DESIRED TELEMETRY SYSTEM CHARACTERISTICS FOR SHOCK, VIBRATION, AND ACOUSTIC MEASUREMENTS

Subcommittee G-5.9 on Telemetry Requirements, SAE Committee G-5 on Aerospace Shock & Vibration
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Summary For over a decade structural dynamicists and acousticians have registered general dissatisfaction concerning the limitations of telemetry systems, especially the insufficient number of channels and insufficient data bandwidths. To spell out the users' need for present and future telemetry, a representative group of dynamicists was organized under the SAE. Requirements for number of channels per flight, data bandwidths, minimum dynamic range (with stationary and transient data signals considered separately), certain accuracy, phase and other characteristics were established. The subcommittee is hopeful that this information will spur the telemetry community into developing and standardizing on new systems with superior characteristics.

Introduction A careful review of the history of aviation shows that shock and vibration is a major cause of failure of aerospace vehicles and equipment. This statement seems to apply as much today as it did during earlier years. There are many reasons for this situation, of course. One of the most significant is the difficulty of estimating the magnitude of the dynamic environment over a broad frequency range. Although there have been many prediction methods developed in the last few years, no single method or combination of methods has been found which provides adequate answers (References 1-8). There are several reasons for this, too, but it is not intended to discuss them here. This situation is mentioned only to point out that an adequate flight measurement program is required to define the environment adequately, and is therefore essential to achieving the ultimate goal of eliminating or reducing shock- and vibration-induced failures.

Flight measurements are made primarily to serve two purposes. First, measurements are used to refine or correct the design and test criteria which are usually based on earlier prediction. In most programs, any necessary redesign and/or ground retesting will be performed before later flights are made. (A direct cause-and-effect relationship may be established between an environmental condition and a failure if a sufficient number of environmental and performance measurements are made). Second, measurements may be used as a basis for predicting the environment for the next vehicle or class of vehicles, if enough similarity exists.

Dynamically-induced failures and malfunctions are frequency sensitive. To be of real use to the structural dynamicist or environmental engineer, the frequency band of flight measurements should cover the range where the fragility level (or failure threshold) is low as well as where the environmental level is high. Unfortunately, the frequency range of both is usually very wide, especially when compared to the telemetry bandwidths commonly available in the past. By *commonly available* is meant the standard IRIG 18 channel proportional bandwidth FM/FM system used since 1943 (Ref. 9-10). In fact, in the past the dynamicist has made it painfully clear to the instrumentation engineer that the number of channels, data bandwidths, dynamic range, and several other characteristics of this telemetry system are wholly inadequate to meet the users' requirements. The demand for wider bandwidths continues to grow. Over the past decade acoustic environments have received increasing importance, requiring a frequency range up to 10 kHz. There is little doubt that in the future many more of these measurements will be required, especially for establishing aerodynamic fluctuating pressure fields (References 11-13). In addition. there is an increasing trend to separate vehicle stages and deploy various equipment devices with pyrotechnic charges. Mechanical shock from these charges can cause operational failures in certain types of equipment, especially at high frequencies (References 14-16). Future flight measurements of pyrotechnic shock will also require frequency bands up to 10 kHz.

If the vibration environment is to be adequately sampled on even a small vehicle, measurements at five or more locations are usually necessary. Medium and large aerospace vehicles often require five to fifty times this number of locations for the total flight test program. Considering that at least half the locations need three vibration measurements per location, and add a few acoustic and dynamic strain measurements to the above vibration, the total number of measurements desired becomes very large indeed.

The problem of predicting environments affects the selection of flight instrumentation sensitivity as much as it does the selection of design and test criteria. Difficulty of prediction produces a tendency for the dynamicist to reduce the sensitivity of measurements to avoid the possibility of having a large data signal clipped or distorted by exceeding the amplitude range of the instrumentation. In many cases, the data signal is not as large as anticipated. Then, difficulty may develop in keeping the signal above the system electrical noise. This problem becomes more acute if flight measurements are desired over several widely-varying phases of the mission, a tendency becoming more common as new vehicles are developed.

Recently the telemetry community has moved to improve this situation. At the suggestion of ARTC Panel 59-A (References 17-18), IRIG will shortly revise its Telemetry Standards (Reference 9) to: (a) extend the range of the standard IRIG proportional bandwidth system to include higher frequency channels, producing data bandwidths up to 5 kHz (for a modulation index of 5 and a deviation of ±15 percent), and (b) permit the use of constant bandwidth channels of data bandwidths up to 1.6 kHz (for a modulation index of 5) as standard replacements for or in conjunction with proportional bandwidth channels (References 19-21). (Obviously, wider data bandwidths can be obtained by using lower modulation indices. Increased interchannel modulation may result.) Most dynamicists welcome the new system as a significant improvement over the present system. However, it will shortly be shown that even the new system falls far short of many of the present and future requirements of the user. This may come as a surprise to instrumentation engineers who believe that structural dynamicists and acousticians were participants in Panel 59-A and concurred with the Panel's recommendations. The membership of ARTC Panel 59-A was comprised entirely of instrumentation personnel. Only a very few dynamicists were aware of Panel 59-A or its recommendations at the time that References 17 and 18 were published, let alone participate in the deliberations. The Foreword of Reference 18 states that "*As a major aerospace companies are represented on Panel 59-A, it can be fairly stated that this document represents the aerospace industry position concerning telemetry system design criteria.*" From the standpoint of the ultimate user, this statement could not be further from the truth.

In the meantime, several nonstandard systems have been developed. Single sideband suppressed carrier amplitude modulated subcarriers on a frequency modulated carrier (SSB/FM) have been used on several flights for stationary vibration and acoustic measurements, even though they could not be used for transient or DC measurements (References 22-25). Double sideband suppressed carrier amplitude modulated subcarriers on a frequency modulated carrier (DSB/FM) have been recently proposed for dynamic measurements but have not yet been used (References 26-27). On-board analysis of vibration and acoustic measurements has also been used, with the analyzer outputs being telemetered on narrow band channels (References 28-29). Although on-board analyzers permit very efficient use of the narrow band channels, they cannot be used for transients or DC measurements.

Many dynamicists are surprised to see that nonstandard systems are used at all. Often it takes great courage for an instrumentation engineer to suggest a nonstandard system. Most DOD contracts involving flight testing list MIL-STD-442 (Reference 30) along with hundreds of other applicable military specifications and standards. This Standard has no provisions for the use of nonstandard systems. The IRIG Telemetry Standards (Reference 9) does provide some relief, but not much. The Foreword of these Standards states that "*Agencies proposing to use equipment that deviates from these standards will* *be required to show that their proposed action is both technically necessary and economically feasible*." Most dynamicists can understand why the ranges must be protected from the whims and vagaries of of the unthinking and demanding user. However, the telemetry engineer might be surprised to find out how many times these words have been used to coerce the user to *prove beyond a shadow of a doubt* that a nonstandard requirement is really necessary. This usually occurs early in the program when flight measurement lists are being prepared and long before measurements from the first flight can be used to *prove* their necessity.

Organization of User's Representatives In the summer of 1965, it was brought to the attention of several dynamicists that the IRIG Telemetry Working Group was considering the recommendation of new standard systems to provide improved telemetry performance. These new standards would be used by all governmental and industrial ranges. These dynamicists considered it important that the users' requirements be known to TWG. They contacted several of their associates through an established organization of their field, the Society of Automotive Engineers' Committee G-5 on Aerospace Shock and Vibration. This committee normally organizes research work on joint problems in shock, vibration, and acoustics, and disseminates technical information to fellow dynamicists. It meets monthly in the Los Angeles area, but has *consultant* members throughout the country. To handle this new activity, the SAE Committee set up Subcommittee G-5.9 on Telemetry Requirements, consisting of: (a) a representative cross-section of dynamicists who use telemetry for flight shock, vibration, and acoustic measurements, and (b) consultants who could assist in defining or resolving joint dynamics-telemetry problems. Subcommittee members are listed in Appendix I with their organizational affiliations, with an asterisk denoting those participating as dynamicists. An effort was made to assure that a wide spectrum of users were included as participants. The objective of the Subcommittee's activities was to formulate a set of basic requirements, hopefully valid for the next ten-year period, to be considered by IRIG in their selection of new standard systems. Although interested in the IRIG selection, the Subcommittee felt that their legitimate interests would not include the selection itself but only the specification of desired characteristics.

Users' Requirements Through a number of meetings held during the last half of 1965, a questionnaire relating to users' requirements was formulated by the Subcommittee and filled out by the participants. The requirements covered were number of channels per flight, data bandwidth, dynamic range (shock and vibration considered separately), certain accuracy parameters, and phase characteristics between various frequencies of a channel or between two or more channels. The results are summarized in Table I and the histograms of Figures I through 8. To avoid coercing a participant to select the *worst case* requirement, each category was split into two cases: a *Normal* requirement and an *Occasional* requirement. This division was expected to be helpful in considering new telemetry system characteristics.

A brief summary of each histogram and equivalent section of Table I, and the process used in developing the numerical result (if applicable), is contained in the following paragraphs.

Number of Channels Per Flight The wide spread in this requirement, shown in Figure 1 on a logarithmic scale, is not surprising when the basic reasons are examined. The small number (3) represents a modest request for dynamic data on a small payload, and does not include additional measurements for the booster. (On an older *standard* booster, little or no additional dynamic measurements will be required and the payload data will probably be the only request.) Large numbers reflect the general tendency of increased vehicle size and/or the fewer number of developmental flights. The largest requirement (200) was generated for a single *structural verification* unmanned flight for a large manned spacecraft.

Data Frequency Range Users' requirements for data bandwidth are shown in Figure 2 on a logarithmic scale. In most cases, two or three frequency ranges were specified for each requirement. The percentage of the number of channels per flight for each range is also presented. With one exception, 10 to 2000 Hz or more was *Normal* for one of these ranges. Every participant had an *Occasional* requirement up to either 5 or 10 kHz, usually for acoustic noise or pyrotechnic shock. There was also some requirement for lower frequency channels. In these cases interest was to be focused on lower frequencies, such as the measurement of basic structural modes or guidance and control functions, or where high frequency vibration was not expected.

Minimum Dynamic Range for Stationary Data Because of the possibility of differing requirements for stationary and transient data, each requirement for dynamic range was established separately. For both cases, dynamic range was defined as

$$DR = 20 \log (2\, x_b/\sigma_y) \tag{1}$$

where ($2\, x_b$) = bandedge-to-bandedge (or maximum linear) data amplitude, σ_y = rms value of electrical noise.

In order to numerically establish this requirement for stationary data (i.e., data where the rms value did not change significantly with time), the participants agreed to use a standardized power spectrum for an envelope of spectral peaks of the data signal, which is illustrated in Figure 9. This data envelope G(f) is comprised of three segments: (1) a low frequency segment from frequency f_ℓ to frequency (f_m/b) with a power spectral density increasing at ±6 dB/octave; (2) a mid-frequency segment from (f_m/b) to (f_m/a) with a white power spectrum; and (3) a high frequency segment from (f_m/a) to f_m with a power spectral density decreasing at -12 dB/octave. To establish a relationship between the data envelope and allowable system electrical noise, a spectral envelope G’(f) of the maximum allowable electrical noise was determined at a factor of r_1 or r_2 below the data envelope. The participants agreed to use the same factor r_1 for the low and mid-frequency segments, and r_2 for the high frequency segment.

Two types of electrical noise are commonly found in telemetry systems: (a) those with a white power spectrum, i.e., F(f) = constant; and (b) those with a *violet* power spectrum with F(f) increasing at +6 dB/octave. Both are band-limited at the maximum data frequency f_m. By setting the system electrical noise power spectrum equal to the maximum allowable envelope, F(f) = G’(f), at one or more frequencies, the minimum dynamic range for stationary data was calculated:

$$DR_{S_{min}} = 20 \log (2M K_x \sigma_x/\sigma_y) \tag{2}$$

where $M = x_b/x_p$ = data safety factor, $K_x = x_p/\sigma_x$ = data crest factor, x_b = bandedge amplitude x_p = minimum value of data signal peaks, σ_x = rms value of data signal. Equations relating the data envelope G(f) and the electrical noise power spectrum F(f) to DR_{Smin} appear in Appendix II. Specific values of the various parameters (M, K_x, a, b, r_1, r_2) used for establishing the minimum dynamic range are shown in Table II.

Users’ requirements for minimum dynamic range appear in Figure 3 and Table 1. For the white spectrum of electrical noise, the *Normal* requirement varied from 31 dB to 41 dB, with 64 dB as the worst case *Occasional* requirement. For the *violet* spectrum, the requirements were 5 dB higher than those for the white spectrum.

Minimum Dynamic Range for Transient Data To establish a requirement for minimum dynamic range for transients, participants used one of two procedures. The first procedure was to determine the ratio of the maximum peak data signal x_p to the rms value σ_y of the electrical noise, and then use

$$DR_{T_{min}} = 20 \log (2M x_p/\sigma_y) \tag{3}$$

The second procedure, similar to the first, was to determine the ratio of the maximum peak data signal x_p to the maximum peak y_p of the noise, and then use

$$DR_{T_{min}} = 20 \log (2M K_y x_p/y_p) \tag{4}$$

where K_y = crest factor for the (random) electrical noise. Both procedures i should establish nearly or exactly the same value of DR_{Tmin}.

Because of the differences in spectral characteristics between low and high frequency transients, as well as differences between the data spectrum and the electrical noise, the participants chose to consider low and high frequency transients separately. Low frequency transients were defined as containing no substantial data signal above 2 kHz.

As shown in Figure 4, both *Normal* and *Occasional* requirements varied widely between participants. Figure 4.A shows that *Normal* requirements for minimum dynamic range of low frequency transients varied from 20 dB to 42 dB, with 60 dB as the outstanding worst case *Occasional* requirement. As shown in Figure 4.B, *Normal* requirements for minimum dynamic range of high frequency transients were generally higher, 26 dB to 54 dB, with 60 dB as the worst case *Occasional* requirement. One user did not submit a dynamic range requirement for high frequency transients.

Maximum Zero Shift When both static and dynamic measurements are made on the same channel, e.g., sustained acceleration and vibration, the accuracy of the static portion will be dependent on the zero shift from the time of DC calibration. As shown in Figure 5, with one exception the participants chose ±5 percent or less as the maximum allowable zero shift, with ±1 percent as the most stringent *Normal* requirement. The worst case *Occasional* requirement was ±0.5 percent.

Maximum Sensitivity Shift The accuracy of dynamic measurements is greatly dependent on changes in gain from the time of calibration. As shown in Figure 6, with one exception *Normal* requirements were generally from ±1 to ±5 percent, with the worst case *Occasional* requirement of ±0.5 percent.

Intrachannel Phase Phase linearity between various frequencies of a channel is important when it is desired to preserve data waveform, e.g., when the data signal is a transient or when it contains phase-related periodic components. As shown in Figure 7, three participants had no *Normal* requirement, indicating in these cases that a random signal was expected. Other *Normal* requirements for maximum deviation from phase linearity extended from ±5 degrees to ±45 degrees. The worst case *Occasional* requirement was ±1 degree. One participant would allow a greater tolerance as long as a calibration curve was furnished for the channel actually used.

Interchannel Phase Between-channels relative phase is important for the proper determination of cross-correlation, transfer function, coherence, propagation velocity, and other joint functions. As shown in Figure 8, most participants had no *Normal* requirement, indicating that single channel data were sufficient. Two participants selected ±5 degrees for the maximum allowable relative phase difference between channels. *Occasional* requirements varied from ±2 degrees to ±10 degrees. Two participants would permit a wider tolerance if a calibration curve were furnished for those channel pairs actually used.

Measurement of Varying Environments The requirements for minimum dynamic range, expressed earlier for stationary and transient data separately, were determined on the basis that the instrumentation sensitivity would be selected to measure only the single most-severe environmental condition. However, for the last few years there has been a growing desire to measure the changing dynamic environment at a specified location (and direction) during various phases of the mission. For example, an accelerometer might measure engine ignition and vehicle release transients, acoustically-induced vibration (caused by engine noise), aerodynamically induced vibration (at transonic and maximum dynamic pressure conditions), one or more vehicle staging transients, deployment of shrouds and equipment devices, and possibly reentry-induced vibration and landing shock, all of differing magnitudes. The dynamic range could easily exceed 70 dB. If a certain subsystem or equipment is operating under a lesser environment and is not operating during a greater one, dynamic data are required for <u>both</u> conditions for evaluation of catastropic failure under the greater environment, operational performance under the lesser environment, and cumulative failures under both. Seven methods of attacking this problem are discussed below.

The first method employs the use of more than one transducer at the same location (and direction) to make the *same* measurement, with each instrumentation system set at a different sensitivity and utilizing a separate telemetry channel. This would require a proportional increase in the number of telemetry channels, which are already in critical supply.

The second method employs the use of a multiple-gain signal conditioner for each transducer, with a step gain change initiated: (a) automatically by a timer, (b) by an *events* programmer or sequencer, or (c) manually. The complexity of this system and the need for careful calibration, checkout, and *debugging* does not lend itself to a highly reliable and economical measurement system at the present time. However, if a reliable and economical system can be developed, this might be the best of the several alternatives.

The third method employs the use of a logarithmic or other nonlinear signal conditioner, with *antilogarithmic* receiving or data reduction equipment. The application of this method to oscillatory data is in its infancy and will probably require some development before it can be considered further.

The fourth method employs the use of on-board analysis, with the analyzer output or outputs being telemetered on a narrow band channel or channels (which also solves the frequency range problem). Commercially available equipment includes: (a) a moderate-bandwidth filter swept through the frequency range, and (b) a set of continguous octave band filters, the outputs of which are suitably squared (or rectified) and time-averaged to give a set of quasi-DC signals. These systems have been used with mixed feelings

(References 28-29). They cannot handle transients, cannot discriminate between random and periodic data, and may have some difficulty analyzing nonstationary data. Like laboratory analyzers, they tend to be expensive, but unlike laboratory analyzers are usually not recoverable. When employed, they are often used in combination with conventional instrumentation, or are relegated to analyzing data later in a flight test program, as a *production* check on the variation of an environment established earlier by conventional instrumentation.

The fifth method employs automatic gain control, a standard technique used in communication. AGC may be used to: (a) vary the gain of each signal conditioner individually before multiplexing, or (b) in the case of suppressed carrier AM systems, vary the gain of the combined signal after multiplexing, but before telemetering. The former choice would reduce the effects of overall system noise, whereas the latter would reduce the effects of system noise except for interchannel modulation. The Subcommittee considered two pertinent characteristics of AGC in Table III: (a) gain range, i.e., the ratio of the maximum to the minimum amplifier gain; and (b) time required to change the gain from 10 percent to 90 percent of the maximum amplitude of an applied step function. Only transient data signals were considered, as the use of AGC for stationary and quasi-stationary data was considered fairly common. Some transients measured in flight have only low frequency content, requiring a lesser response time than high frequency transients. For this reason low frequency and high frequency transients were considered separately, with the former defined as having no significant data signal above 2 kHz. Participants specified gain changes from 2 to 10 and from 10 to 100 as their *Normal* low frequency and high frequency requirement, respectively, with 10 and 400 as the *Occasional* worst case low and high frequency condition. The response time *Normal* requirement varied from 0.5 to 10 ms for low frequencies and from 0.1 to 1 ms for high frequencies, with 0.5 and 0.05 ms as the *Occasional* worst case requirement, respectively. However, three participants flatly disapproved of the use of AGC for transient measurements. In fact, all participants who submitted AGC requirements did so with some apprehension. The additional need for one or several channels for gain information and the consequences of losing gain data were the major concerns.

The sixth method employs on-board analog-to-digital conversion and the telemetering of the digitized data, such as PCM presently used in some applications (Reference 31). To cover a large dynamic range with the desired accuracy shown in Figures 5 and 6, a large-bit digital system is required. (From Reference 22, each bit doubles the range. A 11-bit word is needed to cover 77 dB.) This requires a wide RF bandwidth and, at the present time, is expensive but not beyond the state-of-the-art. However, future developments may bring the cost down. (The matter of cost is often of little concern to the user!) It should be mentioned that the large user of telemetry might prefer his data in digital form, since his subsequent data analysis would probably be performed on a digital computer. On the other hand, the small user would probably prefer his data in analog form, since his data analysis would probably be performed on analog equipment. In the latter case, digital-to-analog conversion would be required on playback after the flight. The small user would probably prefer that the conversion be done at the test range because of the cost of the conversion equipment. Further development of digital systems is required to demonstrate their economy to handling widely-varying dynamic data.

The seventh and last method utilizes improved techniques of modulation and multiplexing to provide lower electrical noise and minimum interchannel modulation. From the users' viewpoint, this is the obvious choice.

A qualitative comparison between the dynamic range for varying environments and the minimum dynamic range for stationary and transient data (DR_{Smin} and DR_{Tmin}) summarized in Figures 3 and 4 can be made. The first and second methods would utilize the same dynamic range as DR_{Smin} and/or DR_{Tmin}. The third through sixth methods could utilize a lesser dynamic range. The seventh method requires a greater dynamic range.

Conclusions The user's requirements summarized in Figures 1 through 8 points out the pressing need to develop a standard telemetry system with superior characteristics for shock, vibration, and acoustic measurements. The requirements shown in Figure 2 show the need for greater flexibility in the choice of data bandwidths in this standard system. Considering the desired number of channels per flight as well as the desired data bandwidths, a typical flexible standard system might be used in one of several arrangements. For example, a standard system might be used with: (a) ten 10-kHz channels, or (b) forty 2.5-kHz channels, or (c) three 10-kHz, sixteen 2.5-kHz, seven 1.25-kHz, and four 312-Hz channels. This type of flexibility would allow the dynamicist the considerable latitude he needs to optimize his flight measurements.

Obviously, all users would prefer to utilize a standard system of sufficient capability. However, it is unlike that even a standard system of greatly improved capability could handle all contingencies. For example, one of the participants, denoted by the double asterisk in Appendix I, is almost totally dependent on nonstandard systems which have data bandwidths to 100 kHz. Therefore, telemetry specifications should be liberalized to permit the use of nonstandard systems when these very special problems arise.

The user's requirements presented here should be a challenge to the entire telemetry and instrumentation field. We hope that the industry will accept this challenge.

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APPENDIX I

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APPENDIX II

Relation of the Minimum Dynamic Range for Stationary Data to the Power Spectra of the Data Envelope and the Electrical Noise The participants agreed to use the power spectrum G(f) shown in Figure 9 as the envelope of spectral peaks of the random stationary data. The mean square value for each of the three segments may be calculated from Reference 33:

$$\Delta x^2_{ru} = \frac{3G_m f_m}{b(R_u+3)}\left[1 - \left(\frac{bf_\ell}{f_m}\right)^{(R_u+3)/3}\right]$$

$$= \frac{G_m f_m}{3b}\left[1 - \left(\frac{bf_\ell}{f_m}\right)^{3}\right] \qquad (R_u = +\ 6\ \mathrm{dB/octave}) \qquad \text{(II-1)}$$

$$\Delta x^2_{rv} = G_m f_m\left[\frac{1}{a} - \frac{1}{b}\right] \qquad (R_v = 0) \qquad \text{(II-2)}$$

$$\Delta x^2_{rw} = \frac{3G_m f_m}{a(R + 3)}\left[\left(\frac{af_m}{f_m}\right)^{(R_w+3)/3} - 1\right]$$

$$= \frac{G_m f_m}{3a}\left[1 - \frac{1}{a^3}\right] \qquad (R_w = -\ 12\ \mathrm{dB/octave}) \qquad \text{(II-3)}$$

where G_m maximum power spectral density of the data envelope, f_m = maximum data frequency. Assuming no superimposed DC data, the total Mean square data signal is

$$\sigma_x^2 = G_m f_m\left\{\frac{1}{3b}\left[1 - \left(\frac{bf_\ell}{f_m}\right)^3\right] + \left[\frac{1}{a} - \frac{1}{b}\right] + \frac{1}{3a}\left[1 - \frac{1}{a^3}\right]\right\} \qquad \text{(II-4)}$$

The power spectra F(f) of the electrical noise commonly found in telemetry systems are band-limited and are either: (a) white, or (b) *violet*. For both cases, the mean square noise is

$$\sigma_y^2 = 3F_m f_m/(R_y + 3) \qquad \text{(II-5)}$$

where F_m = maximum power spectral density of the noise, R_y = slope of the noise power spectrum, dB/octave. For the white spectrum:

$$\sigma_y^2 = F_m f_m \qquad (R_y = 0) \qquad \text{(II-6)}$$

where F_m is constant throughout the band. For the *violet* spectrum:

$$\sigma_y^2 = F_m f_m/3 \qquad (R_y = +\ 6\ \mathrm{dB/octave}) \tag{II-7}$$

where F_m occurs at the maximum data frequency f_m, as shown in Figure 9.

In most cases, the electrical noise power spectrum F(f) is most likely to exceed the maximum allowable envelope G'(f) at the maximum data frequency f_m. Relating the data envelope power spectral density to the noise power spectral density at this frequency:

$$G(f_m) = r_2\ F(f_m) = r_2\ F_m \tag{II-8}$$

For the third segment of the data envelope, it can be shown that

$$G(f_m) = \left[\frac{af_m}{f_m}\right]^{R_w/3} G(f_m/a)$$

$$= G_m/a^4 \qquad (R_w = -\ 12\ \mathrm{dB/octave}) \tag{II-9}$$

Substituting Equation (II-9) into Equation (II-8), the relationship between G_m and F_m is established:

$$F_m = G_m/r_2\ a^4 \tag{II-10}$$

Substituting Equations (II-4), (II-10), and (II-5) into Equation (2) of this paper, the minimum dynamic range for stationary may be expressed as

$$DRS_{min} = ARF + DSF + NSF + R_2 \tag{II-11}$$

where ARF = 20 log (2M K_x) = amplitude range factor

$$DSF = 10 \log a^4 \left\{ \frac{1}{3b}\left[1 - \left(\frac{bf_\ell}{f_m}\right)^3\right] + \left[\frac{1}{a} - \frac{1}{b}\right] + \frac{1}{3a}\left[1 - \frac{1}{a^3}\right]\right\}$$

= data spectrum factor

NSF = 10 log [(R_y + 3)/3] = noise spectrum factor

$$R_2 = 10 \log r_2$$

Substituting the values shown in Table II into Equation (II-11), the users' requirements for DR_{Smin} shown in Figure 3 and Table I are determined.

TABLE I. SUMMARY OF USERS' TELEMETRY REQUIREMENTS

USER ORGANIZATION			AEROSPACE	BBN	DAC		NASA/GSFC			NASA	NAA	
			SBO	LA	MSSD	JPL	S	M	L†	MSFC	S&ID	NSL
Number of Channels Per Flight	N*		9	10	15	25	9	15	25	90	20	3
	O		16	30	200	55	20	40	60	120	50	6
Percentage of Measurements & Data Frequency Range (kHz)	N		67 0- 2 33 0- 0.16	100 0.01- 3	50 0.01-2 30 0.05-5 20 0 -1	67 0.01-2 33 0 -0.1	50 0 - 0.1 50 0.01- 4			50 0.005- 0.5 50 0.02 - 0.5	50 0.01- 1 50 0.01- 2	100 0.01-2
	O		67 0.02-10 33 0- 0.5	100 0.01-10	50 0.01-2 30 0.05-5 20 0 -1	50 0.01-2 30 0 -0.1 20 0.01-5	50 0 - 2 50 0.01-10			95 0.005- 0.5 5 0.02 -10	50 0.01- 1 30 0 -10 20 0 - 0.1	100 0.01-5
Minimum Dynamic Range for Stationary Data (dB)	W**	N	31	32	38	41	41			64	41	41
		O	27	32	38	50	55			64	63	45
	V	N	36	37	43	46	46			69	46	46
		O	32	37	43	55	60			69	68	50
Minimum Dynamic Range for Low & High Freq. Trans. (dB)***	LF	N	37	20	26	42	26			40	42	26
		O	42	46	32	45	48			40	42	60
	HF	N	37	30	26	42	32			-	54	26
		O	42	46	32	45	54			-	54	60
Maximum Allowable Zero Shift (±%)	N		5	5	10	5	2			1	5	5
	O		2	1	10	2	0.5			1	0.5	0.5
Maximum Allowable Sens. Shift (±%)	N		5	5	20	5	2			1	2	1
	O		2	1	10	2	0.5			1	0.5	0.5
Channel Phase Linearity (±deg.)	N		5	45	-	10	5			-	-	-
	O		2	5	10^{Δ}	2	1			-	2	5
Relative Phase Bet Channels (±deg.)	N		-	-	-	5	5			-	-	-
	O		5^{Δ}	10	10^{Δ}	5	2			2	2	-

*N = Normal
O = Occasional

**Electrical Noise Power Spectrum
W = White spectrum
V = Violet spectrum (+6 dB/oct)

***Low frequency transients are defined to have no data signal above 2 kHz.

ΔGreater phase tolerance allowed with calibration curve.

†S = Small vehicles, M = Medium-size vehicles, L = Large vehicles.

TABLE II. RANDOM DATA SIGNAL PARAMETERS USED TO ESTABLISH MINIMUM DYNAMIC RANGE FOR STATIONARY DATA

USER ORGANIZATION			AEROSPACE SBO	BBN LA	DAC MSSD	JPL	NASA GSFC	NASA MSFC	NAA S&ID	NSL
Data Safety Factor M	N		2	1	2	2	2	3	2	2
	O		2	2	4	3	5	3	4	10
Data Crest Factor K_x	N		3	3	3	3	3	3	3	3
	O		3	3	3	3	3	3	3	3
Spectrum Cross-Over Freq. Ratios (See Fig. 9)	N	a	1.3	2	2	2	2	1.8	2	2
		b	5	100	100	10	10	50	5	20
	O	a	1	1	1	3	2	1.8	4	1
		b	10	1000	∞	20	100	330	10	20
Maximum Allowable Electrical Noise (dB) (See Fig. 9)	N	R_1	6	6	6	10	15	30	10	10
		R_2	6	6	6	10	10	30	10	10
	O	R_1	6	10	10	10	20	30	15	10
		R_2	6	10	10	10	15	30	15	10

TABLE III. SUMMARY OF USERS' AGC REQUIREMENTS

USER ORGANIZATION			AEROSPACE SBO	BBN LA	DAC MSSD	JPL	NASA GSFC	MASA MSFC	NAA S&ID	NSL
Gain Range for Low & High Frequency Transients	N	LF	Disapproves	Disapproves	2	10	3	3	4	Disapproves
		HF	of use	of use	10	10	10	-	100	of use
	O	LF	of	of	2	10	5	3	10	of
		HF	AGC	AGC	10	10	20	-	400	AGC
Response Time for Low & High Frequency Transients (ms)	N	LF	for	for	5	10	5	0.5	2	for
		HF	Transients	Transients	0.1	1	0.5	-	0.2	Transients
	O	LF			5	10	0.5	0.5	1	
		HF			0.1	1	0.1	-	0.05	

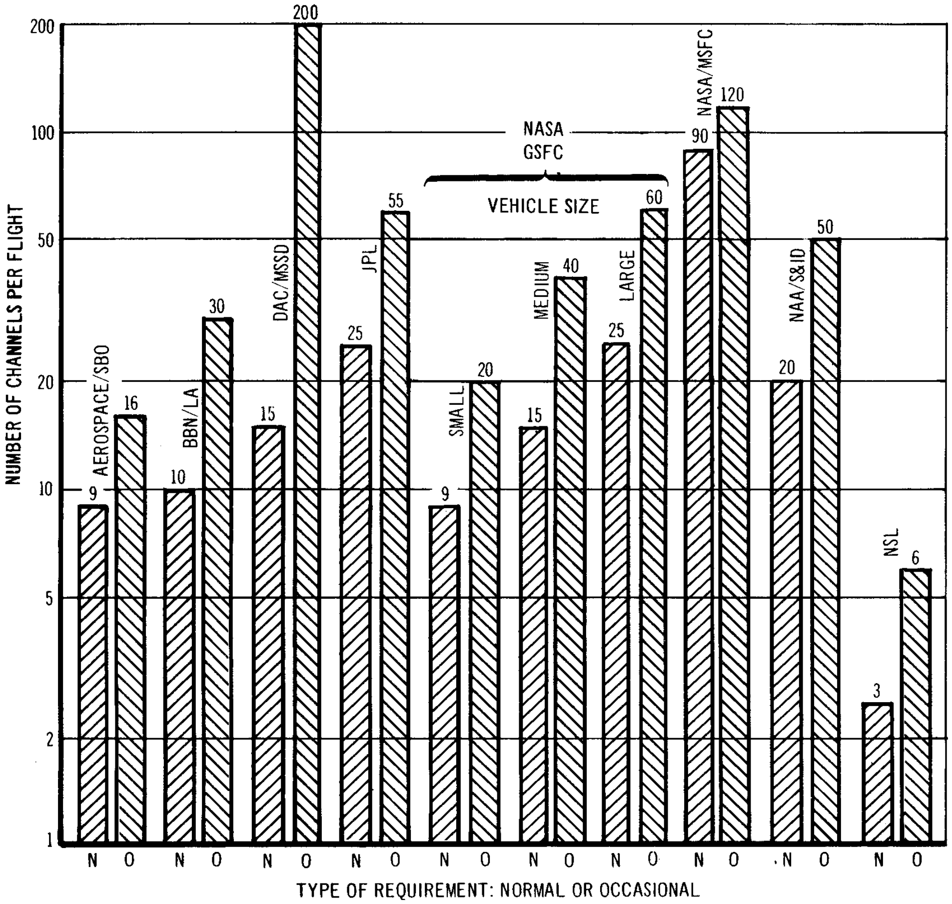


FIGURE 1. USERS' REQUIREMENTS FOR NUMBER OF CHANNELS PER FLIGHT

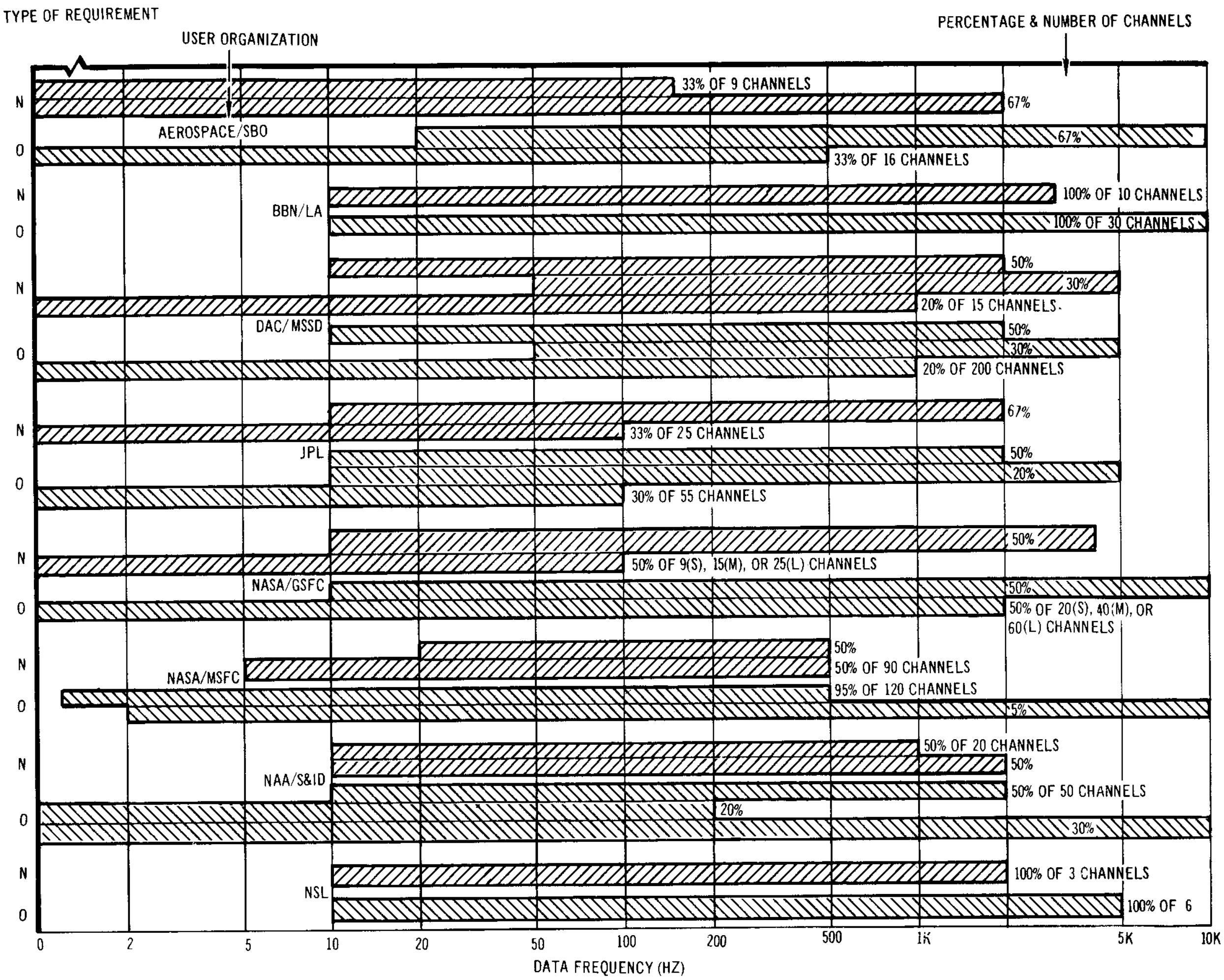
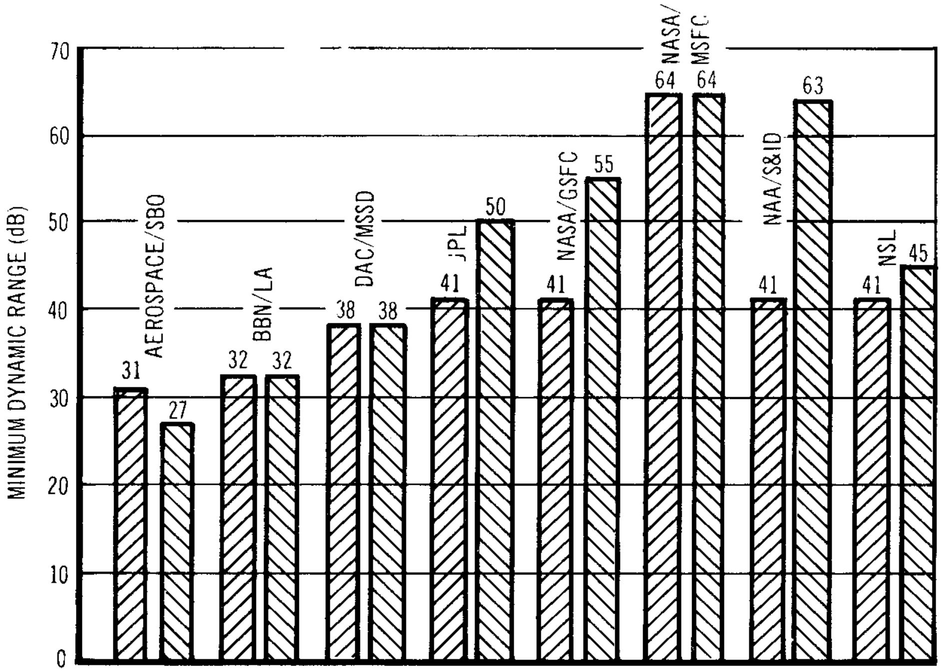


FIGURE 2. USERS' REQUIREMENTS FOR DATA FREQUENCY RANGE

A. WHITE POWER SPECTRUM FOR ELECTRICAL NOISE



B. "VIOLET" POWER SPECTRUM FOR ELCTRICAL NOISE

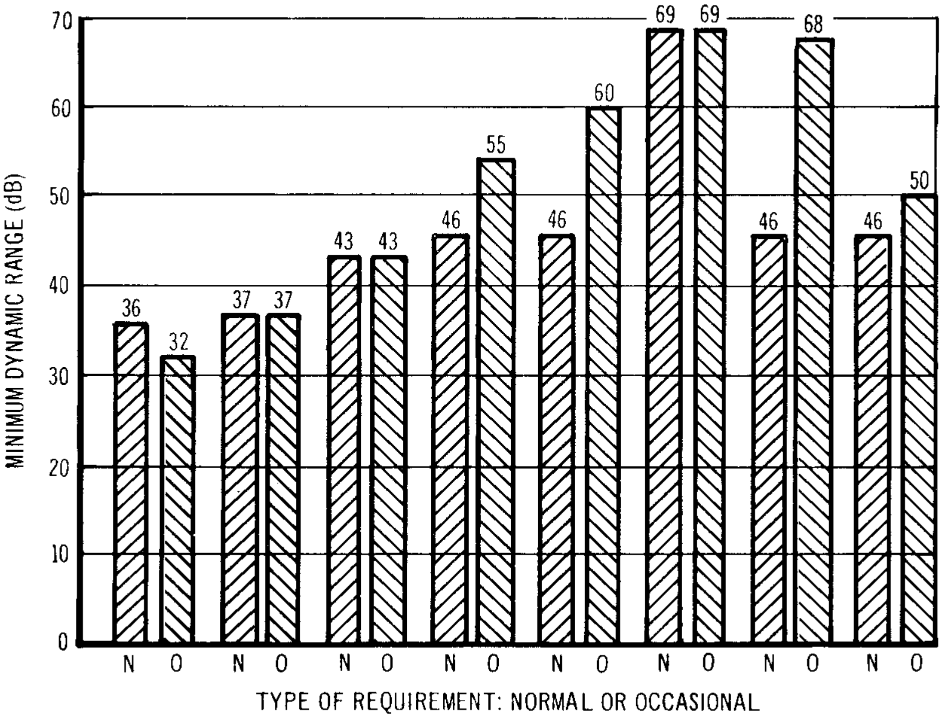
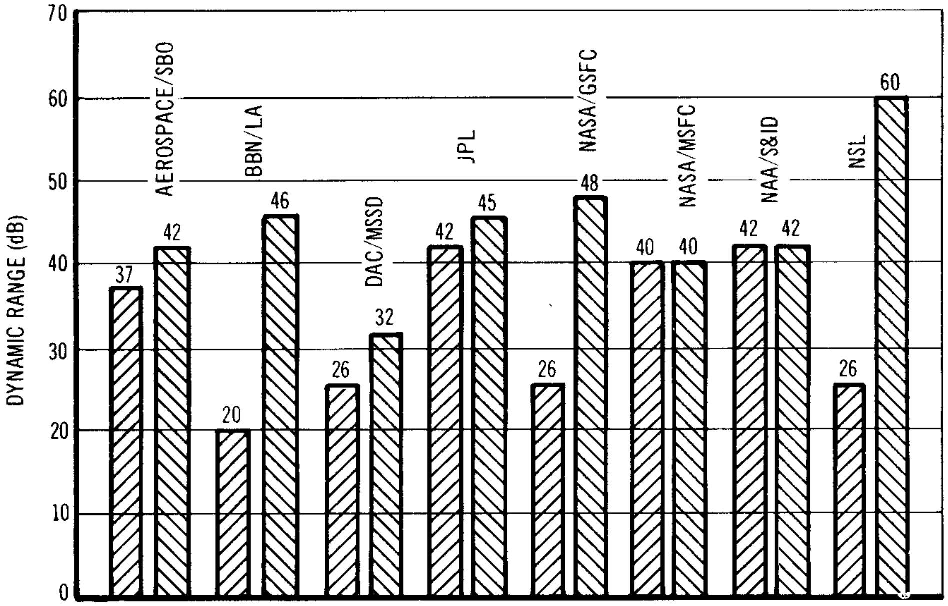
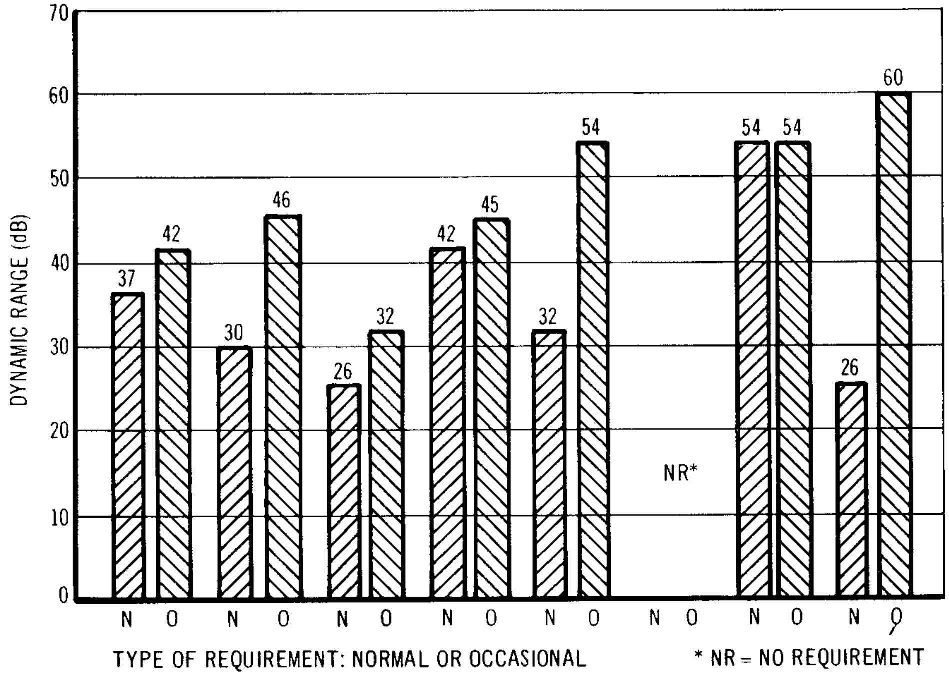


FIGURE 3. USERS' REQUIREMENTS FOR MINIMUM DYNAMIC RANGE FOR STATIONARY DATA



A. LOW FREQUENCY TRANSIENTS (NO SUBSTANTIAL SIGNAL ABOVE 2 k Hz)



B. HIGH FREQUENCY TRANSIENTS

FIGURE 4. USERS' REQUIREMENTS FOR MINIMUM DYNAMIC RANGE FOR TRANSIENT DATA

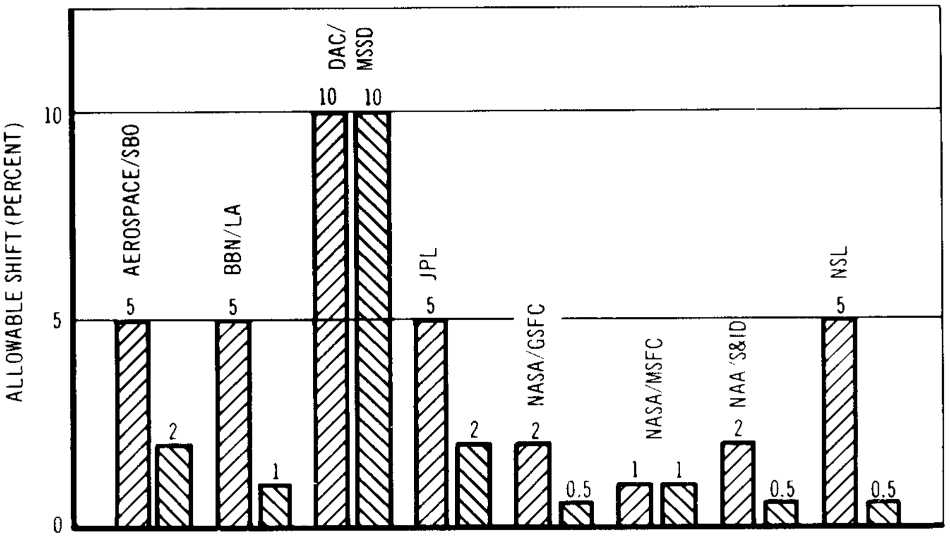


FIGURE 5. USERS' REQUIREMENTS FOR MAXIMUM ALLOWABLE ZERO SHIF

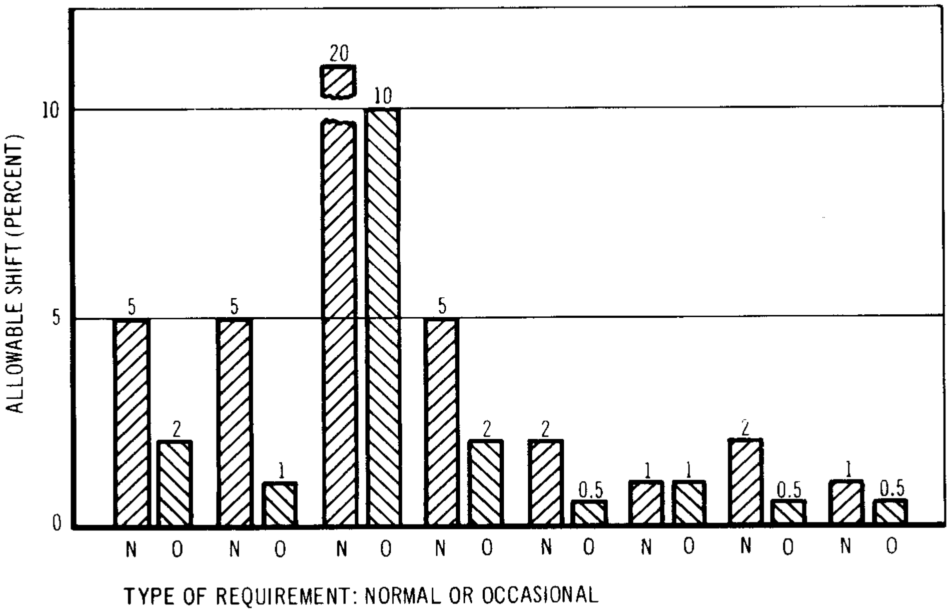


FIGURE 6. USERS' REQUIREMENTS FOR MAXIMUM ALLOWABLE SENSITIVITY SHIFT

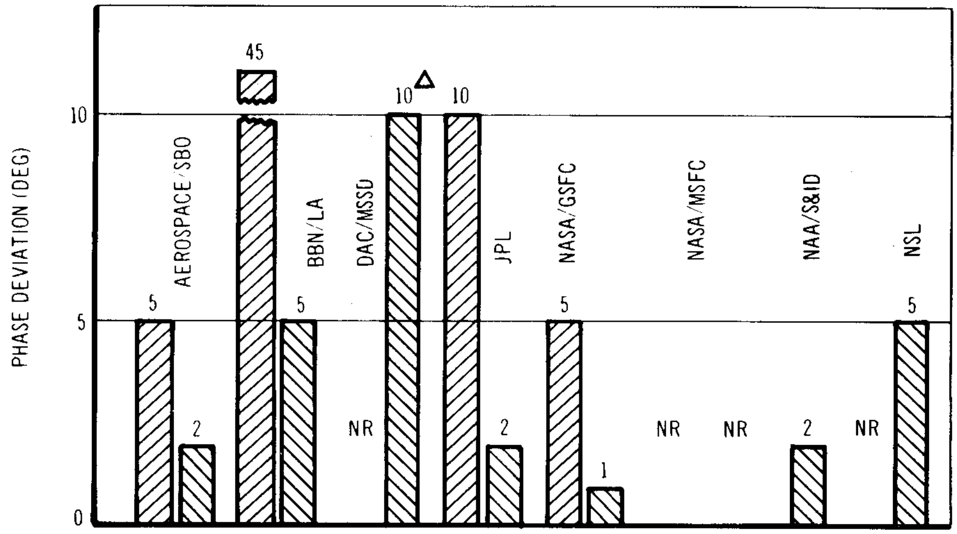


FIGURE 7. USERS' REQUIREMENTS FOR MAXIMUM DEVIATION FROM PHASE LINEARITY BETWEEN CHANNEL FREQUENCIES

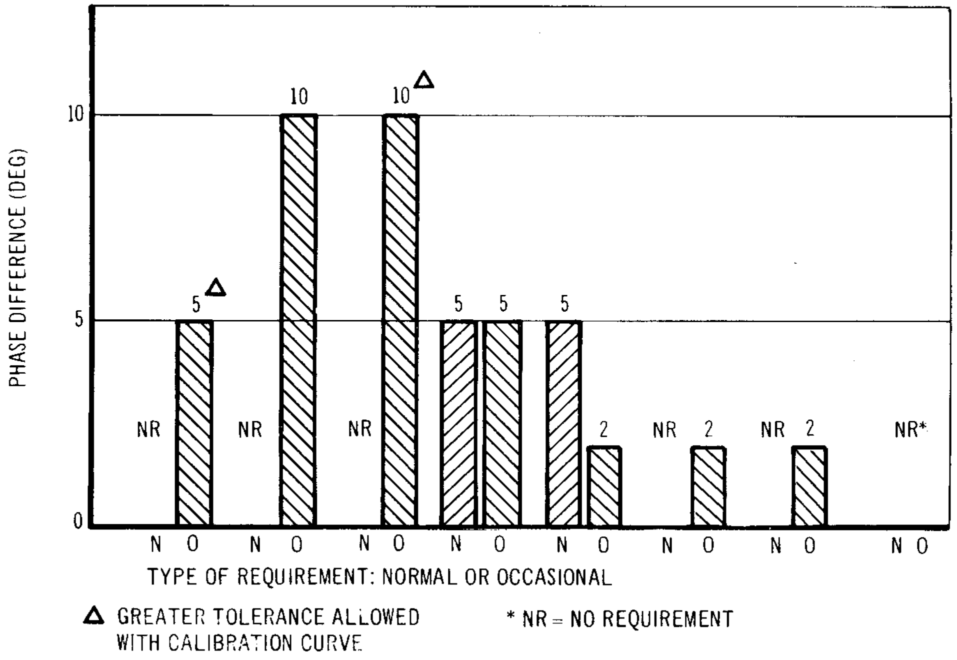


FIGURE 8. USERS' REQUIREMENTS FOR MAXIMUM RELATIVE PHASE DIFFERENCE BETWEEN CHANNELS

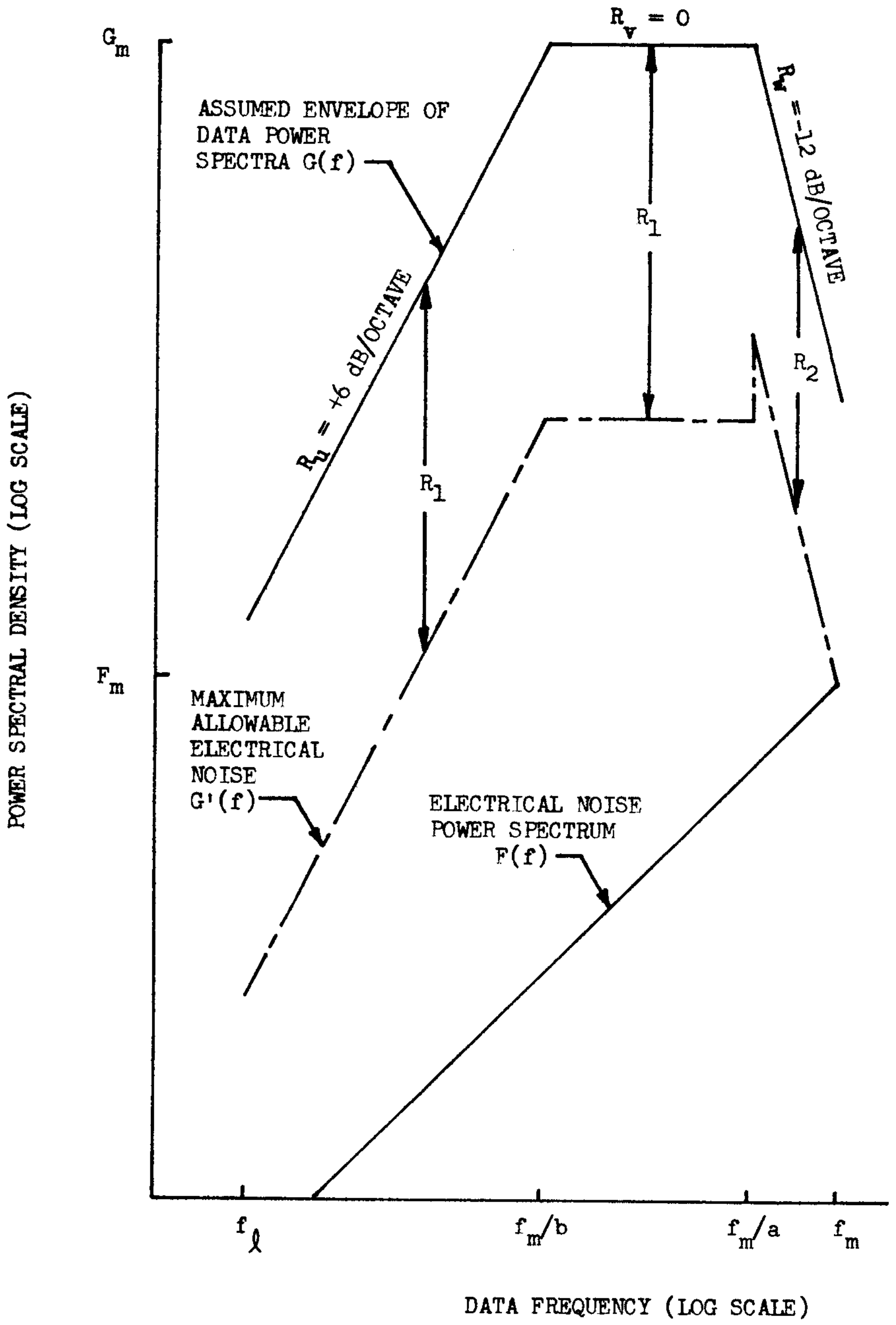


FIGURE 9. POWER SPECTRA OF STATIONARY DATA SIGNAL AND SYSTEM ELECTRICAL NOISE