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# Description of the Lincoln Laboratory Wideband ELF Noise Recording Systems

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LINCOLN LABORATORY

# DESCRIPTION OF THE LINCOLN LABORATORY WIDEBAND ELF NOISE RECORDING SYSTEMS

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## ABSTRACT

This report describes the systems used to record wideband (12 Hz - 300 Hz) extremely low frequency (ELF) electromagnetic noise in a number of geographic locations. The first section centers on the analog recording system employed in Florida. Simply stated, analog tapes were recorded and later converted to digital tapes for further processing. Section II describes the "NAVCOM" system which employed on site digital recording. The final section describes the calibration procedures used to relate the digitalized data to absolute electromagnetic field levels.

A distinctive feature of both systems is the care taken to preserve the wide dynamic range of the ELF noise while reducing the amount of man-made interference recorded. Results of analyzing the recorded noise data to optimize communications system performance in this frequency band are described in companion reports.

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## I. INTRODUCTION

A decision was reached by the Laboratory during the Fall of 1967 to enter a program to collect and analyze extremely low frequency (ELF) electromagnetic atmospheric noise after it became apparent that previous noise-measurement programs had concentrated on narrowband measurements that might conceal properties of the noise which could be exploited in a receiving system. The objective of the program was to record and analyze, in as wide a band as practical, ELF noise from geographical locations with low power-line interference and high thunderstorm activity.

A description of the recording effort is facilitated if it is undertaken in three sections. The first section centers on the analog recording system employed in Florida. Simply stated, analog tapes were recorded and later converted to digital tapes for further processing. Section II describes the "NAVCOM" system which employed on site digital recording. In both cases the antennas and front ends are essentially identical. The final section describes the calibration procedures used to relate the digitalized data to absolute electromagnetic field levels. Some results of the analysis effort are described in [4-6].

## II. DESCRIPTION OF RECORDING SYSTEM AND DIGITAL TAPE FORMAT FOR "LASA" FORMAT DIGITAL TAPES (FLORIDA RECORDINGS)

The initial noise-measurement effort concentrated on the design and procurement of equipment and the location of a suitable site. A satisfactory site was located on property of the Lykes Brothers Steamship Lines near LaBelle, Florida ($26^{\circ}$ 51'N, $81^{\circ}$ 31'W). A preliminary field survey showed that 60 Hz electromagnetic fields did not interfere. In addition, the site was removed from all well traveled roads, thus eliminating ground vibration as an interfering effect. The site is located in a region where there is extremely high thunderstorm activity from June through September.

A. Description of Antennas

Two loops and one whip antenna were constructed to measure the horizontal magnetic and vertical electric fields. The loops are oriented in a north-south, east-west configuration and are mounted inside a temporary 8- by 8- by 8-foot hut constructed of 3-inch Dyrelite foam laminated onto 0.25-inch plywood. Both loops are rigidly mounted onto a base which is then physically isolated from ground motion by several layers of packing material. Each of the loops is 1.57 meters in diameter and contains 471 turns of No. 14 copper wire. The turns area product is 910 square meters. The low-frequency series equivalent circuit of the loop is comprised of a 0.75-henry inductance in series with a $19\Omega$ resistor. Self-resonant frequency of the loops is approximately 6 kHz.

Electrical field strength is sensed by a 12-foot vertical whip antenna enclosed in a 12-inch fiberglass cylindrical windshield. Guying is provided for the windshield in the event of high winds, but it is otherwise self-supporting. The whip antenna is located approximately 40 feet from the hut enclosing the loops. A ground system is established with 12 bronze rods driven 8 feet down and interconnected by 1-inch copper braid. Figure 1 shows the site in May 1968.

B. Electronics Description

The initial measurements were accomplished with an analog tape-recording system. This instrumentation was superseded by the digital recording system described in the next section. The following description is that of the analog recording system. Noise data was recorded in the FM mode and returned to the Laboratory where digital tapes were made for detailed digital processing. Since the only available tape recorders required 60 Hz power for the tape drive, it was necessary to separate the recorder and the sensitive antennas by 200 feet to reduce self-interference. The hut contains its own batteries, preamplifiers, calibration circuits, and line drivers; a distant vehicle contains line receivers, tape recorder, monitoring circuits, batteries, and remote control of the hut electronics. A detailed block diagram of the recording system is shown in Fig. 2.

1. Hut Electronics

Located in the hut are the three preamplifiers for the three sensors. Each loop is coupled into its amplifier through a 50-to-1 step-up transformer. Loop amplifiers are the high-input impedance field effect transistor (FET) type. These amplifiers have a gain of 20 dB and are mechanically insulated from their surroundings to avoid microphonic effects associated with such high-impedance devices. Input transformer characteristics restrict the useful bandwidth to approximately 300 Hz. An additional low-pass filter with cutoff at 320 Hz and a steep skirt follows each loop preamplifier to further remove out-of-band noise. Tangential signal sensitivity at 20 Hz for the loop channels is calculated as - 30 dB with respect to $1\ \mu a/m/\sqrt{Hz}$.

An FET high-input impedance source follower is utilized as an impedance transformer for the whip channel. A voltage gain of 1.0 is suitable for this channel since voltage levels derived from the whip are higher and dynamic range is extended if a lower gain is employed. The first field trip revealed signal contamination due to wind movement of the whip and possible "fair weather fields" that were unacceptable. A 12 Hz cutoff high-pass filter was installed to diminish these effects. A 320 Hz low-pass filter also serves to eliminate out-of-band interference and noise, including some VLF stations.

The dynamic range of the atmospheric noise tends to be very large in an area like Florida so some means are necessary to record the data without compromising this range. In order to accommodate the 40 dB dynamic range of the tape recorder a high and low gain version of each channel was recorded. A 20 dB difference in gain was maintained between the two channels. Using this method the recording process can be accomplished with a 60 dB range of signal levels. Odd numbered channels were reserved for the low gain version, even numbered channels are used for high gain recording. A limiter clips the high noise peaks in the high gain channel prior to recording.

2. Remote Electronics

The actual recording process takes place in an air-conditioned vehicle some 200 feet from the hut. Balanced line receivers accept the six-channel information and apply it to six channels of the Ampex FR 1300 tape recorder. A seventh recording channel is operated with zero input for reasons to be discussed later. Tape speed is 15 inches/second corresponding to a recording bandwidth of 5 kHz, and a record time of approximately 40 minutes/reel. Some of the later tapes were made at 1 7/8 rps. Power for the tape recorder is derived from a DC-to-60 Hz inverter contained in a doubly shielded magnetic enclosure. Operation of the tape recorder does not introduce measurable additional 60 Hz components in the recording process. An auxiliary edge track recording channel is supplied to allow insertion of voiced comments including tape and time identification. Monitoring of recorded signals is accomplished with an oscilloscope and a channel-selector switch. All battery and supply voltages are displayed on the monitor panel.

A rustrak strip chart recorder was also available to plot the average of the mean square wideband signal. Averaging time was approximately 40 seconds for this recorder. Such a recording allows one to refer a particular short-term tape to the general background intensity as measured over several hours. It is particularly useful in establishing the rise and decline of local thunderstorm activity.

C. Procedure

In making an analog tape, the following procedure is used:

(a) A voice entry is made identifying the day, time and any important meterological phenomenon.

(b) One minute of the 30 Hz triangular wave calibration is recorded.

(c) Six channels of data are recorded for approximately 37 minutes. During this time, local forecasts and weather conditions are recorded from the AM radio in the vehicle as available. Any changes in local weather conditions are also noted.

(d) One minute of the calibration signal is recorded at the conclusion of the tape.

A simple direction of arrival unit has been constructed which operates in conjunction with the two loops and one whip sensor to read out an x, y plot on an oscilloscope. This unit has been used to verify the general location of high-intensity storms and, on one occasion, the display was highly correlated with a known storm center in the Fort Myers area.

D. Summary of Data Taken

Approximately 40 hours of analog recordings have been obtained during several trips to the Florida site during 1968-69. All the 1968 data and part of the 1969 data has been converted to digital tapes. Data thus far reveal the noise characteristics during a quiet period in February and a moderately active period in May. In addition to the two Florida trips, one investigatory trip was made to a remote area in New Hampshire to verify that the general characteristics of noise measured at that site correspond to that found in Flordia. Although the 60 Hz interference was high at this site, it was possible to conclude that the noise at both sites was similar and, furthermore, that there was nothing peculiarly different at either of the sites.

E. Analog-to-Digital Conversion

The analog tapes are returned to the Laboratory where they are played back from an identical tape recorder at the record speed. At this time, the output of channel 7 which does not contain data is subtracted from the remaining six channels with the result that wow and flutter components are diminished. The resultant signals are then applied to a multiplexer which may be programmed to select from one to six channels for A/D conversion via a 14-bit Adage model VMX-32B A/D converter and subsequent digital recording. This digital tape is then the basis for further analysis. The computer allows data analysis to take place with the full 60 dB dynamic range.

In Figs. 3 and 4 we show the spectrum and amplitude probability density function of the output of the A/D converter when the input terminals were shorted. These two figures give a measure of the degradation in data on the digital tapes due to jitter during the A/D conversion process.

Prior to A/D conversion, the playback electronics are adjusted so that the 30 Hz triangular wave calibration had a 1.0 volt peak-to-peak input level.* This enables one to check the digital tape produced to determine what deviation, if any, exist between the actual ratio of digital levels/volt input to the nominal level of 2144 digital levels/volt input.

F. Format of Converted Data on the Digital Tape

The output of the A/D converter is buffered onto a 7 track 800 bit per inch digital computer tape by a Digital Equipment PDP-7 computer. The particular tape format used is an adaptation of a format used for recording seismic array data on computer tape and has been given the name "LASA" format tape for the purposes of this documentation. (References 1 and 2 give a description of the use of such tapes in the seismic work.) The converted data words are stored in the computer memory until 400 samples from each channel have been converted whereupon a physical record consisting of 4 header words together with the 400 samples from each channel are written on the tape. To make the tape IBM compatible, the data is placed on the tape in 6 bit blocks (with an odd parity bit in the seventh track**) and a 3/4 inch gap between physical records.

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*Any A/D conversions with a playback gain that deviates from this level have the playback level noted on the record of the particular A/D conversion.

**Also, seven "longitudinal parity bits" are placed at the end of a physical record to further aid in error detection.

In Fig. 5, we show the relation of the 14 bit A/D converter output to the 18 bit data word put on the digital tape. The computer program (i.e., read package "IOPAK") that reads the data from the digital tape into core memory of the computer shifts the value on the tape right one bit so that the least significant bit on the tape is lost (this was done to reduce effects of the telephone line noise in the seismic program). Thus, the A/D converter output is shifted left one bit before being recorded on the digital tape.

In Fig. 6 we show how the 18 bit words in the core memory of the PDP-7 are placed onto the digital tape while in Fig. 7 we indicate the organization of the header word information.

## III. DESCRIPTION OF RECEIVER AND DIGITAL TAPES FOR "NAVY COMMUNICATIONS" FORMAT TAPES

The second generation recording systems used in the field* to acquire broad band atmospheric noise data utilize digital tape-recording techniques and, with the exception of the antennas and associated preamplifier electronics are contained in mobile, self-supporting motor vehicle terminals. A block diagram of one system is shown in Fig. 8. The following is a description of this digital tape recording system which superseded the analog system in September 1968.

Included in the first block to the left of the dashed line in Fig. 8 are Ithaco preamplifiers, low-pass filters (320 Hz), and Burr-Brown line drivers using a balanced input and output configuration. This portion of the system is essentially the same as the front end of the analog system.

The conditioned signals from the dual loops and vertical whip antenna are carried to their respective line receivers over approximately 200 feet of twisted pair shielded balanced line. The 200 feet represents the separation between the antenna location and the data-recording terminal. All equipment to the right of the dashed line in Fig. 8 is found in the recording terminal, and all to the left, with the exception of the whip antenna, is enclosed within a

*To date, this system has been used successfully in Norway, Malta and Saipan.

prefabricated wooden shelter. The whip antenna is contained in a separate cylindrical fiberglass enclosure to reduce wind loading. A full description of the antenna configuration, both physical and electrical, was given in the previous section.

Following the line receivers is a calibrate switching network where calibration signals are injected in place of the antenna signals. The calibrate switching is effected by means of an analog multiplexer utilizing high-speed FET's.

The three outputs of the switching net are amplified and passed through twin "T" active 400-cycle notch filters. System power is supplied at 28 and 12 volts DC. However, some of the equipment is standard off-the-shelf hardware and was not designed around a DC power source. Therefore, DC to 400-cycle AC solid-state inverters are used to supply the required 115-volt AC primary voltage for those particular devices. The purpose of the 400-cycle notch filters is, of course, to eliminate any possible interference from the 400-cycle inverters.

At the output of the notch filters, the three signals are divided into two paths each, with more amplification in each leg to scale the signals up in level for the ± 10 volt peak signal reference used in the following analog-to-digital conversion process. One of the paths of each signal has an additional 36 dB of gain represented by amplifiers G in Fig. 8. The function of this additional amplification is to effect a better than 90 dB dynamic range using only a single 12-bit analog-to-digital converter. The way in which this is performed will be discussed later.

The resulting six signal paths, a high-and low-gain channel of each of the three original signals, form the inputs to six sample-and-hold amplifiers. The sample-and-holds are Raytheon models SH9 with aperature times in the order of 50 nsec and settling times of 5 μsec maximum. At this point, the analog signals are simultaneously sampled at a 1 kHz rate and held as they are sequentially multiplexed through to a 12-bit analog-to-digital converter.

The multiplexer and A/D converter combination is a Raytheon multiverter package using a model ADC21-12B converter with 11 bits plus sign in 2's complement code. Since the throughput rate of the multiverter is 50 kHz, the analog signals are sampled and converted to digital form in 50 kHz bursts at a burst rate of 1 kHz. Each burst is composed of six (12-bit) digital words, with a high-and-low-order word describing samples of each of the three original analog signals.

With 36 dB of additional gain in the low-order (high-gain) path of each signal, the combination of the high-and low-order (12-bit) samples effect a data sample word length of 18 bits. This may be more easily described by referring to Fig. 9. For simplicity, two A/D converters are shown in the figure, where in the actual system only one is time-shared in the multiverter. The point labeled "analog data sample" is the point at which the signals are divided into two paths each, with one path of each containing the additional gain. Both samples are converted to 11 bits plus sign (sequentially through the multiplexer by a single A/D converter in the actual system) and passed onto the recording as two separate words.

During processing of the recorded tape on a computer, the programmer may select which of the two words will be used as the data sample or, after checking for correlation of the five overlapping bits, may use the combination of both words for an effective 18-bit data word.* The 17 bits of magnitude represent a dynamic range of 102 dB, but discounting the first couple of bits to system noise results in a more realistic figure of 15 bits of resolution for a dynamic range of 90 dB.

It must be noted that the dynamic range figure given above assumes that all recorded data is of equal interest. If, however, strong background

*The algorithm used to date at Lincoln Laboratory has been to:

1. Set the data value = (low order data word - low order dc offset) if the low order data word absolute value is less than or equal to 1024 (= $2^{10}$).

2. Otherwise, set the data value = (high order dataword - high order dc offset) x (ratio of high order gain/low order gain). The equipment is normally adjusted to produce a ratio of 64:1.

interference (e.g., that caused by power lines) is present in the data the useful data to noise ratio obtained with the above system may be well below that obtained using an 18 bit A/D converter. This situation was observed experimentally in recordings at a site in Malta where the very strong 50 Hz radiation from a nearby power line caused the lower order data word to saturate continually so that the high order data word was generally utilized. The quantization noise of the high order data word has an rms value of 19 levels which was comparable to the natural ELF noise levels. Thus, even though the 50 Hz power line could be removed from the digitized data by appropriate digital filtering, the filtered data was not representative of natural ELF noise due to the increased quantization noise. This particular problem was solved by additional analog notch filtering prior to the A/D converter.

Additional insight into the differences between the 18 bit data word obtained by combining the two overlapping 12 bit data words and an 18 bit data word obtained from an 18 bit A/D converter can be obtained from Fig. 19. In Fig. 19, we have plotted the ratio, R, of signal level to rms quantization noise as a function of signal level. We see that R is monotonically increasing with signal level for an 18 bit A/D converter whereas there is a drop in R for the ELF noise recording system when the low order data word saturates. From Fig. 19, we see that it is important that the useful signal level be no worse than 20 dB below the recorded signal level for recorded signal levels near 1000 digital levels.

At the output of the A/D converter the 12-bit words are split into six-bit characters, odd parity is added, and the resulting 7-bit characters are passed on by means of a digital multiplexer to a tape buffer/formater (core memory). Parity is checked for correctness first at the output of the memory as the characters are transferred to the tape recorder, and again by the read-after-write electronics in the tape transport. Visual error indicators are available for both check points.

The digital tape transport used for recording is a Potter model FT-152 designed for field recording work and powered from a 12-volt DC source. Recording is on seven tracks at a density of 800 BPI in IBM format.

At the 1 kHz sample rate of the three inputs with two 12-bit words per input, the data rate is 12,000 6-bit characters per second. Each data record is one second long with each headed by four additional 12-bit header words for a total of 12,008 characters per record. Allowing for the IBM-compatible, 3/4 inch, inter-record gaps, the data-recording rate is 12.63 kHz. With an 800-BPI density and 3/4-inch gaps, the tape speed is a conservative 15.8 inches per seond. The transport accommodates 10 1/2-inch reels containing 2400 feet of tape. Each tape therefore holds approximately 30 minutes of recorded data.

The format of the record header information is as shown in Fig. 10. With the data record lengths of one second each, the count described by header word 4 indicates record count from tape start as well as elapsed time (seconds in binary) after the initial start time of header words 1 and 2. All header information with the exception of the record counter and the calibration indicator bit (automatically set during calibration records) is initially set up by thumbwheel switches and automatically inserted at the proper time to head up each record. In Fig. 11, we show how the header words and data words are organized on the digital tape.

Calibration signals are inserted at the calibrate switching point (Fig. 8). Calibration takes place automatically at the beginning of, periodically during, and near the end of each digital tape recording. The periods of calibration are one record length (1 second) duration repeated every 7 minutes through-out each tape recording. The period length and repetition rate is thumbwheel selectable from the control panel. Manual calibration control is also available for initial calibration prior to recording. This calibration is used to check gain and any change in DC offset between the line receivers and the A/D converter output and is not to be confused with the absolute field strength calibration of section IV, which is performed bi-weekly by inserting a known signal level in series with the antennas.

Various signals can be used for the digital calibration. The waveform used with recorded tapes prior to January 23, 1969 was a series of step inputs, the amplitudes of which exercised full scale of both the high and low order legs of the A/D conversion and also intermediate levels to fall within the 5 bit crossover area of the two words.

To eliminate DC offset drift problems and also to simplify system alignment procedures, the DC coupling between the analog front end and the sample and hold input to the A/D converter was replaced with RC coupling on 23 January 1969. The 400 Hz notch filters were also deleted from the circuits at that time. Since that time, both recording systems have used a 40 Hz sine wave calibration signal for the recording calibration source. As before, this cal signal is used only to check gain ratio between the high and low channels and also aid in the detection of any existing offset at the A/D output.

As mentioned earlier, all equipment shown to the right of the dashed line in Fig. 8 is found in a recording terminal. The recording terminal in this case is a Clark Cortez camper vehicle, one model of which is shown in Fig. 12.

In Figs. 13-15 we show the results of some tests made to determine the dynamic range of the recording system. Figure 13 shows the spectrum of the NS loop for Malta tape AN1-047 of 25 November 1968 when the antenna was replaced by an .8 henry choke. Figure 14 shows the spectrum of the EW loop for Malta tape AN1-047 when the input to the EW loop preamplifier was shorted. Figure 15 shows the spectrum of the NS loop when the input to the NS loop sample and hold amplifier for the NS loop. From Figs. 13-15, it appears that the observed system noise is quite low relative to the few bits hypothesized for the system noise, and thus, the system dynamic range is above 90 dB.

## IV. CALIBRATION OF NOISE DATA TAPES

In this section, we outline the procedure used in obtaining absolute calibration for the noise data tapes from the special data tapes in which a known signal was injected at the antenna terminals as shown in Fig. 16. There are two types of signal used to establish the absolute calibration at all frequencies in the passband:

1. A sine wave of known amplitude and frequency (generally 100 Hz) is used to obtain the absolute calibration at a single frequency.*

2. A periodic train (with period .25 seconds) of narrow pulses (less than 100 μsec duration) is used as an approximation to a periodic train of impulses to give the relative frequency response across the system bandwidth.

By combining the results from the two signal inputs, the absolute calibration is established across the entire system passband. The remainder of this note discusses the procedure currently used at Lincoln Laboratory to establish the absolute calibration.

### A. Absolute Calibration at a Single Frequency

#### 1. Measuring Equipment and Error Analysis

Calibration of results in terms of absolute field strength is based on the following considerations. Absolute field strength measurements are based entirely on the loop antennae. No estimate of field strength based on the whip data is discussed or used in this report.

The loop antennas are wound on a "PVC" form approximately 5' in diameter, and securely mounted in a wood frame with brass support rods. All loops are fabricated in an identical manner. A discussion of magnetic field strength and loop antennas is grounded in its relationship between open circuit terminal voltage ($v_{oc}$) and the impinging field (H).

*In doing this, we assume that an injected signal of amplitude $v_o$ at frequency f is equivalent to an H-field of amplitude $v_o/(2\pi f \mu_o NA)$ where NA = turns-area product of the loop. It would be desirable to calibrate with a known H-field, but this is quite difficult to do at ELF in a satisfactory manner.

$v_{oc} = \mu_o \text{HNA} \omega$

$\mu_o \equiv$ permeability of free space, $4\pi \times 10^{-7}$ henry/meter (used for air core antennas discussed here)

$H \equiv$ magnetic field, amps/meter

$NA \equiv$ turns area product of loop, $(\text{meters})^2$

$v_{oc} \equiv$ open circuit terminal voltage due to effect of H field averaged over area of loop, volts

$\omega \equiv$ $(2\pi f)$ angular frequency of assumed sinusoidal field in radians/second.

Several questions related to the authenticity of loop measurements are suggested by an examination of this formula.

(a) Turns Area (NA). Number of turns on the loop was established with great care. Area was determined by direct measurement, and verified by an independent experiment. Following the technique described in [3], a one turn loop, one meter in diameter was constructed. Utilizing this loop as a transmitting antenna coaxial with the large receiving loop excellent agreement with the predicted results were obtained. On the basis this experiment and physical measurements the NA product is correct within ± 0.8%.

(b) Permeability ($\mu_o$). Permeability of free space has been assumed for the air core loops. During the experiment described above measurements were conducted with and without mounting supports with no noticeable effect. Placement of the front end electronics near the loop in the normal mounting location produced no effect either. No error is assumed to be present using the permeability of free space.

(c) Frequency. For calibration purposes it is necessary to establish the calibration frequency with some accuracy. A HP 204C oscillator was generally employed at the field sites to insert the calibration signal at the antenna. Laboratory experiments reveal that the oscillator will probably be set to an accuracy of ± 4% at 100 Hz. Fortunately, this field misalignment does not have to be tolerated as degrading the calibration since the analysis programs can be used to ascertain the actual frequency employed for a particular tape. Providing this method is employed no error need accrue due to frequency mis-alignment. Frequency stability of this oscillator (1 part in $10^4$ per 20 minutes) is sufficient to impose narrow band filtering (.244 Hz) in the analysis program.

As stated before, the calibration signal is injected in series with the loop antenna as shown in Fig. 16. In connection with this calibration method several other factors will have a bearing on the resulting accuracy of the calibration.

(a) A Ballantine Model No. 323 true rms voltmeter is used to ascertain the signal level injected into the attenuator pad. If it is assumed that the cal signal was measured at, or near full scale then the result has an accuracy of ± 2% at 100 Hz. If an average error in reading the meter is assumed to be 1% then the most probable error to be attributed to the meter is ± 2.2%.

(b) The attenuator has been measured on a bridge and it is accurate to ± 0.1%.

(c) Wideband noise picked up by the antenna and coupled back to the voltmeter is negligible.

(d) Atmospheric noise and possible power line harmonics at or near the calibration frequency will affect the energy in the passband of the analyzing filter used to "pick out" the calibration signal. This effect is minimized by using a large calibration signal relative to the interference. A signal to noise ratio of 40 dB in a 1 Hz bandwidth has been the typical ratio in most of the calibration runs. Based on this ratio it is possible to say that background noise has not affected the calibration signal estimate in any significant manner.

(e) Gain stability and frequency response of the recording system has remained relatively constant from calibration to calibration.

Maximum variation in gain has been 1% over a one month period.

(f) Quantization errors due to the 12 bit A/D converter are insignificant at the signal levels used and no error is attributed to the digital processing employed.

(g) Variation of sample rate is determined by the stability of a temperature controlled crystal oscillator. Drift rate of this oscillator is one part in $10^7$ /day. If the frequency drift is assumed monotonic then the equivalent change in frequency at 100 Hz would be .01 Hz after 1000 days. No error is associated with this source.

After consideration of the factors discussed here the following error estimate is considered representative of the factors involved in the noise measurement program.

| Source | Error |
|---|---|
| Turns area | ± .8% |
| Meter reading | ± 2.2% |
| Attenuator pad | ± 0.1% |
| Gain variation | ± 1.0 |
| Peak error | ± 4.1% or ± .35 dB peak. |

The most probable error assuming that the error from each source is independent of the other and represents the $1\sigma$ level is

$$\sqrt{(.8)^2 + (2.2)^2 + (.1)^2 + (1)^2} = 2.54\% \text{ or } \pm .22 \text{ dB.}$$

2. Absolute Calibration at a Single Frequency from the Spectral Analysis Results for Sine Wave Calibration Tape

In this section, we discuss a method of determining the absolute calibration at a single frequency from the results of spectrum analysis using a spectral analysis computer program and the known amplitude of the injected sine wave. The steps are as follows.

(a) Spectrum estimates are obtained every (1000/4096)Hz from 1.024 seconds of data. From the value of the spectrum at the frequency of the injected sine wave, one can determine the amplitude of the sine wave using formulas presented later on in this section.

(b) The recording site data log sheet that accompanies the tape indicates the amplitude of the sine wave (generally in rms-volts) injected at the antenna terminals.

(c) The H-field in amps per meter that is equivalent to the injected signal is assumed to have amplitude

$$H = \frac{v_{oc}}{2\pi f NA} = \frac{1.3918 \times 10^2}{f(\text{Hz})} \quad v_{oc} \text{ (volts)} \tag{1}$$

for the antennas with a turns-area produce NA = 910 square meters.

(d) From (a) and (c), we can establish the ratio between $(\text{digital levels})^2$ and $(\text{amps/meter})^2$ at the frequency of the injected sinusoid [one digital level $\triangleq$ least significant bit in the high gain channel data word].

We now want to determine the formula relating the amplitude in digital levels to the value of the spectrum obtained by the spectral analysis computer program. The method by which this computer program obtains spectra is discussed in Ref. 4. We will consider here the case where the number of data segments averaged over is one (the number of segments averaged over affects the stability of estimates for noise data, but has no effect on the results for a deterministic signal such as the sine wave used for calibration).

The computer program computes the estimate of the spectrum at frequency $f_o$ as:

$$s(f_o) = 10 \log_{10} \left[\frac{1}{\text{SUMWT}} \left| X(f_o) \right|^2\right] \tag{2}$$

where

$$X(f_o) = \sum_{k=0}^{N-1} w(k)x(kT)e^{-j2\pi f_o kT} \tag{3}$$

$$\text{SUMWT} = \sum_{k=0}^{N-1} w^2(k) \tag{4}$$

$X(kT)$ = value of the input waveform at time $kT$

$w(k)$ = data window used to reduce effects of power lines on the spectrum estimates

= 1 for all $k$ if "no window" is used

$= 1 - \left|\frac{k-(N/2)}{N}\right|$ if a "$1 - |t|$" window is used.

When the input is a sinusoid at frequency $f_o$ with amplitude $A$, it can be shown* that $s(f_o)$ is closely approximated by

$$s(f_o)=10 \log_{10}[\tfrac{1}{2}(N\langle w(k)\rangle A)^2/N \langle w^2(k)\rangle] \tag{5}$$

$$=10 \log_{10} [\frac{NA^2}{4} \frac{\langle w(k)\rangle^2}{\langle w^2(k)\rangle}] \tag{6}$$

where $\langle w^m(k)\rangle \triangleq$ time average value of $[w(k)]^m$. The quantity

$$\frac{\langle w(k)\rangle^2}{\langle w^2(k)\rangle} = 1 \text{ for "no window"} \tag{7}$$

$$= \frac{3}{4} \text{ for "}1 - |t|\text{" window.} \tag{8}$$

Example

We now illustrate the above steps using data from Norway tape AN2-002. The injected signal was of amplitude 25 mv rms into a 1000-1 pad (i.e., the value of resistance R in Fig. 16 was 1000 ohms) at a frequency of 1000 Hz. In Fig. 17 we show the spectrum of the NS loop channel on this tape using $N = 1024$ and a "$1-|t|$" data window. We now go through the steps of the procedure outlined above:

(a) From Fig. 17, we see that the computed spectrum level was approximately 93.97 dB at 100 Hz. Thus, from equations (6) and (8), we conclude that the injected sinewave had an amplitude (peak) of $A = 3.622 \times 10^3$ digital levels.

*By substituting $x(kT) = A \cos(2\pi f_o kT + \theta)$ into equation (3).

(b) The injected signal at the terminals had an amplitude (peak) of

$$v_{oc} = (25 \times 10^{-6} \text{ volts})(1.414) = 35.35 \times 10^{-6} \text{ volts (peak)}.$$

(c) This is equivalent to a H-field of amplitude (peak)

$$H = \frac{1.3918 \times 10^2}{1 \times 10^2} (35.35 \times 10^{-6}) = 4.92 \times 10^{-5} \text{ amps per meter}.$$

(d) Thus, we conclude that at 100 Hz

$\underline{1 \text{ digital level} = 1.36 \times 10^{-8} \text{ amps per meter}}$.

3. System Relative Frequency Response from the Spectrum Analysis Results for Impulse Train Calibration Tapes

The determination of the system relative frequency response from spectrum analysis of a calibration tape generated by injected periodic train of narrow pulses at the antenna terminal (as indicated in Fig. 16) is quite straight-forward. In Fig. 18, we show the results of such an analysis (using N = 1024 samples of data and transforms of length 4096 samples) on Norway tape AN2-003. It should be noted that the frequency response shown in Fig. 18 does not include the antenna transfer function between H-field and volts at the antenna terminal. This antenna transfer function (of 6 dB per octave) must be included in determining the absolute calibration at all frequencies from the single frequency calibration.

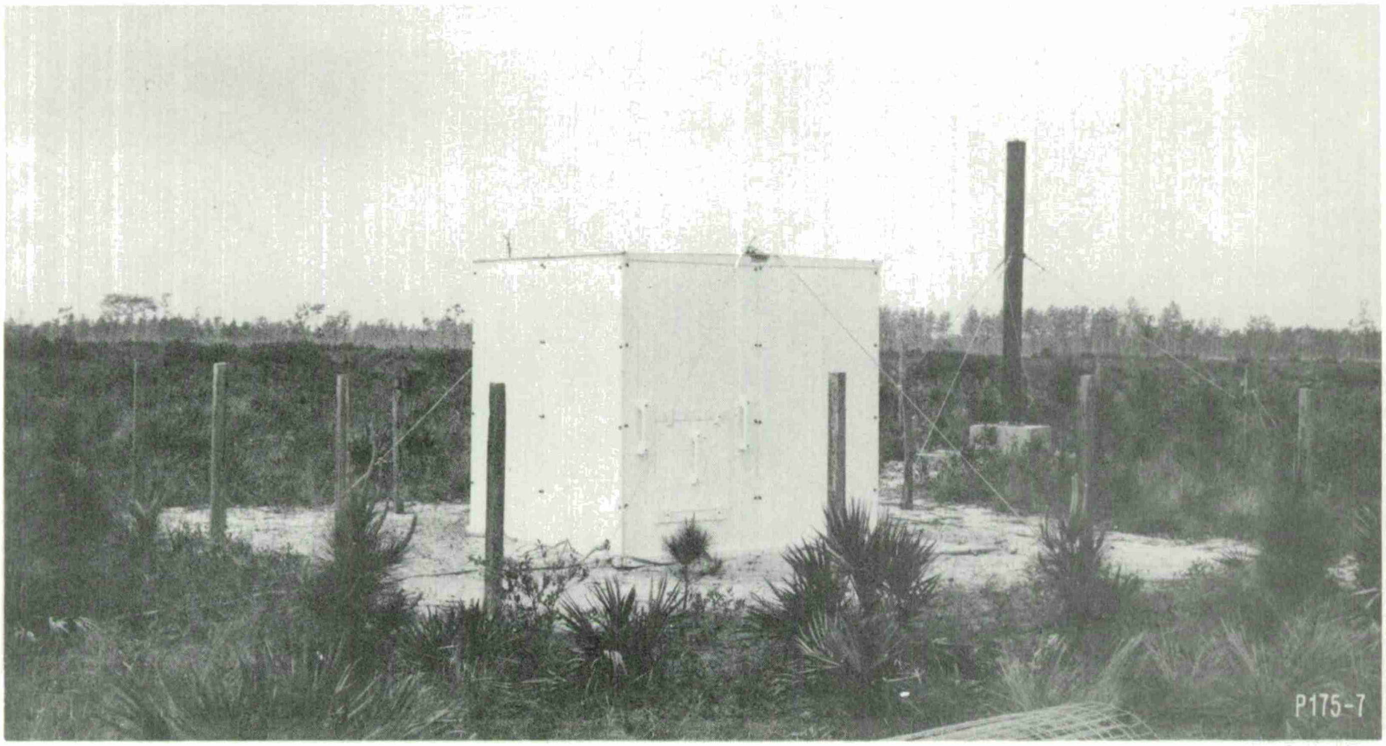


Fig. 1. Florida noise measurements site.

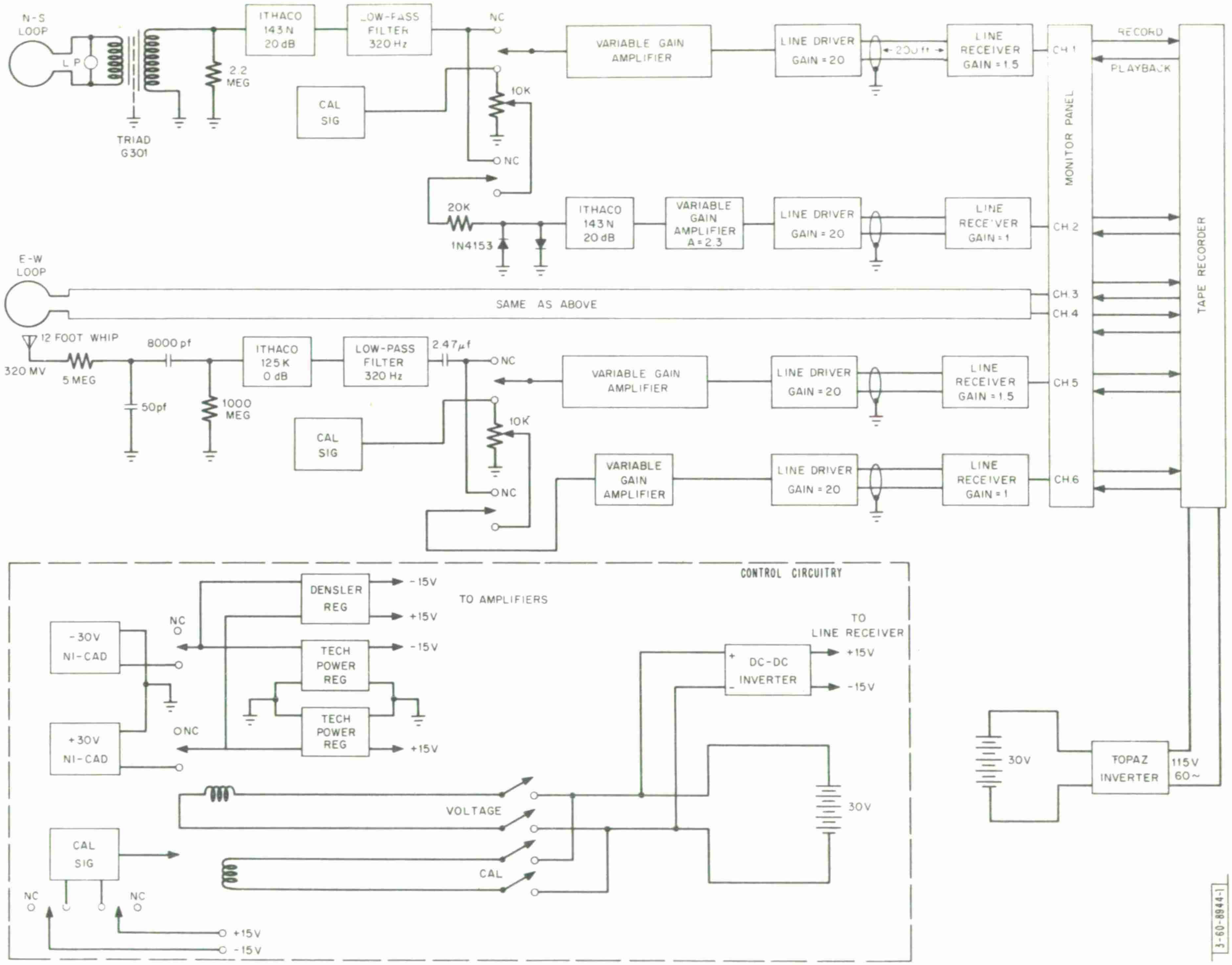


Fig. 2. Detailed block diagram of noise instrumentation.

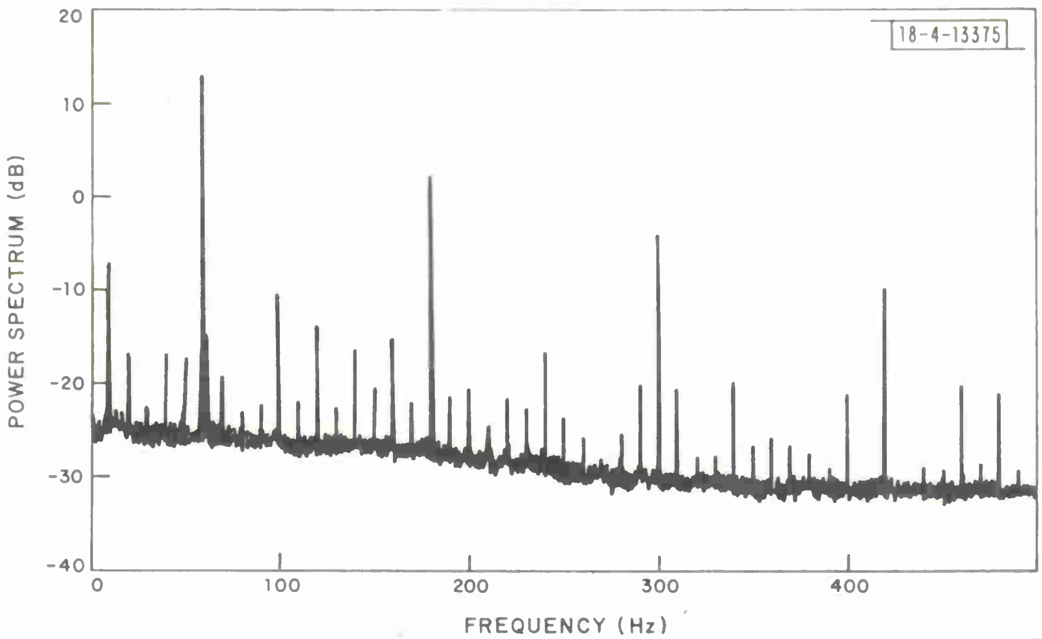


Fig. 3. Spectrum of output of A/D converter with input shorted.

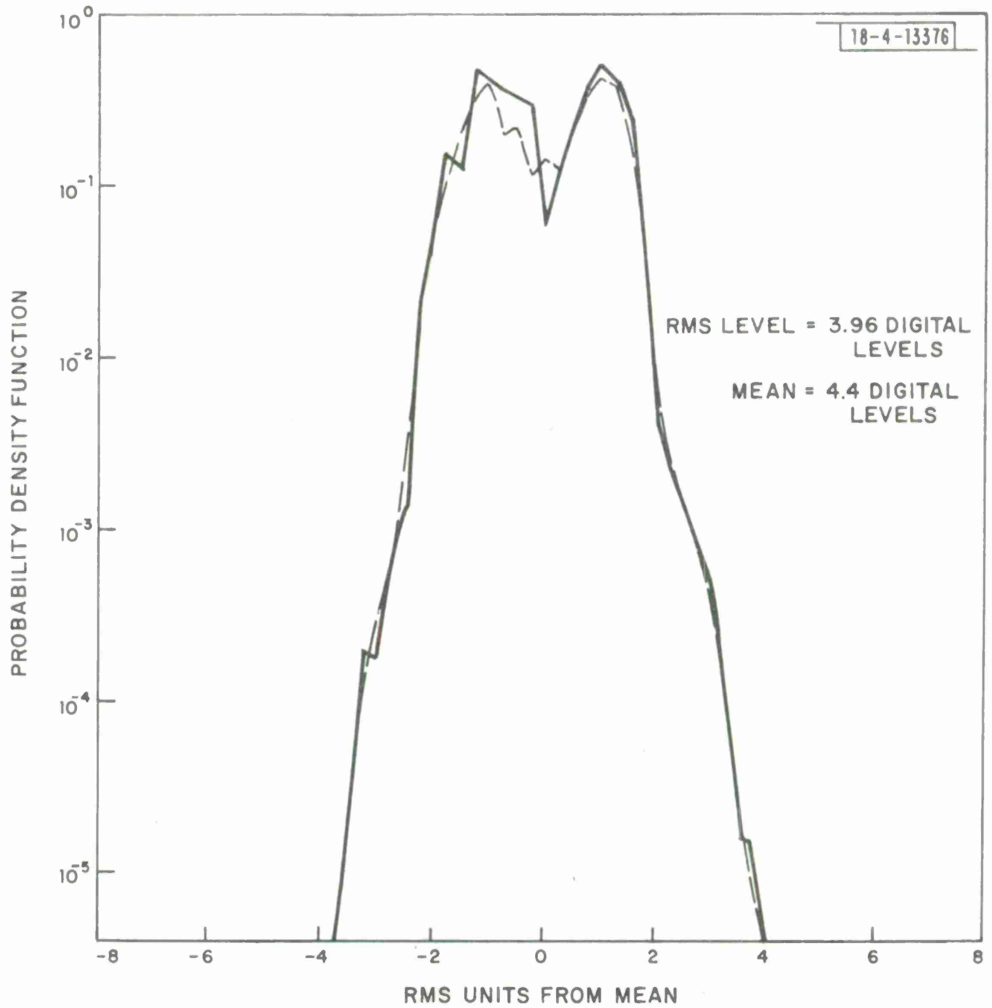


Fig. 4. Probability density function of output of A/D converter with input shorted.

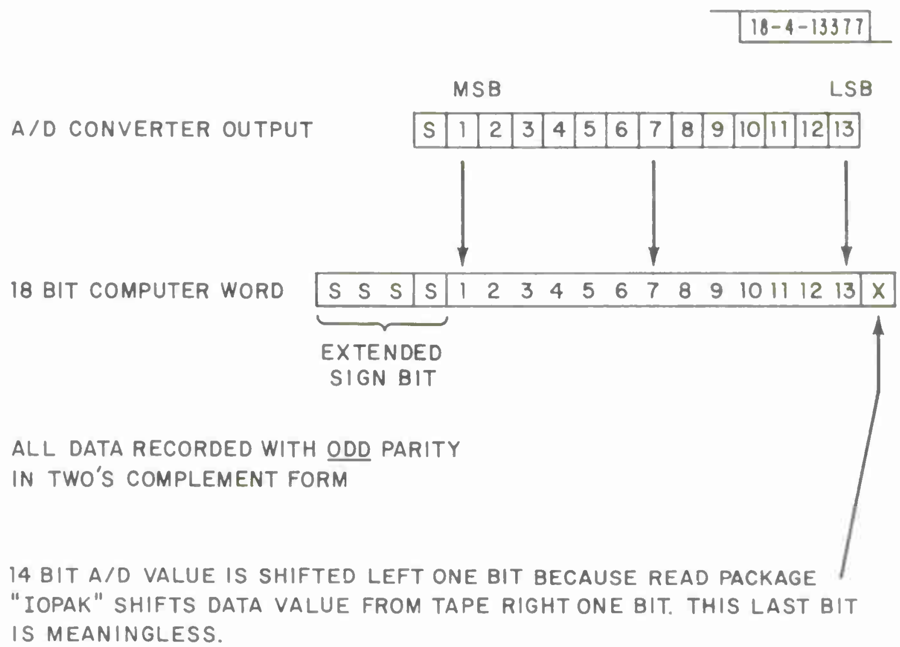


Fig. 5. Relation of 14 bit A/D converter output to 18 bit data word for "LASA" format digital tapes.

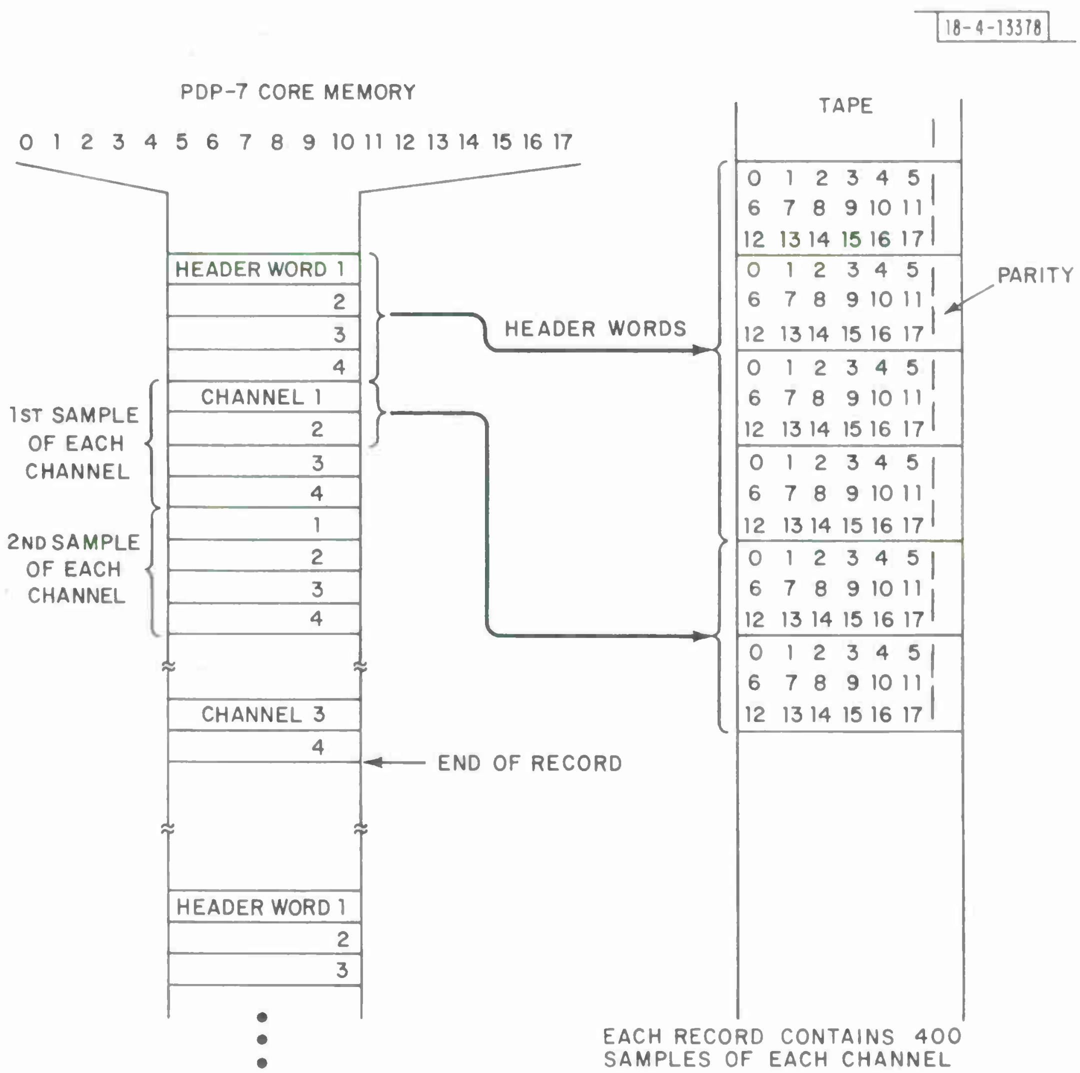


Fig. 6. "LASA" digital tape format for 7 track tape.

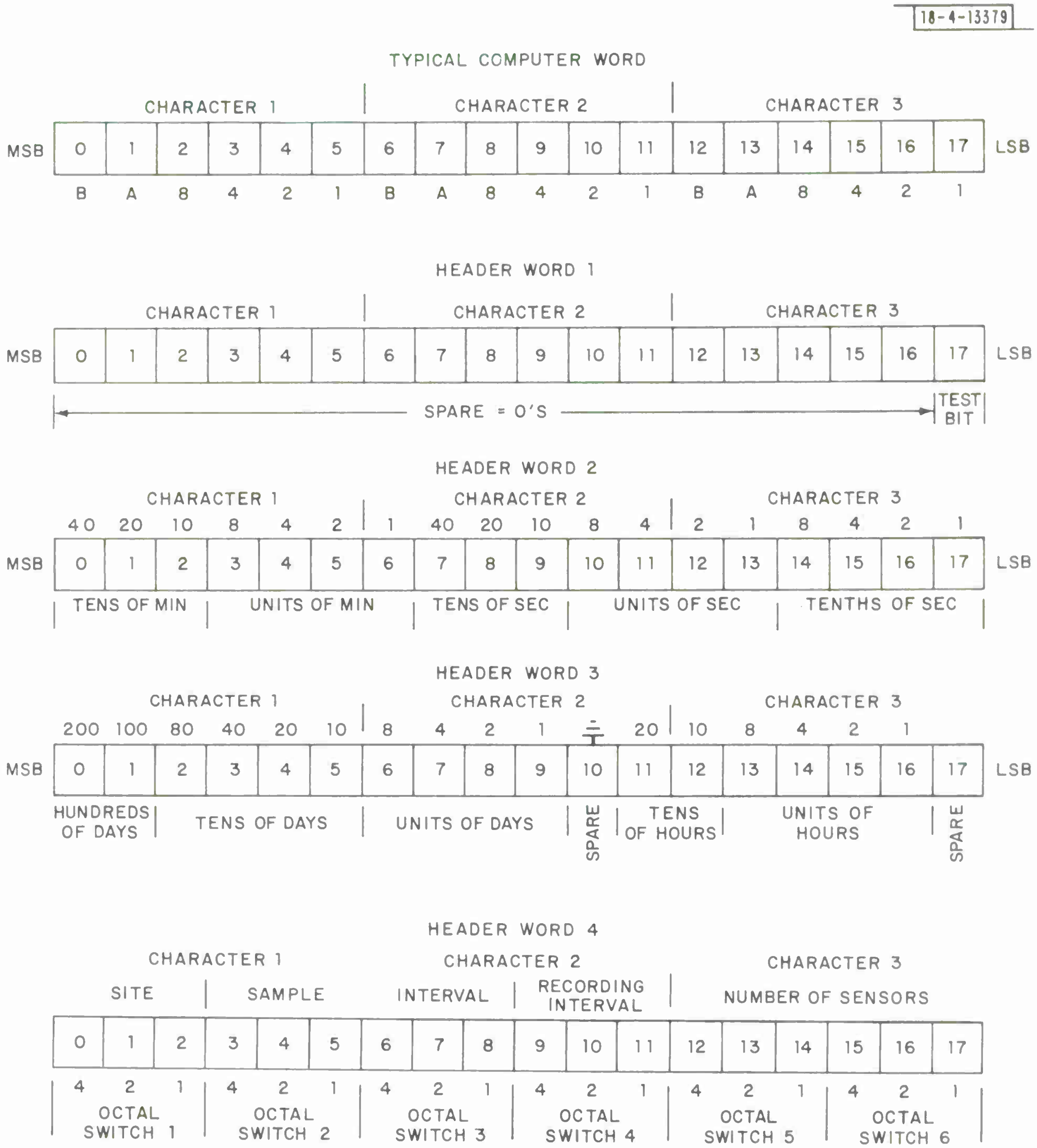


Fig. 7. "LASA" format tape header description.

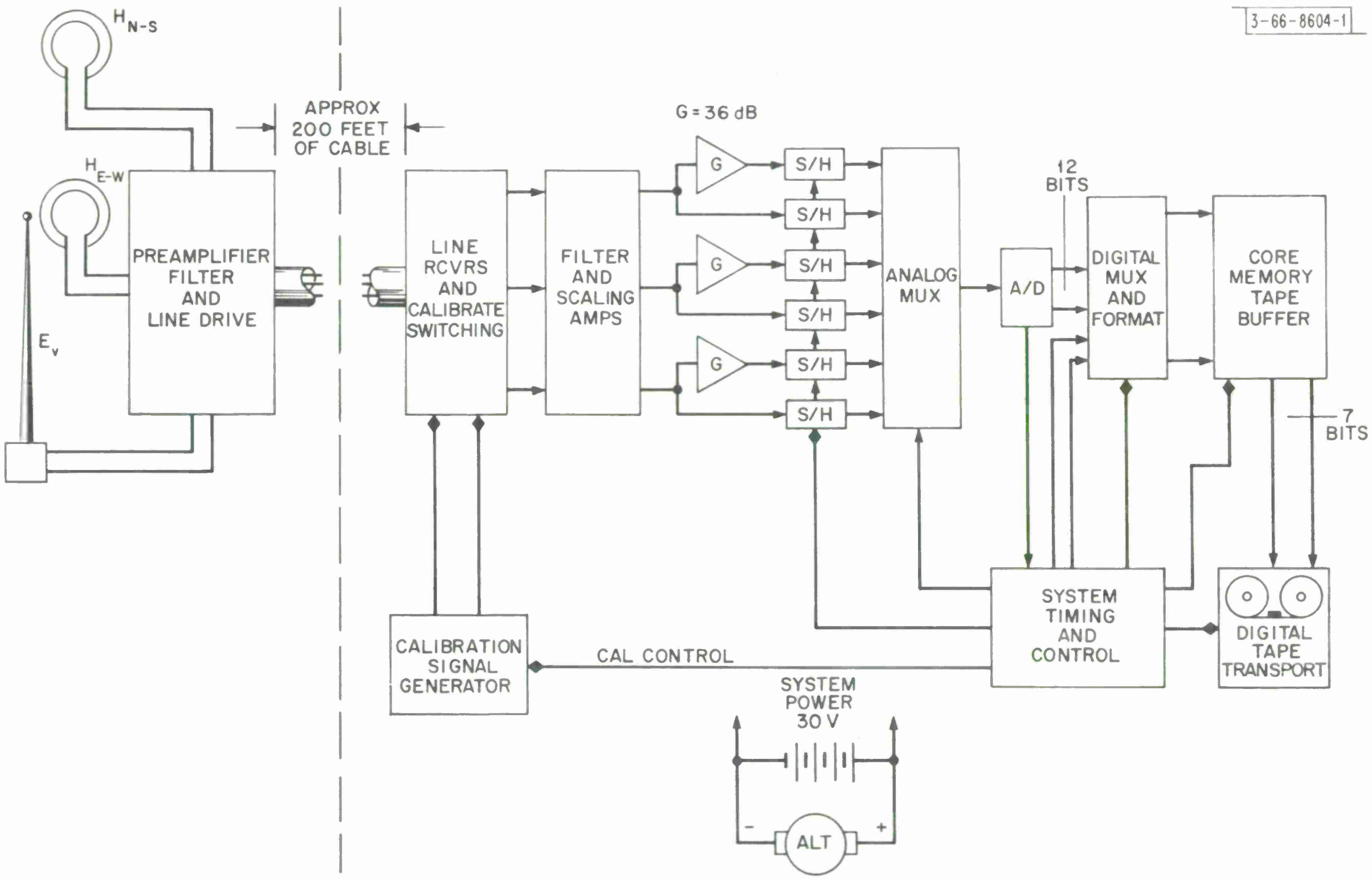


Fig. 8. Atmospheric noise data acquisition system.

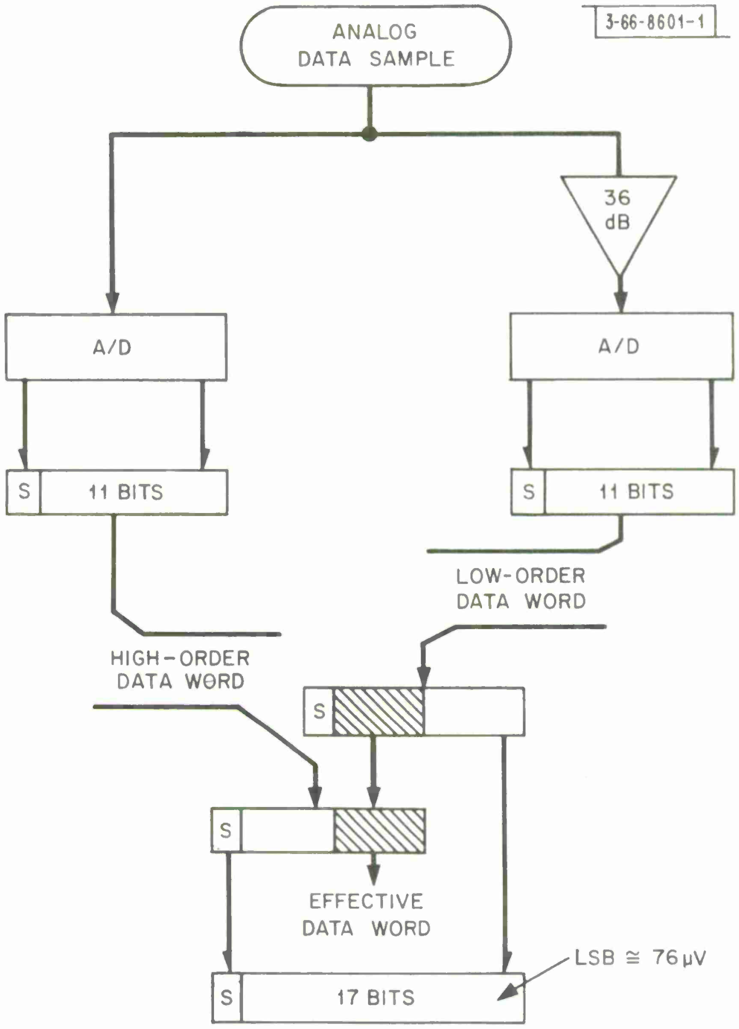


Fig. 9. Analog-to-digital conversion.

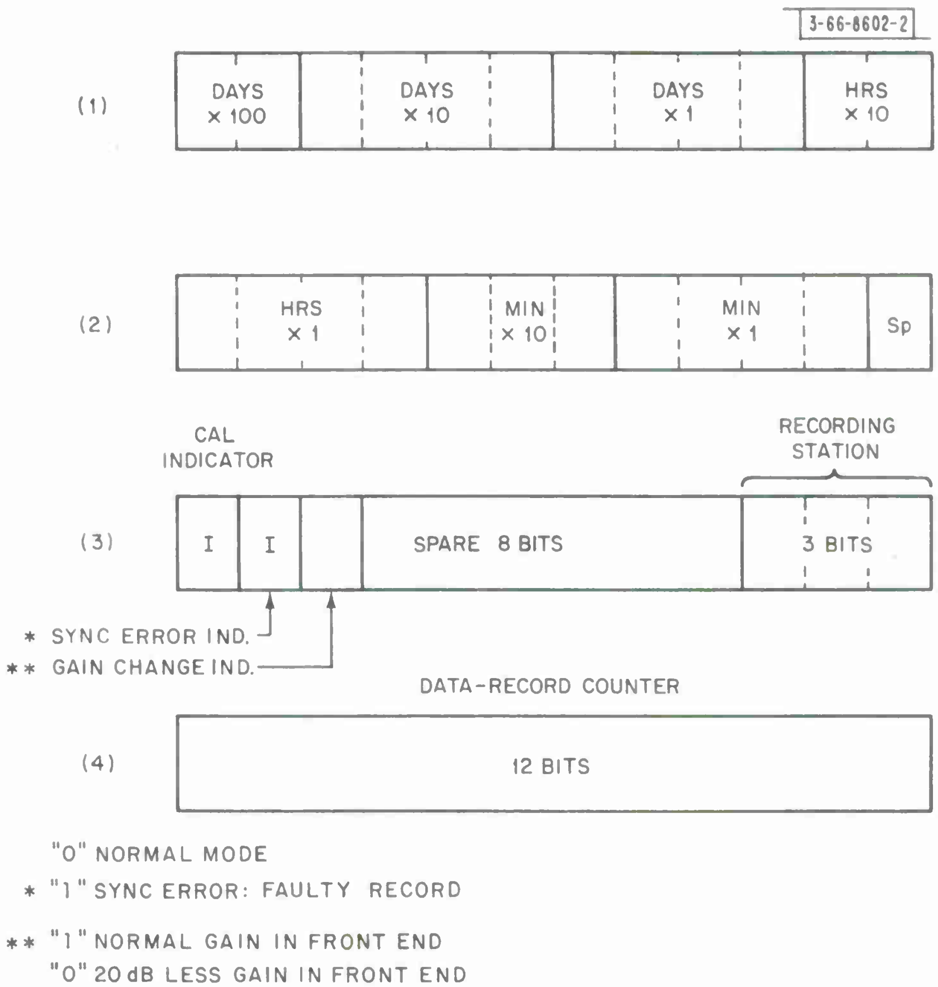


Fig. 10. Tape record header words (12 bits each).

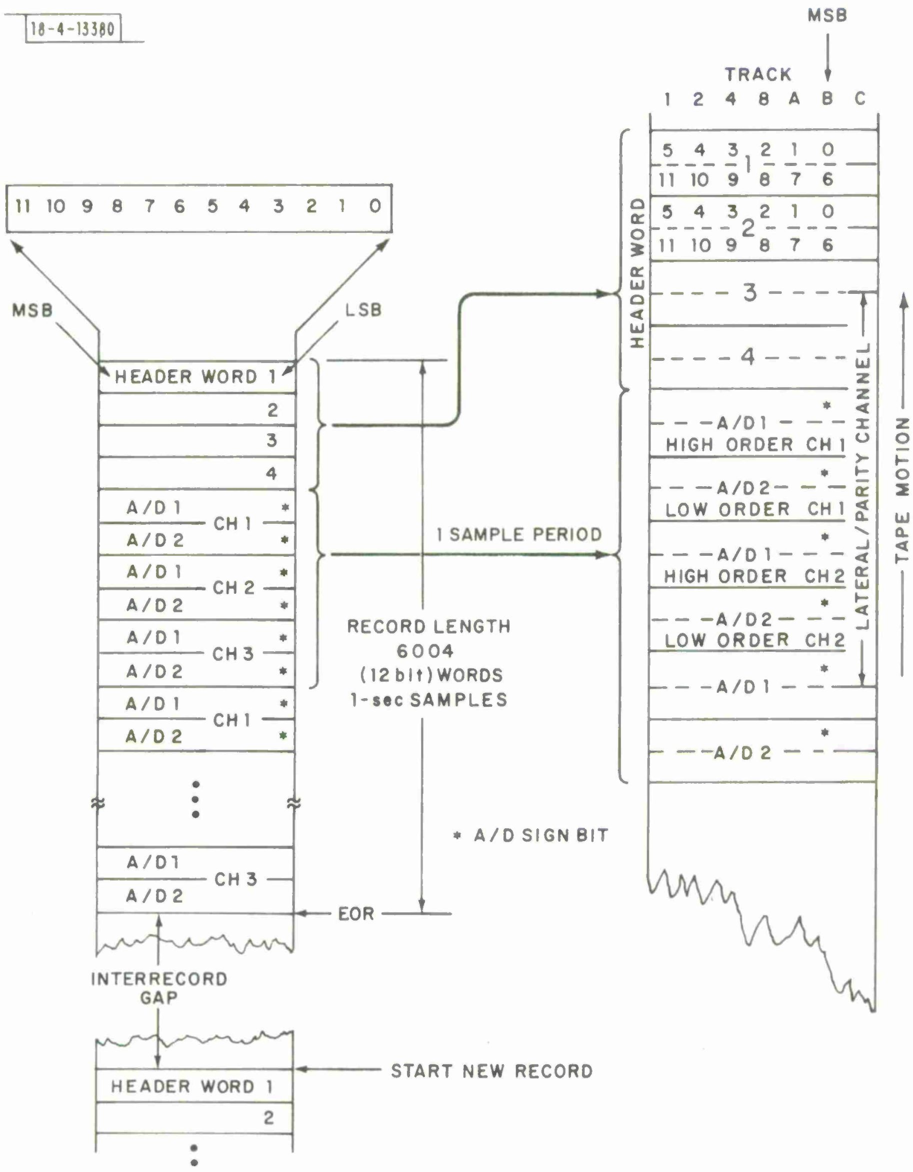


Fig. 11. Digital data format for "NAVCOM" tapes (shown for 7 track recording).

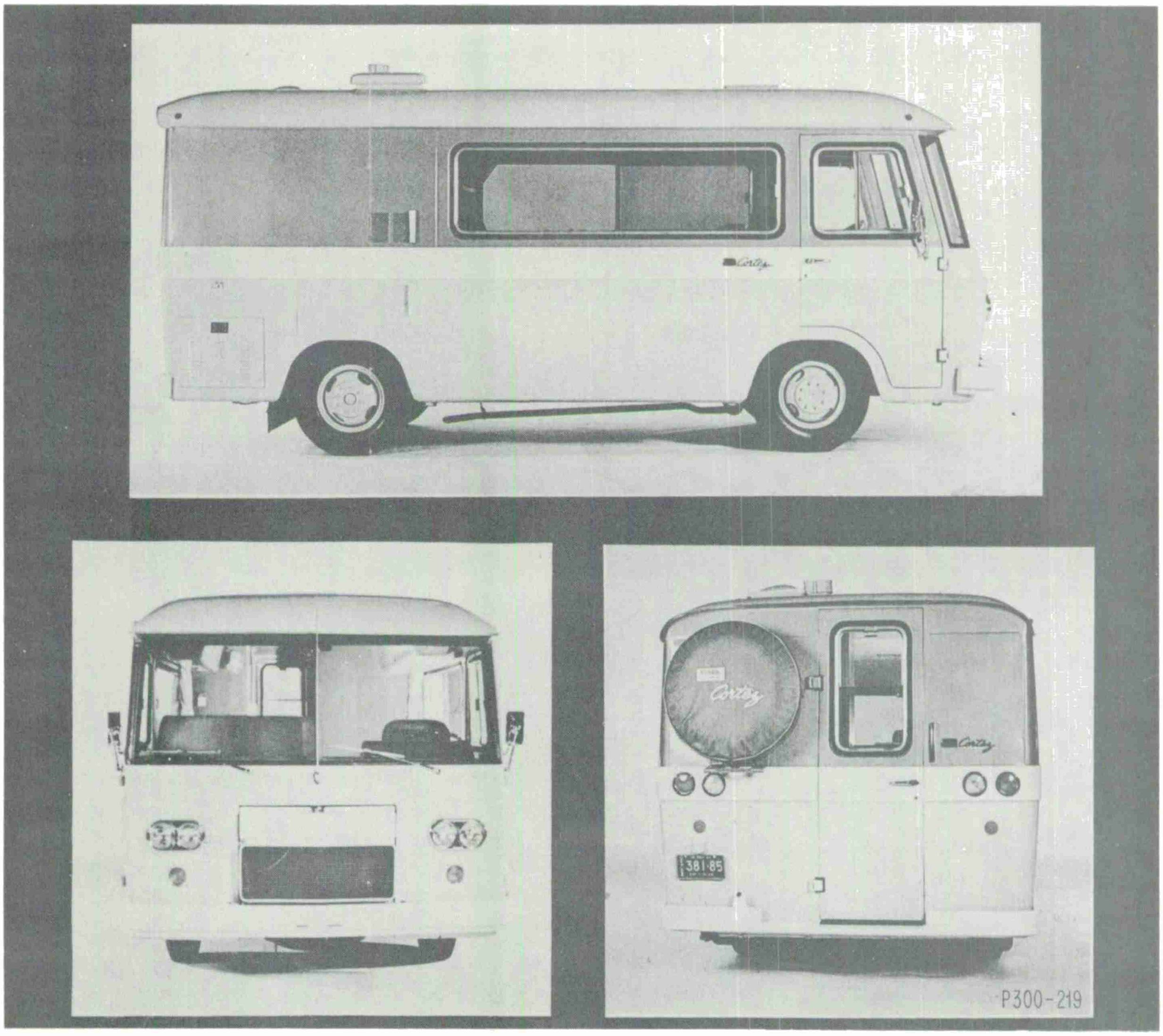


Fig. 12. Clark Cortez vehicle.

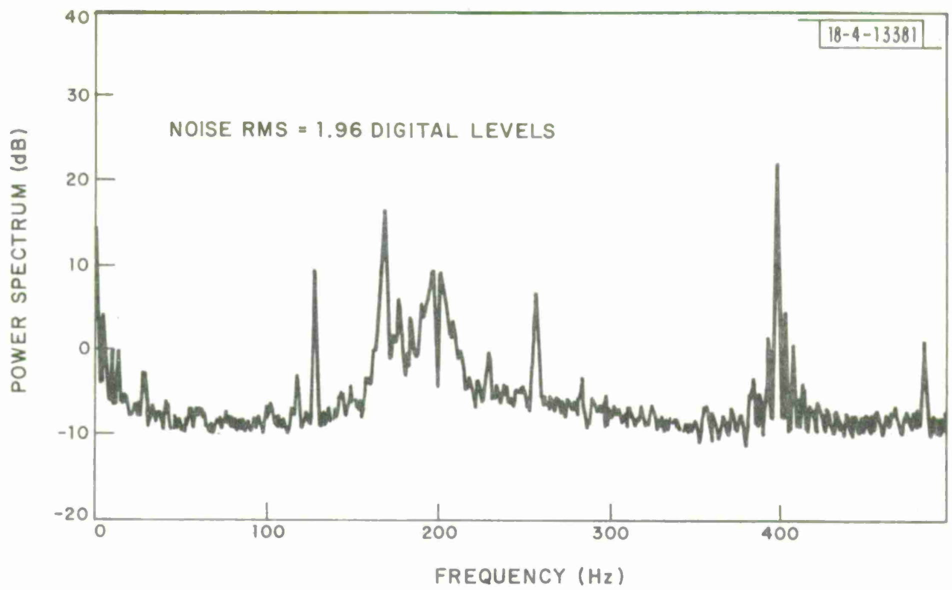


Fig. 13. Spectrum of NS loop channel with 0.8 Hz choke in place of antenna.

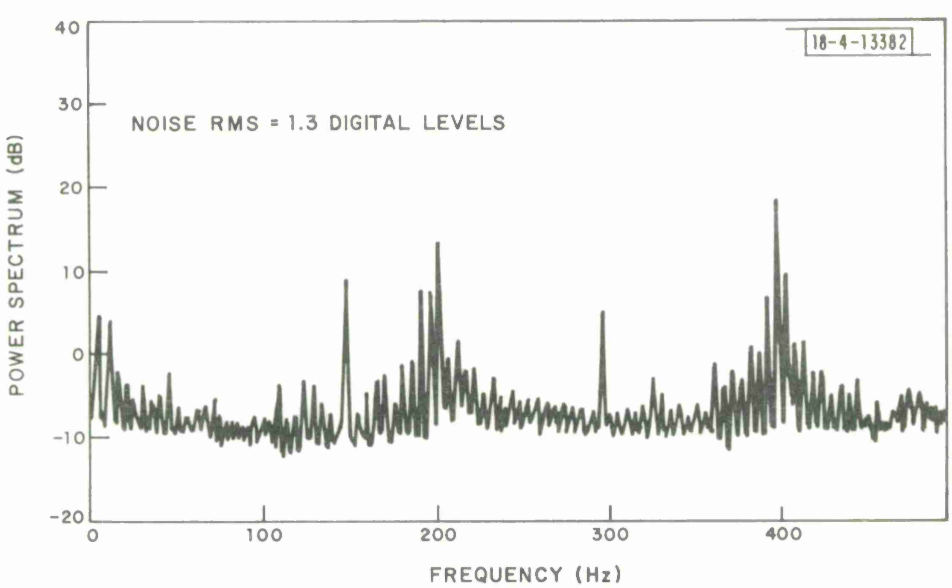


Fig. 14. Spectrum of EW loop channel with input to EW loop preamplifier shorted.

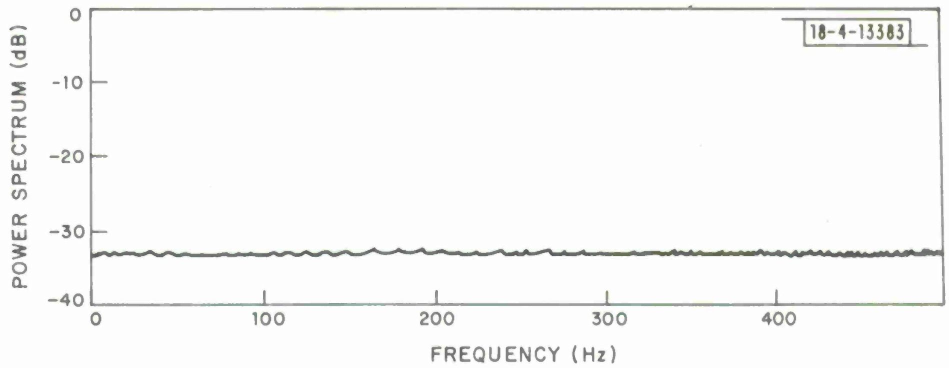


Fig. 15. Spectrum of NS loop channel with input to sample and hold amplifier shorted.

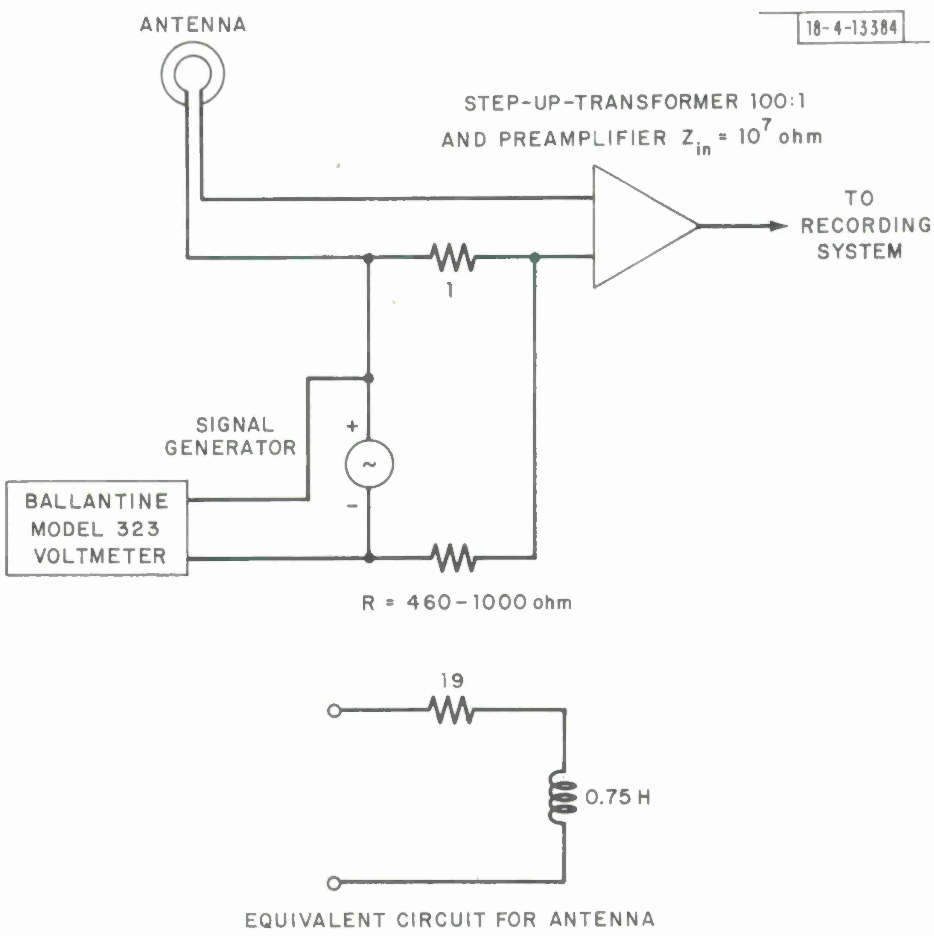


Fig. 16. Signal injection setup for absolute calibration.

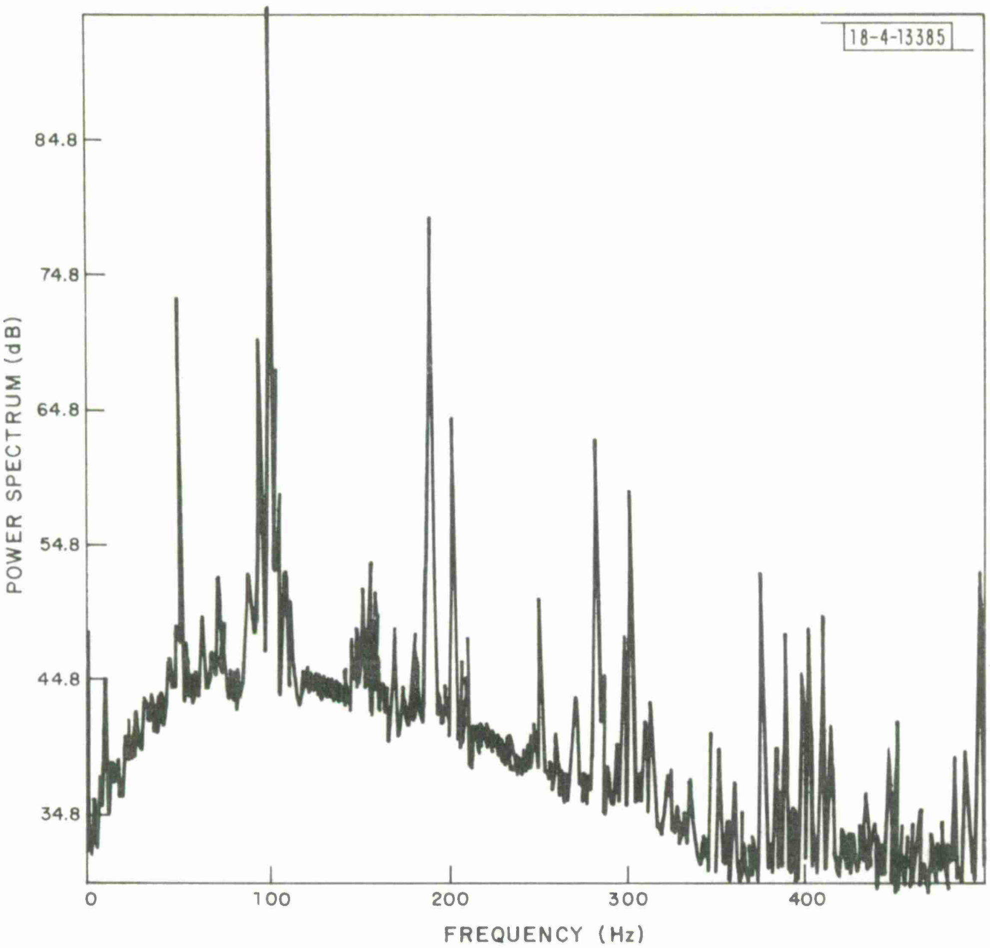


Fig. 17. Results of spectrum analysis on sine wave calibration tape AN2-002.

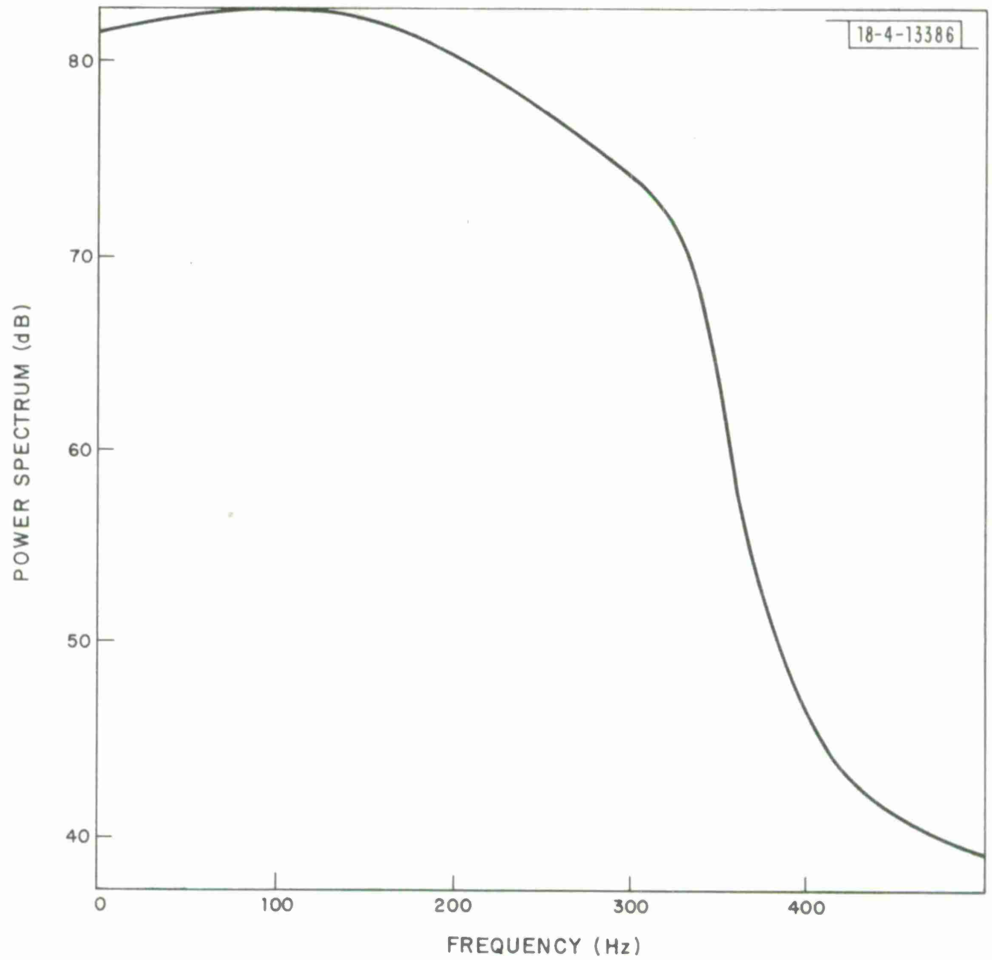


Fig. 18. Results of spectrum analysis on impulse response tape AN2-003.

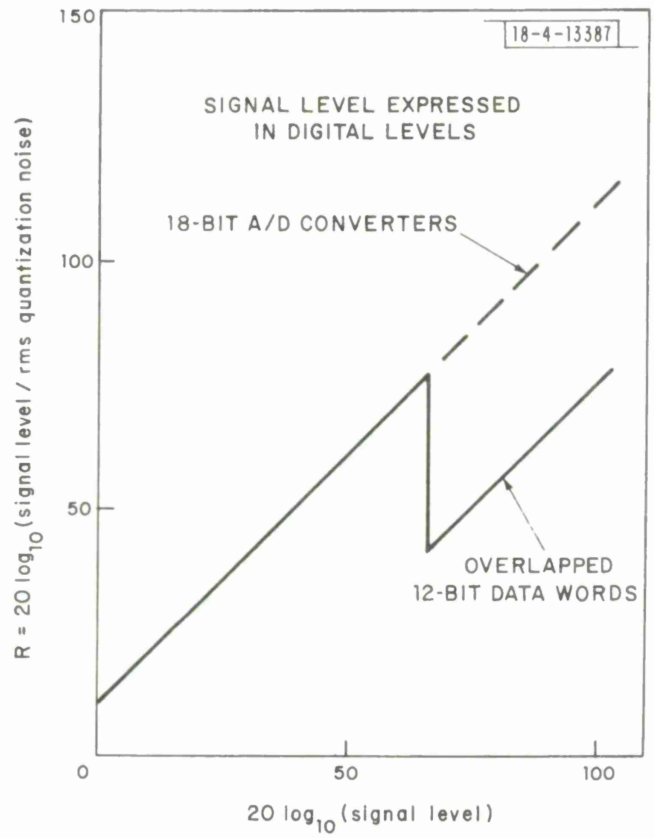


Fig. 19. Signal to quantization noise as a function of signal level.

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13. ABSTRACT

This report describes the systems used to record wideband (12 Hz – 300 Hz) extremely low frequency (ELF) electromagnetic noise in a number of geographic locations. The first section centers on the analog recording system employed in Florida. Simply stated, analog tapes were recorded and later converted to digital tapes for further processing. Section II describes the "NAVCOM" system which employed on site digital recording. The final section describes the calibration procedures used to relate the digitalized data to absolute electromagnetic field levels.

A distinctive feature of both systems is the care taken to preserve the wide dynamic range of the ELF noise while reducing the amount of man-made interference recorded. Results of analyzing the recorded noise data to optimize communications system performance in this frequency band are described in companion reports.

14. KEY WORDS

| | |
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| extremely low frequency (ELF) electromagnetic noise | analog-to-digital (A/D) conversion |
| NAVCOM system | |



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