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SIGNAL-TO-NOISE RATIOS IN MAGNETIC RECORDING

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SUMMARY

In recording telemetry signals from scientific satellites at remote locations, for subsequent reduction at a central facility, the system signal-to-noise ratio is established at the receiver input terminals, when the input signal-to-noise ratio is low. Under these conditions the noise contributions of the tape recorder-reproducer are usually insignificant.

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INTRODUCTION

The following discussion is intended to clarify some widespread misconceptions concerning signal-to-noise ratios in magnetic recording. These are due, probably, to incautious application of general tape recording practice to specific problems of recording telemetry signals from artificial satellites, where different conditions obtain. Because they strongly affect the choice of equipment and operating doctrines used in field stations and at data processing facilities, these factors should be delineated in the interest of good judgment.

Complex telemetry data processing systems pose the problems of adjusting analog signal levels to the characteristics of the many successive stages in order that the integrity of the signals is preserved from degrading effects of noise and nonlinearities. This is a traditional concern of long-line telephone and radio systems, voice and vision recording and reproduction systems (including radio and television networks), radars, etc. The critical stages tend to be those in which the signal is at its lowest level, where stage noise of both external and internal origin sets the lowest limit of the system; and this establishes an upper bound to the S/N ratio.

Since magnetic tape recording is presently the most expeditious method for storage and transportation of large quantities of data, both the introduction of low-level random noise and the non-random effects at or near maximum levels are important considerations. The term "dynamic range" is used to denote the ratio in db of the maximum usable signal level (set by distortion) and minimum usable level (set by the noise of the device). A signal having no noise of its own, recorded at the highest level, would have a S/N ratio equal to the dynamic range. It is not always obvious how these terms are interrelated, and without thorough understanding of them and proper monitoring of each stage's performance, one may improperly adjust a stage and vitiate the effects of many others which are properly adjusted. It is a case of the chain being no stronger than its weakest link.

The effects of noise in the input stages of a receiver have been studied for years, generally having been brought to the current treatment by Friis in 1944 (Reference 1). At the input stage, the upper limit of the signal level is likely to be 100 db (or more) greater than the noise. At later stages, the signal level has been raised by the gain of the receiver to a region where the non-linear effects are primarily limiting and distortion; at this juncture the internally generated noise level is usually low enough to be ignored as a primary concern.

SIGNAL-TO-NOISE RATIOS WITH MAGNETIC TAPE RECORDERS

Receiver Noise

Telemetry signals from scientific satellites are recorded on magnetic tape at remote sites throughout the world, and returned to the U. S. for processing, reduction, and analysis. One of the first steps is to quantize the analog signals onto digital magnetic tape. Most subsequent processing steps are accomplished in special or general purpose digital computers. Since it is necessary at the telemetry site to examine some data for satellite command or control purposes, some processing equipment is located at the tracking station. There are signs that this trend may continue, and consequently it has been suggested that the preliminary processing of the signal onto digital tapes be accomplished at the tracking station, eliminating possible deterioration associated with recording in analog form. This type of deterioration is mainly due to operator errors and equipment faults and not, as is commonly thought, to inherent systematic shortcomings or S/N degradation caused by analog recording and playback.

The signal-to-noise ratio obtained at the telemetry station is a function of the satellite power output, the transmission loss, the receiving antenna gain, the exogenous noise (galactic noise, earth noise, etc.), and the receiver noise factor.

In effect, the combination of signal and exogenous noise, presented at the receiver input terminals, may be considered as a noisy signal to which is added internally-generated noise contributed almost entirely by the first stage of the receiver.* For convenience, receiver noise is often described by the term "noise factor" often expressed in decibels, this factor being defined (Reference 2) "as the ratio of 1) the total noise power per unit bandwidth at a corresponding output frequency available at the output port when the noise temperature of the input termination is *standard* (290°K) to 2) that portion of 1) engendered at the input frequency by the input termination." When the antenna resistance is at standard temperature (290°K), the output S/N ratio of a receiver may be obtained by subtracting its noise factor in db from the input signal-to-noise ratio. At other antenna temperatures $\left(T_{z_{in}}\right)$ this becomes

$$\frac{S_{out}}{N_{out}} = \frac{S_{in}}{N_{in}} \cdot \frac{1}{\left[1 + \frac{290}{T_{z_{in}}}(F-1)\right]}$$

*Where properly employed, a preamplifier, even if remote, is considered part of the receiver and would then be the "first" stage.

Since each stage of a receiver provides gain, the effect of the noise contribution of succeeding stages becomes less and less; and in most practical cases, the noise factor of the receiver is a function of the first stage alone, provided the gain of the first stage exceeds 20 db. When the first stage gain is low, the noise figure of the first and second stage is (Reference 1):

$$F_a + \frac{(F_b - 1)}{g_a} .$$

When the first stage gain is high, this is approximated by

$$F = F_a + \frac{F_b}{g_a} ,$$

and for succeeding stages

$$F_{abc \ldots} = F_a + \frac{F_b - 1}{g_a} + \frac{F_c - 1}{g_a g_b} \cdots$$

When recording signals from the smaller scientific satellites, we are presented with signal-to-noise ratios ranging from below the threshold of our comb filters (at -14 db) up to +20 db. If we take the precaution of recording our signal at or near the highest permissible level, it can be seen that the recording/reproducing process will have little degrading effect on the S/N ratio.

In some of the larger scientific satellites and in some of the application satellites, much higher signal-to-noise ratios are expected, perhaps as high as 25 to 40 db. Present intentions are that these signals also be recorded on analog magnetic tape. Standard charts of error rate as a function of S/N ratio lead us to expect that error rates corresponding to S/N ratios of this order will be far below commonly specified limits for most digital systems.

If a recorder/reproducer is included in the chain, its S/N ratio may be such (as low as 30 db) that the noise introduced by it may exceed the amplified noise of the input stage (F_n may approach the value of g_{ab} in the foregoing equation).

Actually recorders are not rated in terms of noise factor, since the sources of noise in recorders are diverse and different from those in RF amplifiers and this fact would make the term ambiguous. There is a random noise component in recording, related to the heterogeneous nature of the oxide recording medium and analogous to the thermal and shot noises of the input stages. Care must be used in combining random noise from these two sources, however, because of their spectral differences. As is indicated in this report, there are few cases where this will be called for.

Tape Recorder Noise

The foregoing discussion of receiver noise was presented to introduce the effects of tape recorder noise, because of the similarity of the problems. In the latter case, we have "signal" source which consists of signal and noise, available at any reasonable level, since unlimited gain can be provided. The tape recorder must record both the signal and the noise presented to it, and both look like "signal" to it. Since the recorder itself introduces noise of several varieties, we must adjust the recording level so that their effects are minimized. The gain/noise characteristics of the recorder will resemble the curve of Figure 1, in which the upper curve represents the frequency response of the unit, and the lower curve represents the noise generated by the unit in the reproduce mode. This noise has several components, of which the high frequency ones are predominantly due to the tape and the amplifier electronics, and the low frequency ones to the electromechanical causes (rumble and flutter, etc.). Over the usable portion of the spectrum, the maximum usable signal-to-noise ratio, or dynamic range as it is sometimes called, is about 60 decibels. Since we are dealing with a S/N ratio which may range from -14 db to +40 db, if we take the precaution of recording the signal at near its maximum amplitude, the tape recorder noise will have a negligible effect on the S/N ratio. The fact that the recorder S/N ratio may fall off by 20 db or more at each end of the scale becomes unimportant for our purposes.* The cases in which this is not true include those where the S/N ratio of the received signal exceeds the dynamic range (max. S/N ratio) of the recorder, or where the signal is recorded at too low a level to utilize an otherwise acceptable recorder dynamic range, and where signals are being recorded which approach the frequency response limits of the recorder. System deterioration due to these must be insured by checking to see that the recording level is set properly and that sufficient recording speed is available to provide adequate frequency response.

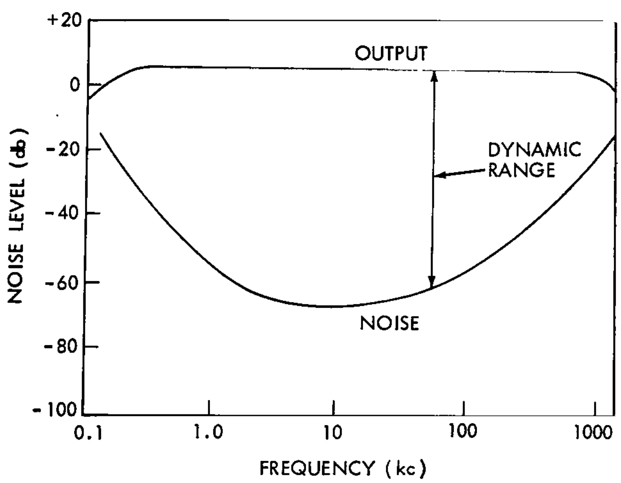

Figure 1—Analog tape recorder response (idealized).

An important consideration in establishing a lower limit on the S/N ratio in a telemetry system is the effect of the S/N ratio on the integrity of the data. In digital systems, this is usually expressed as the bit error rate, a function of the S/N ratio. The relationship has been derived for the case of white Gaussian noise (Reference 3) in terms of the error function:

$$\text{Prob. error} = \frac{1}{2}\left(1 - \operatorname{erf} \frac{Ac}{2\sqrt{2}\sigma}\right)$$

$$\left(\operatorname{erf} x = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2}\, dy\right)$$

*It is important to note that in the traditional uses of tape recording of high quality audio entertainment programs, different conditions obtain and different conclusions are reached. Audio program material frequently achieves a S/N ratio of 65 db on lacquer discs from which tape recordings may be made. Under these conditions the noise associated with the signal may be less than that of the recorder, in which case the noise of the recorder would affect the S/N ratio of the program material as recorded.

This curve is rarely plotted for error rates lower than 10^{-6} (corresponding to a signal-to-noise ratio of +10 db). It is interesting to note, however, that this curve, when extended to higher signal-to-noise ratios, rapidly yields error rates so low as to be beyond our experience. For instance at +20 db the probability of a bit error is reduced to the order of 10^{-23}. It is likely that the errors due to origins other than that of white noise will manifest themselves and become predominant in establishing system performance long before this signal-to-noise ratio is reached.

As a final precaution, it must be pointed out that non-uniform recording system response, the result of improper equalization or of exceeding the nominal bandpass, has only a second order effect on overall signal-to-noise ratio, and in the normal circumstances can be neglected in that particular respect. There are often other vital reasons, however, why uniform response should be maintained; but noise is not among them.

CONCLUSION

Under most conditions of satellite telemetry usage, it has been shown that the random high frequency noise contribution of magnetic tape recording and subsequent reproduction can be kept to a negligible amount. Other deleterious effects such as frequency and phase errors, wow, flutter and jitter, have not been treated here since with proper system design, equipment maintenance, and operating practice, they have not been observed to cause significant deterioration to data processing of analog tapes. This is also belived to be the case for impulse noise and dropouts due to inhomogeneities of the tape itself.

(Manuscript received November 11, 1964.)

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