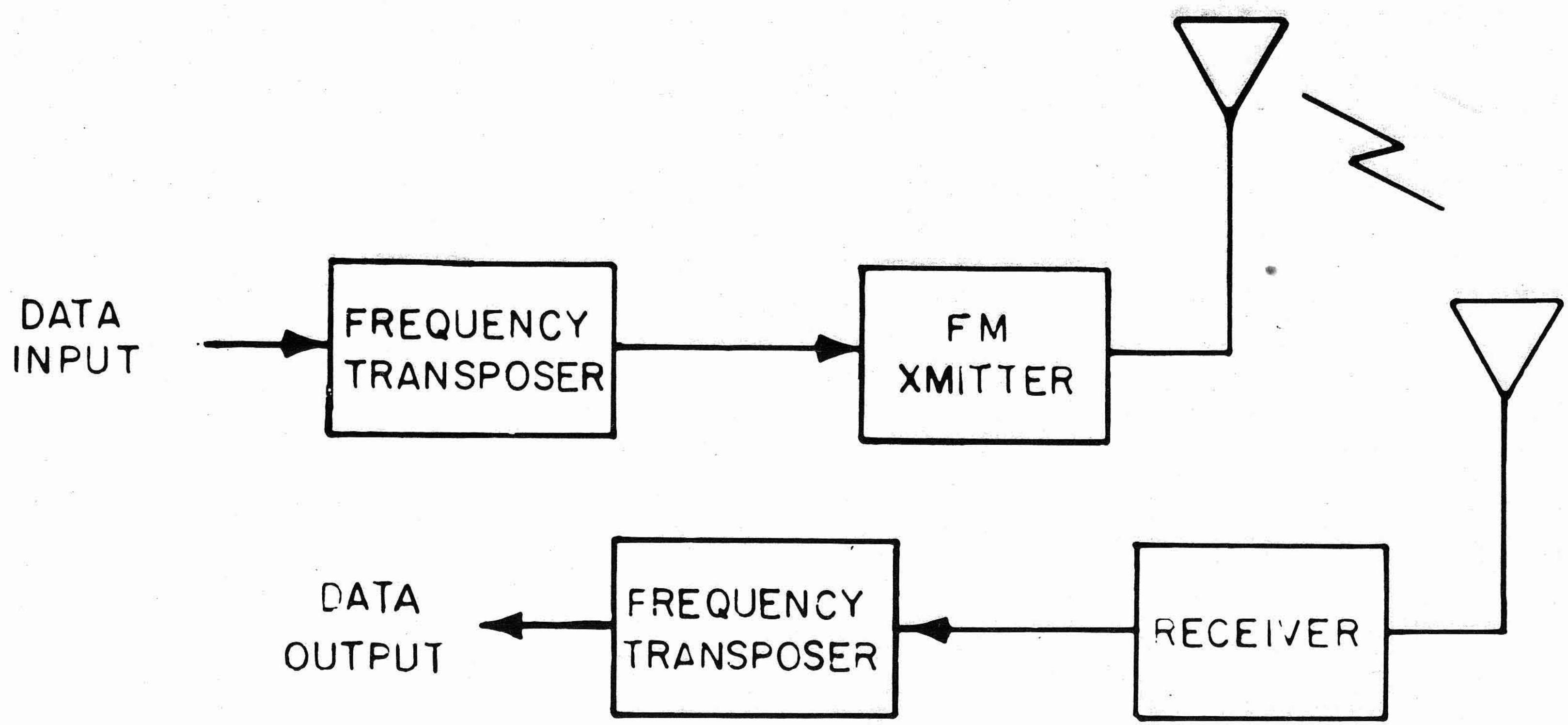

FIGURE 1. SS-FM DATA CHANNEL

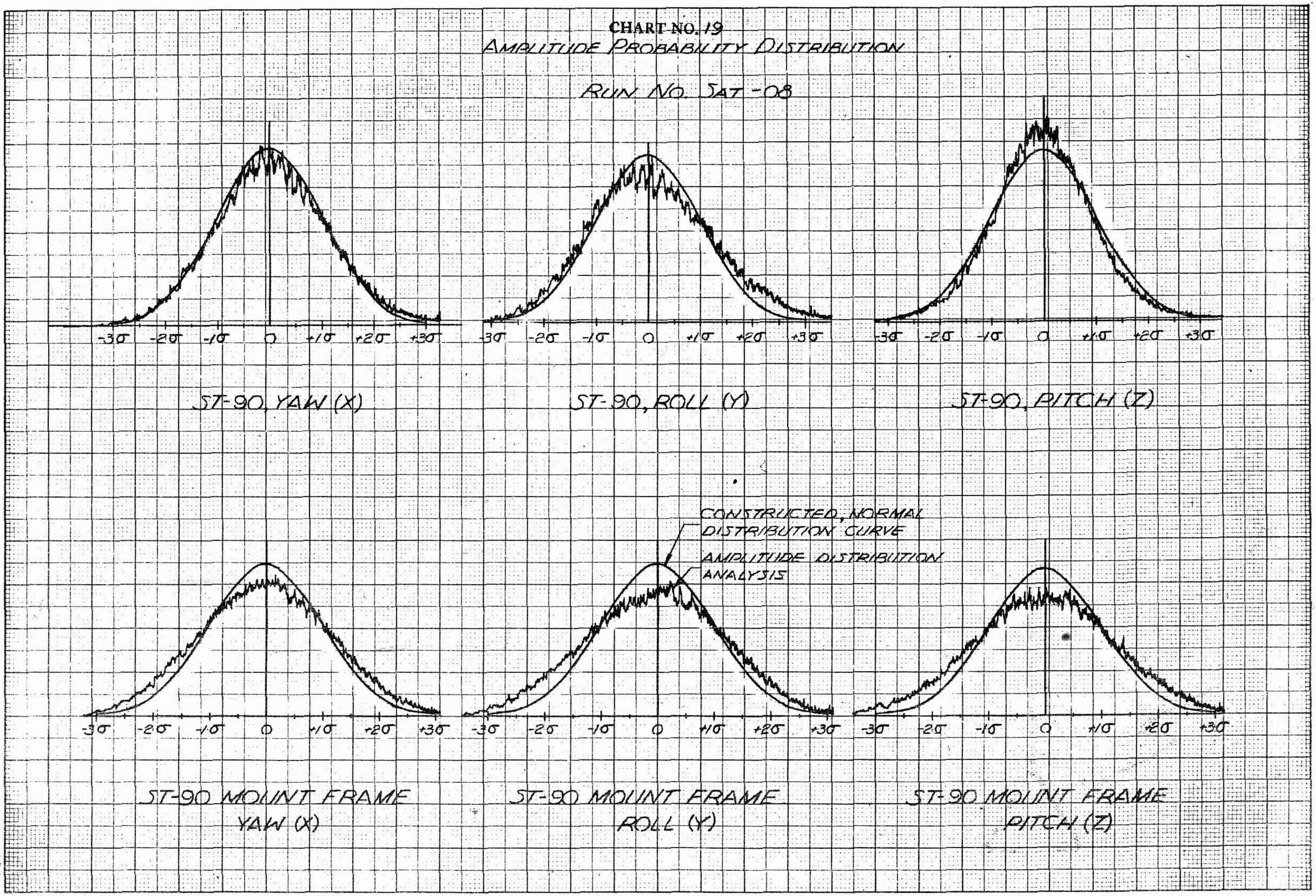

FIGURE 2. DATA FROM SATURN STATIC FIRINGS

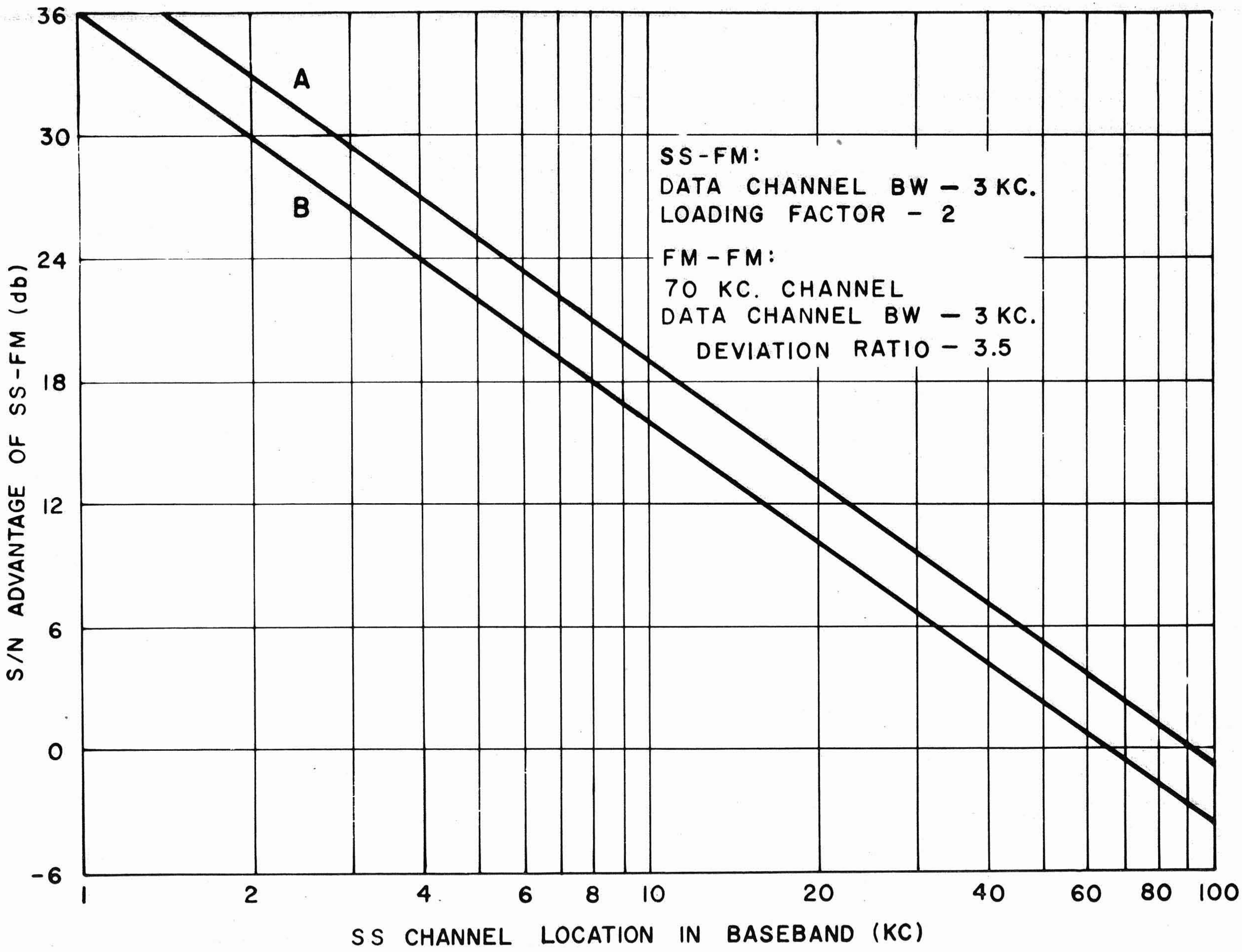

FIGURE 3. S/N COMPARISON OF SS-FM AND A REFERENCE FM-FM CHANNEL 15

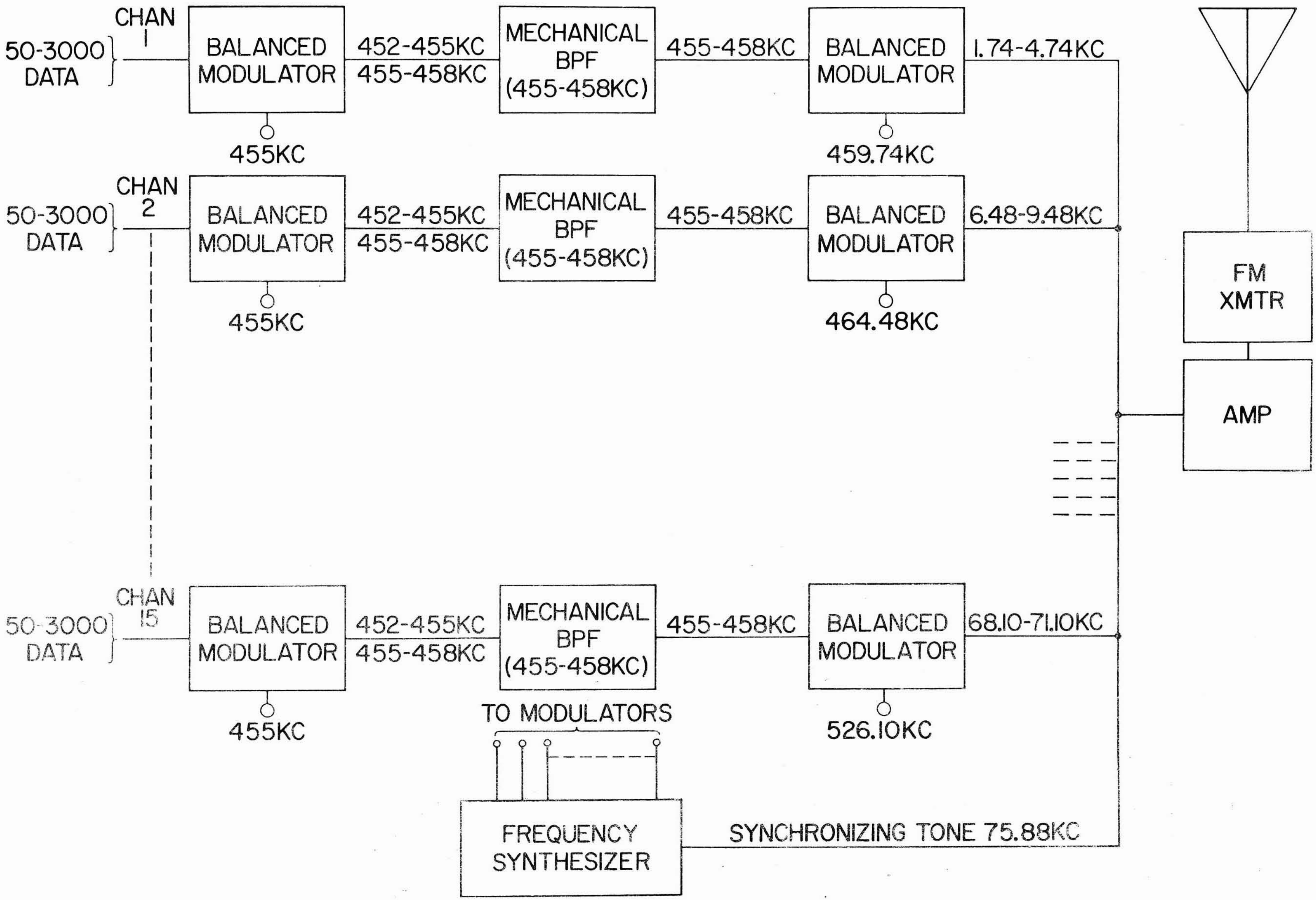

FIGURE 4. SS-FM TELEMETRY SYSTEM FOR VIBRATION AND OTHER WIDEBAND DATA

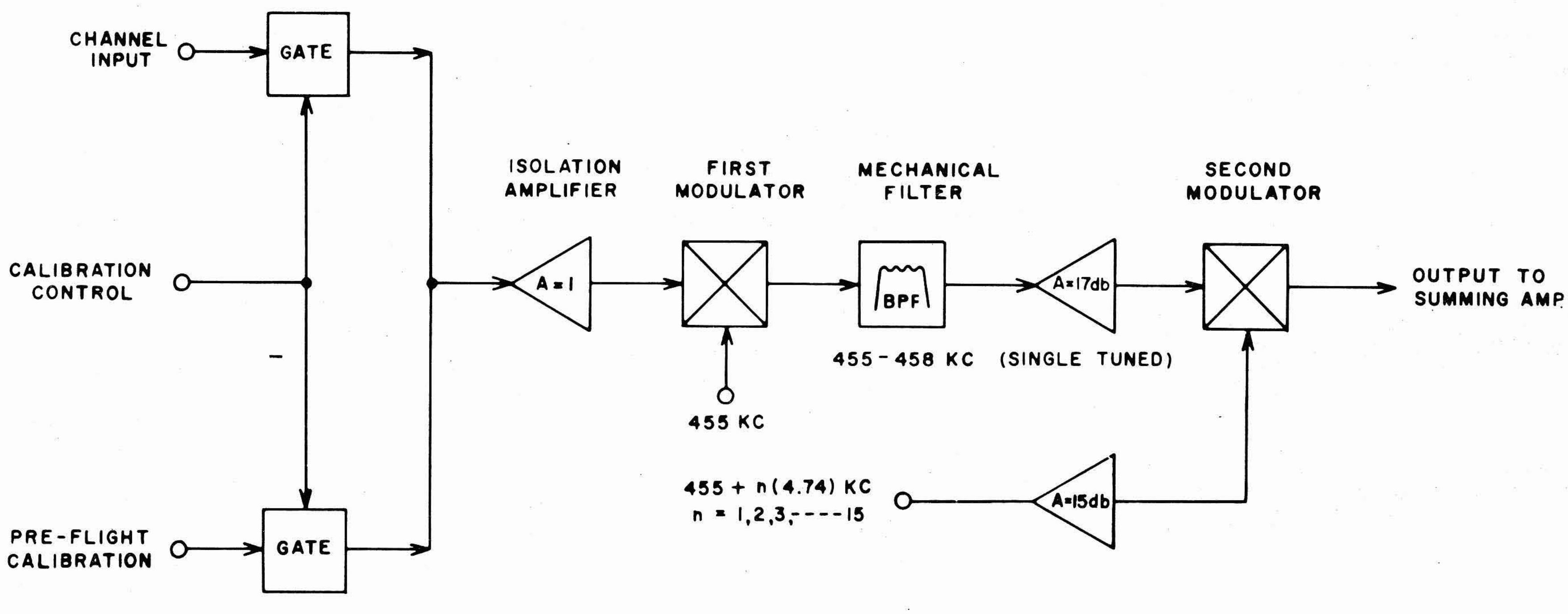

FIGURE 5. BLOCK DIAGRAM - VEHICLE CHANNEL UNIT

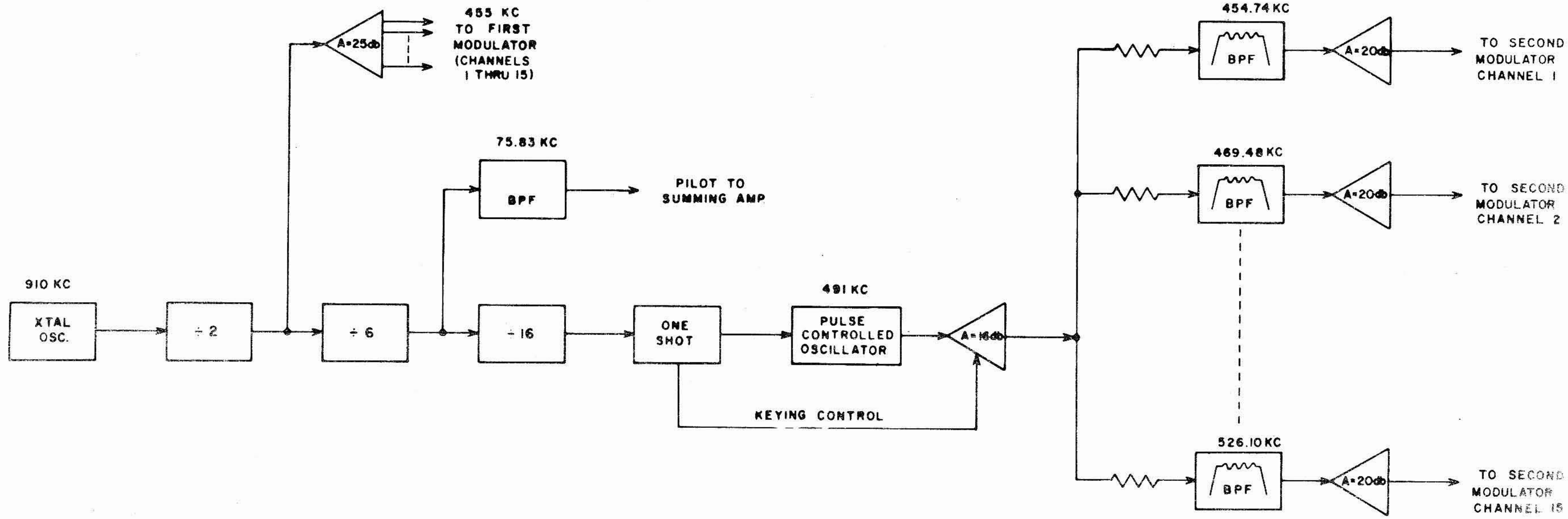

FIGURE 6. BLOCK DIAGRAM - VEHICLE CARRIER SUPPLY

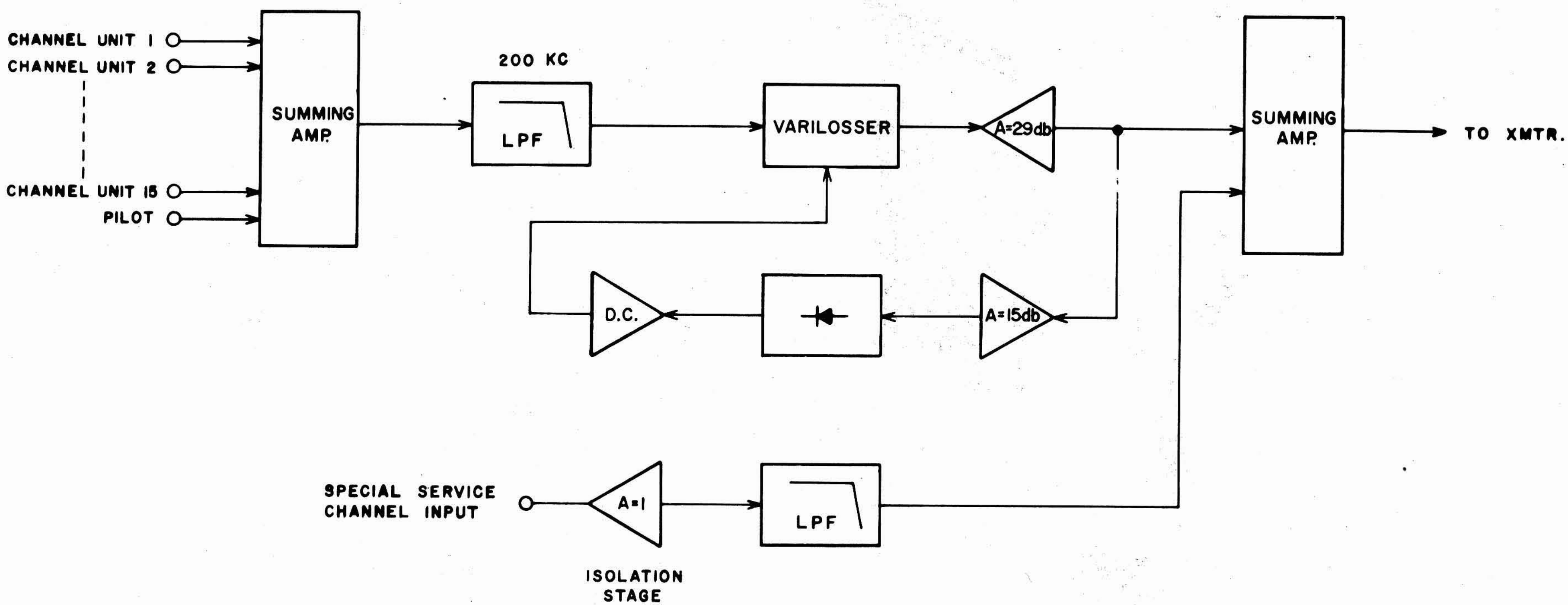

FIGURE 7. BLOCK DIAGRAM - VEHICLE COMMON EQUIPMENT

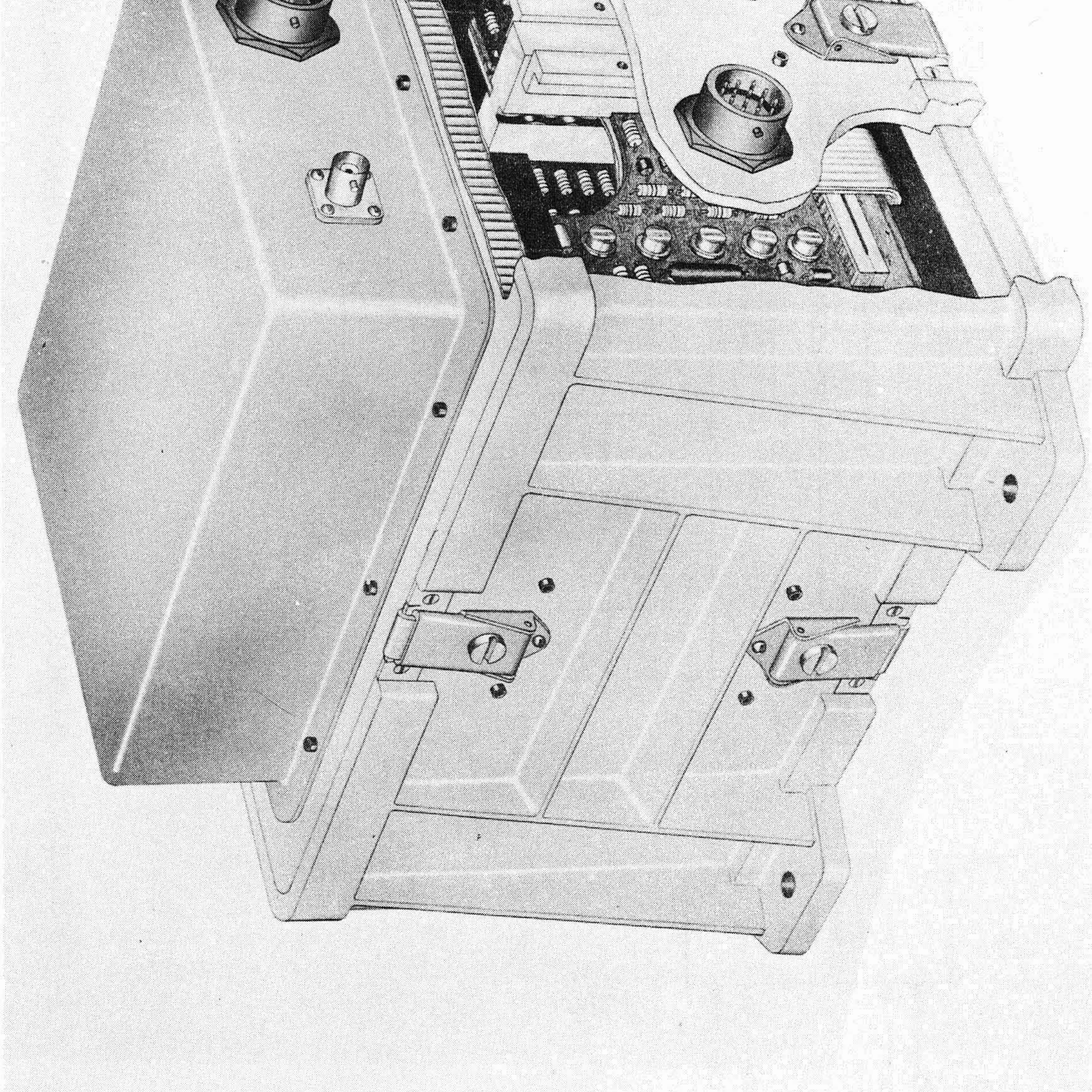

FIGURE 8. SATURN VEHICLE SS-FM SYSTEM

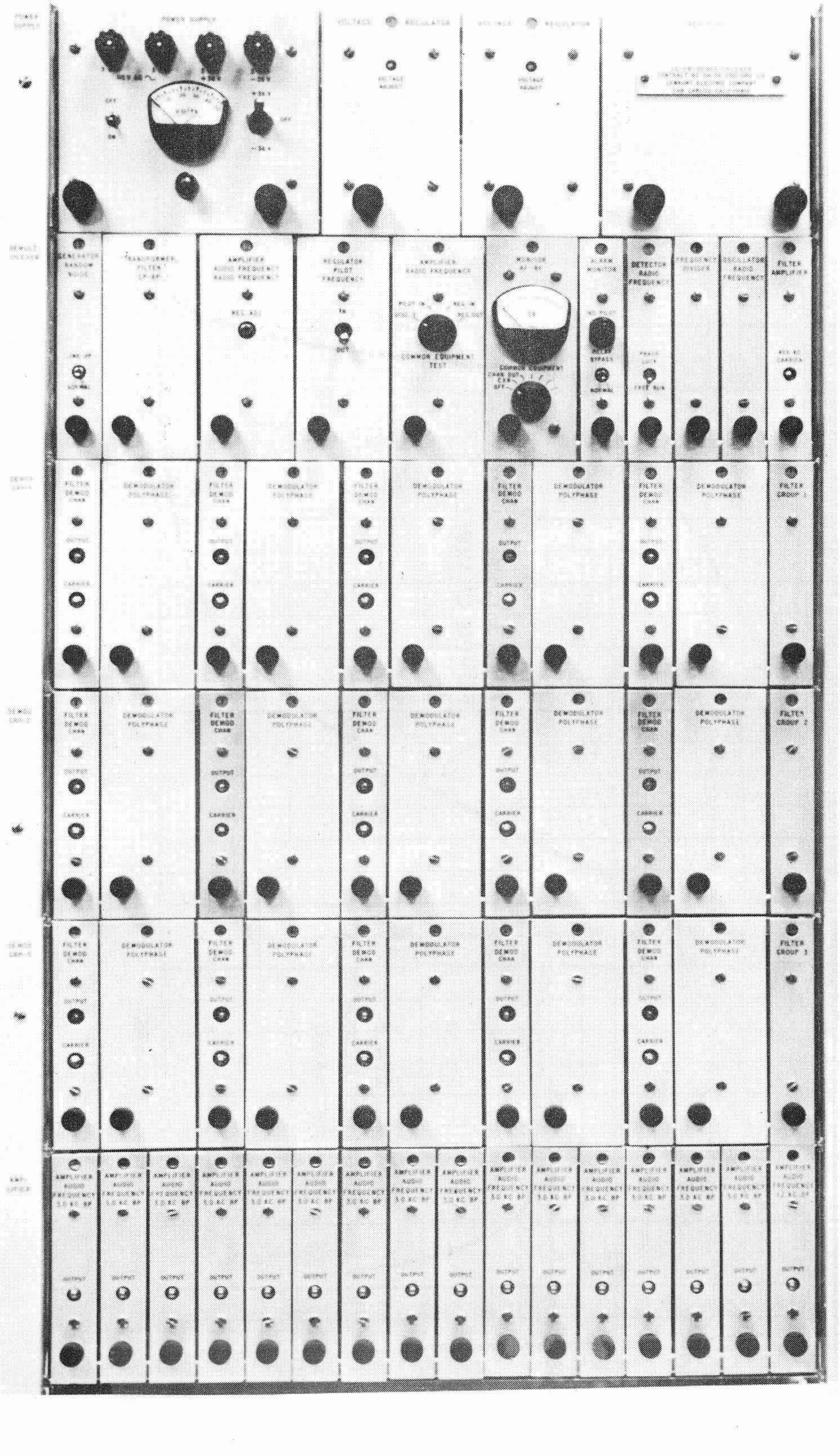

FIGURE 9. SS-FM DEMULTIPLEXING EQUIPMENT

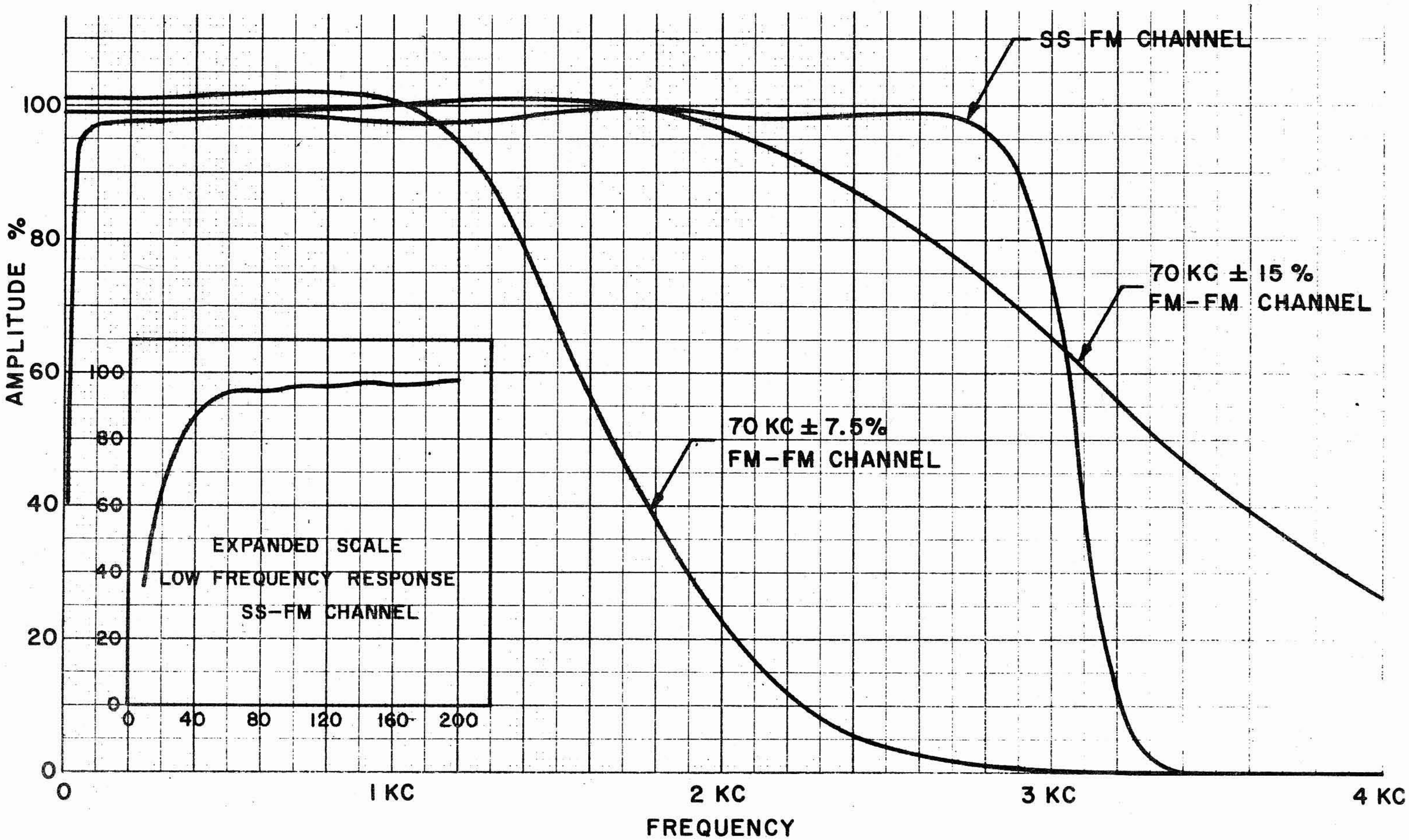

FIGURE 10. SYSTEM FREQUENCY RESPONSE COMPARISONS

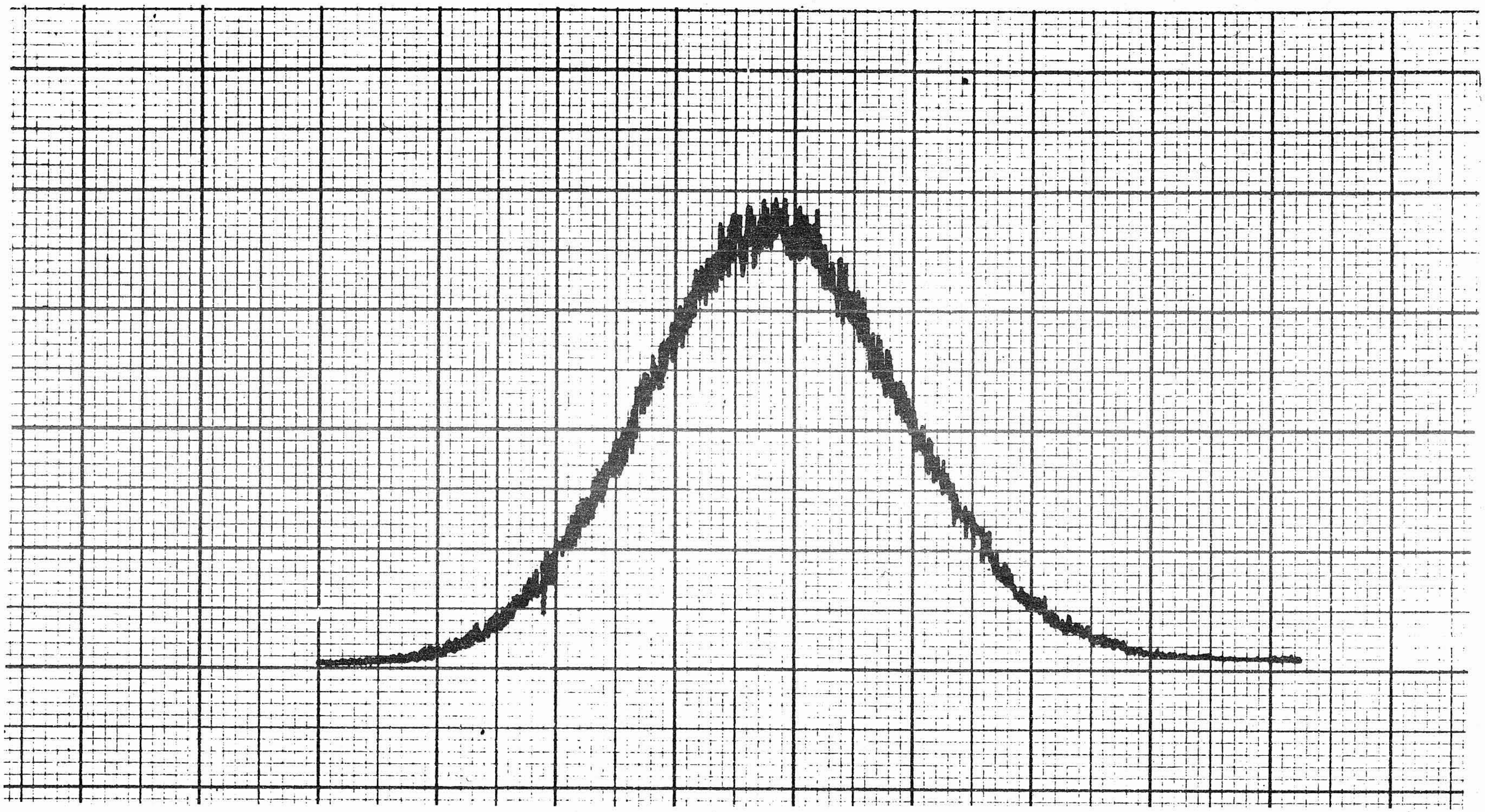

FIGURE 11. AMPLITUDE DISTRIBUTION OF WHITE NOISE AFTER TRANSMISSION THROUGH SS-FM SYSTEM

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1. Landon, V. D., Theoretical Analysis of Various Systems of Multiplex Transmission, RCA Review, pp. 287-351, June 1948 and pp. 433-482, Sept. 1949.

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