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PROJECT ECHO – FM DEMODULATORS WITH NEGATIVE FEEDBACK

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SUMMARY

The primary experimental objective of Project Echo was the transmission of radio communications between points on the earth by reflection from the balloon satellite. Owing to the large path losses from transmitter to receiver via the satellite, a wide-band frequency modulation technique was used in which bandwidth was traded for signal-to-noise ratio. This paper describes the FM receiving demodulators employed. Negative feedback applied to the local oscillator reduces the FM modulation index in the receiver IF amplifiers, resulting in threshold performance superior to that of conventional FM receivers.

PREFACE

The Project Echo communications experiment was a joint operation by the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), and the Bell Telephone Laboratories (BTL). The equipment described herein, although designed by BTL as part of its own research and development program, was operated in connection with Project Echo under Contract NASW-110 for NASA. Overall technical management of Project Echo was the responsibility of NASA's Goddard Space Flight Center.

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INTRODUCTION

In the Project Echo communications experiment the path loss from the transmitter to the receiver via the satellite was very large. Even with reasonably large antennas, high power outputs, and low-noise receivers, the received signal was so small that a modulation technique was required which traded bandwidth for signal-to-noise ratio (S/N). Wide-band frequency modulation was used, with receiving demodulators that were FM receivers having negative feedback (FMFB). The negative feedback provides an improved FM threshold and a resulting output S/N better than in other well-known techniques, such as the single-sideband technique.

S/N RATIO AND THRESHOLD IN FMFB

A simplified block diagram of the FMFB demodulator (References 1 and 2) is shown in Figure 1. As is indicated, a part of the baseband (audio) output is used to frequency modulate the local voltage-controlled oscillator (VCO). The audio signal is phased in such a manner that the VCO frequency tends to follow the frequency variations of the RF input signal. The result is a reduction of the modulation index of the IF signal relative to the index of the RF signal and this is, of course, negative feedback. If the RF index

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and on the phase shift in the circuit. Optimizing the threshold of this FMFB receiver is equivalent to designing the feedback network for minimum closed-loop noise bandwidth.

The performance of the FMFB receiver above the threshold can be understood with the aid of Figure 1. When the feedback loop is opened at X the receiver is an ordinary FM receiver. Above the threshold the output signal-to-noise power ratio is

$$\frac{S_0}{N_0} = 3M^2 \frac{C}{N} \tag{2}$$

where M is the modulation index and C/N is the carrier-to-noise power ratio at the input of the frequency detector, i.e., the noise power measured in a bandwidth of $2f_b$. The threshold for this case is described by Rice (Reference 5).

When the loop is closed, the FM index in the IF is reduced by the feedback factor F. This is true for both signal and noise; thus S_0/N_0 remains unchanged. The index at the transmitter can now be increased by F to restore the original FM index in the IF; this increases the output S_0/N_0 by the factor F (Reference 2). It is evident then that, for operation above the threshold, the output S_0/N_0 is given by Equation 2 where M is the FM index at the transmitter. This is true for both FM and FMFB.

In summary, the signal-to-noise performance above the threshold in FMFB is given by Equation 2, and the threshold occurs at a C/N which depends on the closed-loop bandwidth. However, a word of caution is needed here. The foregoing statements assume a large feedback. For very small amounts of feedback, the threshold behavior approaches that of conventional FM.

PROJECT ECHO RECEIVER

A complete block diagram of the receiver is shown in Figure 3. The main feedback loop includes the mixer, 1.2 Mc IF filter, preamplifier, limiter, disciminator, baseband filter, attenuator, and voltage-controlled oscillator. Another feedback loop includes the input amplifier, mixer, 1.2 Mc IF filter, preamplifier, and automatic gain control (AGC) detector-amplifier.

The purpose of the AGC is twofold. The amount of FM feedback (i.e., loop gain) is proportional to the carrier level at the input of the discriminator. The AGC maintains this level constant and stabilizes the loop gain. Practical limiters are not good enough to do this and, in fact, limiter input amplitude should be controlled for the best limiting (Reference 6). The second purpose of the AGC is to provide a measure of the received carrier strength. The AGC voltage is calibrated in terms of known signal levels at the antenna input (Reference 7).

Measurements of the performance of the receivers were made both in the laboratory and in the field. Figure 4 is a measurement graph of audio S_0/N_0 versus input C/N; it also shows the threshold. The C/N is referred to a 6-kc noise bandwidth. An image-rejection filter precedes the mixer, and the RF carrier-to-noise ratio is measured ahead of this filter.

The exact C/N at which the threshold occurs is somewhat arbitrary, since the knee of the curve is not sharp. However, in this receiver, when the C/N is above the threshold the circuit is very quiet. At the point marked "threshold" in Figure 4, a cracking or popping sound begins. Chaffee (Reference 1) noted this effect, which sounds remarkably like the popping of corn. In this work, the threshold is assumed to occur when the popping starts. This effect, to the ear, is much more drastic than is indicated by the measured rms value of S_0/N_0. It is safe to say that at 1 db below this threshold the circuit is not usable in a practical way, while just above the threshold the quality is excellent. A measurement of S_0/N_0 versus C/N for the case where the feedback is zero (loop open) is included in Figure 4. In this figure it is actually $1/N_0$ that is plotted and referred to the signal output S_0 obtained above the threshold. The threshold improvement of this receiver, compared to a conventional FM receiver with the same RF bandwidth, is about 9 db.

The audio-frequency response of the receiver is given in Figure 5, and is determined primarily by the filter in the audio amplifier.

During the operations the receiving systems were tested by inserting known signals into the antennas and plotting the output S_0/N_0 versus input carrier power. Figure 6 is an example of such a calibration made at the Jet Propulsion Laboratory facility at Goldstone Lake, California. For this particular case the threshold occurred at -120 dbm, and the feedback is approximately 23 db.

When the whole receiving system is involved, the accuracy of the threshold measurement is a function of the accuracy of the RF input signal level and the gain and noise-temperature stability of the RF receiver. The -120 dbm threshold was often observed and is probably correct to within 2 db.

CONSIDERATIONS IN FEEDBACK DESIGN

The minimum bandwidth required for a frequency-modulated signal is twice the bandwidth of the modulating signal. The IF filter in the FMFB receiver therefore has this bandwidth, $2f_b$. As was discussed previously, the maximum threshold improvement is obtained when the closed-loop bandwidth is a minimum for a given feedback factor. Any excess phase shift will increase the closed-loop bandwidth and is therefore undesirable.

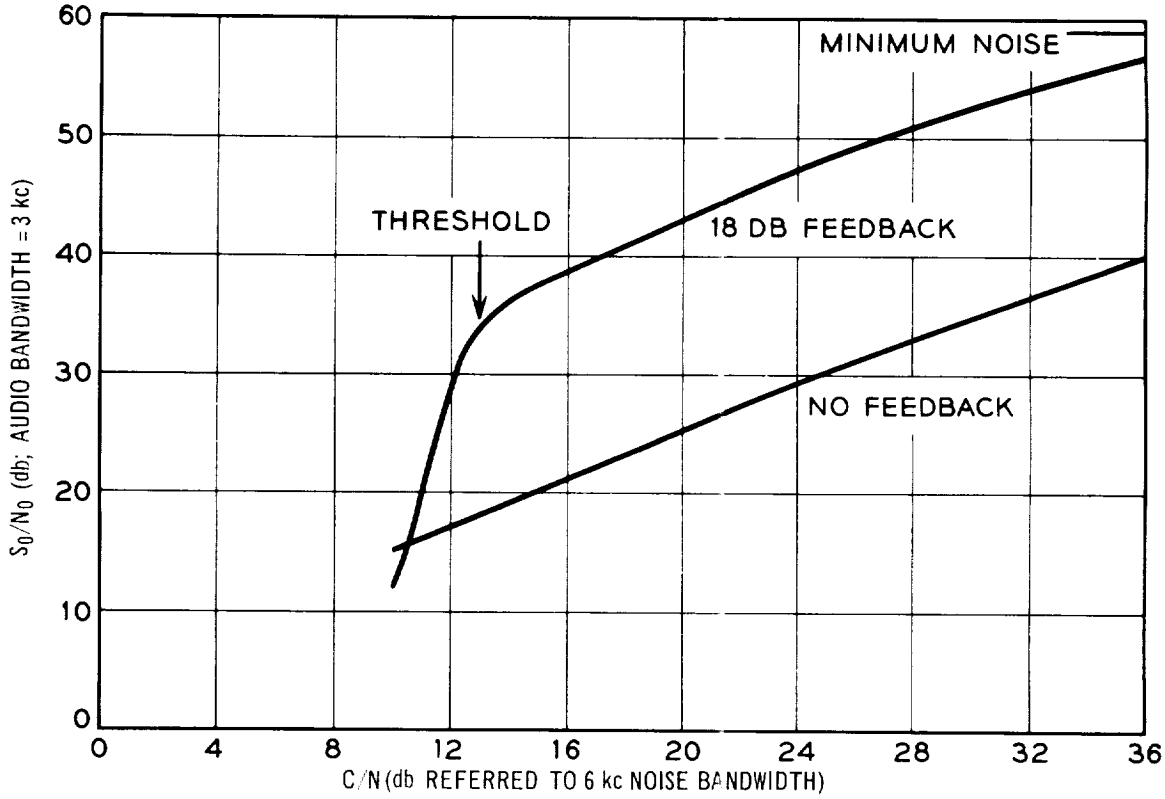

Figure 4 - Threshold measurements

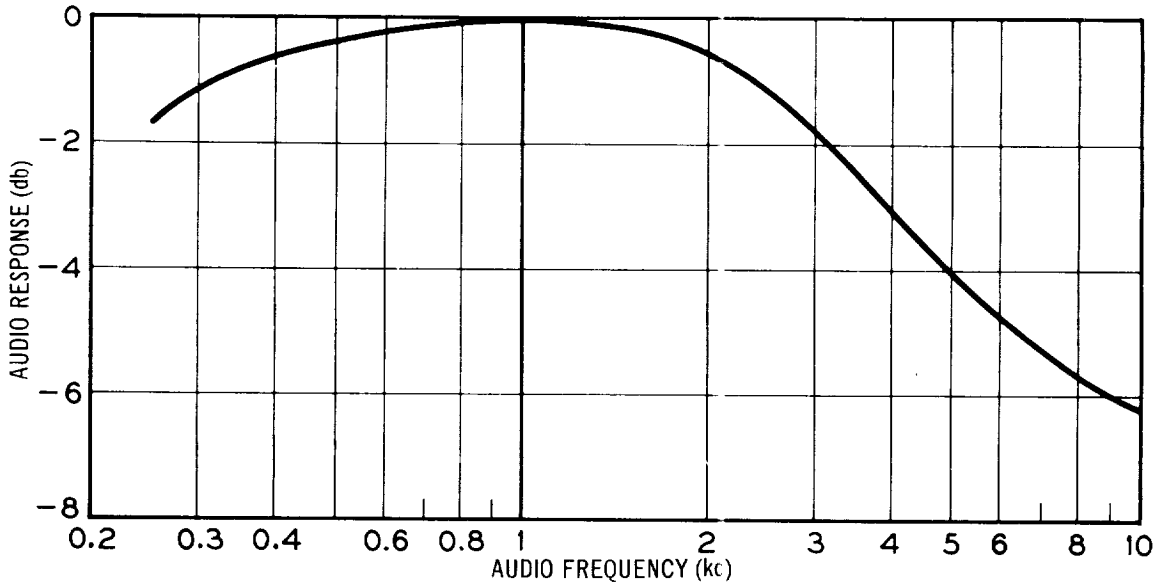

Figure 5 - System audio response.

In the Echo receivers, all circuits were made extremely broad in order to minimize excess phase shift, and the shaping was done in the IF filter. There are several important factors which warrant discussion.

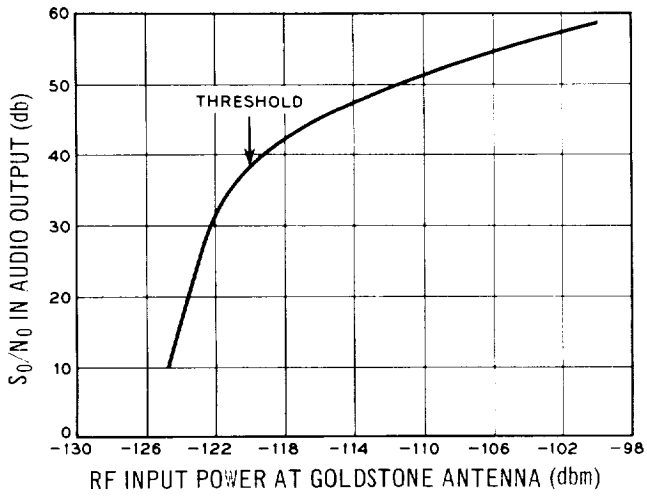

Figure 6 – Demodulator calibration at Goldstone Lake, August 11, 1960

IF Frequency

The output of the broad-band discriminator is largely carrier power. This cannot be allowed to reach the VCO, so a filter is required to reduce the carrier and its harmonics and allow the baseband through with the least possible phase shift. Therefore the IF frequency should be as high as possible. The upper limit is determined by the circuit Q obtainable for the IF filter. Coil Q's in the megacycle region are limited to 400 to 500, so an IF frequency of 1.2 Mc was chosen, requiring loaded Q's of approximately 1200 kc/6kc = 200. The corresponding baseband filter is M-derived, with a cutoff frequency of 1 Mc.

Discriminator

The discriminator is a balanced circuit with a single-ended output. No filtering is used on the output side of the diodes except for the baseband filter. The usual filtering with capacitors would increase the output but would also introduce excess phase shift. The balance property provides some limiting in the absence of modulation.

Limiter

Limiters contain reactive elements and therefore add to the excess phase. For this reason, multistage limiters were avoided and a single-stage limiter was used. For best results, this limiter requires a controlled input level (Reference 6); hence the AGC operates to fix the level at the limiter input.

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REFERENCES

1. Chaffee, J. G., "Application of Negative Feedback to Frequency-Modulation Systems," Bell System Tech. J. 18: 404-437, July 1939

2. Carson, J. R., "Frequency-Modulation: Theory of the Feedback Receiving Circuit," Bell System Tech. J. 18: 395-403, July 1939

3. Bode, H. W., "Network Analysis Amplifier Design," New York: Van Nostrand, 1945

4. Enloe, L. H., to be published

5. Rice, S. O., "Statistical Properties of a Sine Wave Plus Random Noise," Bell System Tech. J. 27(1):109-157, January 1948

6. Ruthroff, C. L., "Amplitude Modulation Suppression in FM Systems," Bell System Tech. J. 37(4):1023-1046, July 1958

7. Ohm, E. A., "Project Echo - Receiving System," Bell System Tech. J. 40(4):1065-1094, July 1961; also NASA Technical Note D-1130, in publication, 1961