APPENDIX A

MEASUREMENT METHODS USED TO OBTAIN THE DATA BASE

Data used in this report were obtained using the OT/ITS mobile radio noise lab. The exclusion of other data was felt justified, not on the basis of the validity of the other data, but because of lack of compatibility with data used in this report. In many instances parameters have been measured (e.g., peak or quasi peak) which by themselves do not provide sufficient information for frequency management or system design considerations and, without further information about the noise process from which the measurements were obtained, cannot be related to other parameters of the radio noise. In general, other measurements provided information at only one or two frequencies, and attempting to combine these measurements with others proved futile since frequency, time, and location statistics were hopelessly intermixed.

Since the entire data base used here came from measurements taken with the OT/ITS mobile radio noise lab, a description of the noise lab and the equipment involved, as well as some information on measurement techniques, may prove helpful in providing a better understanding of the predictions. This appendix is principally a description of this facility and its advantages and limitations for use in obtaining an adequate man-made radio noise data base. The mobile laboratory consists of a tractor and van. The tractor utilizes a full diesel engine and was purchased under the MIL-specifications for a quiet vehicle. Additional noise suppression was added after delivery; e.g., suppression on windshield wiper motor, alternator and controls, wheel bearings, etc. A diesel generator set was installed between the cab and the fifth wheel to provide power for mobile or remote operation. A low-boy type semitrailer van is used so that a two-meter-high vertical antenna on the van roof will clear power and telephone lines that might be encountered during mobile measurements. The van has an exterior aluminum skin with the roof acting as the ground plane for the receiving antennas. The van is heated and air-conditioned for temperature stability, thus providing for measurement stability after approximately a half-hour equipment warm-up period.

The measuring-recording system is shown in the block diagram figure A1. Any eight of the ten nominal recording frequencies can be used simultaneously. The ten frequencies were chosen with approximately octave spacings between 250 kHz and 250 MHz. As shown on figure A1, these frequencies are 250 and 500 kHz, 1, 2.5, 5, 10, 20, 50, 100, and 250 MHz. Relatively clear channels were used when possible, e.g., the WWV guard bands. Limited frequency adjustment about the nominal frequencies is provided to assist in tuning away from signals in the recording channels. Two receiving antennas are used, 2 meter and 0.5 meter vertical whip antennas. The eight lower frequencies are recorded from the 2-meter antenna, and the two higher frequencies are recorded from the 0.5 meter antenna. Each antenna is connected to a passive coupling unit which provides some preselection and gives 50 Ω outputs for the preamplifiers.

The basic data source in the van is the set of eight noise receivers and metering strips. Each of these measures the rms envelope voltage, the ratio between the rms and the average voltage (V_d), the ratio between the rms and the average of the logarithm of the voltage (L_d), and the ratio between quasi-peak voltage and rms voltage (Q_d). The quasi-peak detector uses a 1 ms charging time constant and a 160 ms discharge time constant. Currently the receivers are modified general purpose superhetrodyne communications receivers, and the metering strips are of a running average type with time constants in the

50-100 sec range. The receivers, as modified, operate with a 4 kHz effective noise bandwidth (the original noise bandwidth was 10 kHz). All channels have preamplifiers such that the system noise figure (excluding antenna losses) is less than 5 dB. The instantaneous dynamic range is approximately 85 dB, 50 dB above and 35 dB below the rms voltage. The recording ranges of the averaged values are 70 dB for the rms voltage, 20 dB for V_d, 30 dB for L_d, and 30 dB for Q_d.

The data recording system consists of an analog multiplexer, an A-D converter, a digital multiplexer, and an IBM-compatible incremental digital tape recorder. Each of the 32 averaged detector outputs (rms, V_d, L_d, and Q_d on each of eight channels) are sampled every 10 sec, and the values are recorded. Time, location, and channel status are also recorded at the 10-sec intervals.

Other equipment available includes a distribution meter (DM-2) which can be used to obtain the APD or the ACR, giving more detailed noise information on any one of the 8 channels. The DM-2 utilizes 15 level detectors spaced at 6 dB intervals. Counters at each level accumulate the time the noise was above each level when measuring the APD or the number of positive crossings at each level when measuring the ACR. When used with the data recording system, the counters are read every 10 sec, and the results are recorded on the incremental tape recorder. The 15 levels can be divided so that part of the 15 channels can be used to obtain APD information and the balance can be used to obtain ACR information. The DM-2 will operate on the output of any of the receivers, but can be used on only one frequency channel at a time. The DM-2 contains built-in calibrators and power supplies, as well as direct visual readouts, and is often used separately in a manual mode for obtaining the APD or ACR for radio noise samples obtained by other recording means.

An FM tape recorder is used with special associated circuitry to provide analog recordings of the predetection noise process. The analog tape system (ATS) is designed to record accurately wide dynamic range electromagnetic noise signals. Up to three noise channels can be recorded simultaneously. The system has a bandwidth of 4 kHz and a dynamic range of 90 dB. The wide dynamic range is achieved by taking the logarithm of the higher levels, thus decreasing the dynamic range of the signal recorded on tape. The lower 30 dB of the dynamic range is handled linearly throughout the system, while the upper 60 dB is log-compressed into an effective 10 dB range. Consequently, the signal recorded on the tape will require only a 40 dB dynamic range. The tape recorder, operating in its FM mode at 60 ips, will adequately handle a 40 dB dynamic range, and most of its accuracy is in the upper part of the dynamic range where it is needed to recover accurately the log-compressed portion of the signal.

The noise to be recorded is obtained from the IF output of a receiver, with a 4 kHz bandwidth, tuned to the desired frequency. The noise signal is translated to zero frequency by two balanced mixers, with local oscillators supplying the sine and cosine components of the IF. This results in two outputs, each of which will have components in the range of d-c to 2 kHz. This mixing scheme gives a bandwidth whose lower limit is d-c, without losing phase information (i.e., without detecting). These outputs are compressed and recorded.

The recorded outputs can be recovered using complimentary circuits (providing the antilog of the log-compressed portion) to obtain the original 90 dB dynamic range of the noise. These two outputs (one created by mixing with the sine component and the other with the cosine component) are mixed with a sine and cosine local oscillator, respectively, and added together. This gives the original noise centered on an IF, which may or may not be the same as the original IF.

The recording and playback system consists of the tape recorder, the auxiliary recording electronics (mixers, local oscillators, log compressors, etc.), and the auxiliary playback electronics (antilog expanders, mixers, local oscillators, etc.). Figure A2 shows a block diagram of the analog recording system.

The advantage of such a system are considerable. Enough dynamic range is available to make accurate recordings of the high amplitude impulses which occur relatively infrequently but still contain most of the energy in the noise process. The noise can be played back at any desired center frequency, with the original phase information retained. This makes it useful for system simulation studies and detailed analysis by computer data systems too large or expensive to be carried in the van. Software has been developed which obtains all of the above-mentioned (section 2) amplitude and time statistics from such recordings. The use of a well-analyzed noise sample in system simulation studies provides an accurate means of comparing theoretical performance with actual performance.

Another available piece of equipment measures the correlation coefficient between two noise envelopes. This equipment has been used to obtain information on spatial and directional correlation, and the correlation between the vertical and horizontal components of the noise. The correlator is a wide dynamic range device with inputs at 455 kHz. It not only provides the product of the two channels, but measures the average voltage and rms voltage in each channel, which is necessary to obtain the correlation coefficient and permits combining 10-sec correlation data to calculate the correlation coefficient for larger time intervals. This equipment accurately handles noise information over a 70 dB instantaneous dynamic range. Automatic gain control and integrate-and-dump circuitry are responsible for the wide dynamic range performance of this device. The correlation coefficient C_{12} between the two received noise waveforms is

$$C_{12} = \frac{\langle v_1 v_2 \rangle - \langle v_1 \rangle \langle v_2 \rangle}{(\langle v_1^2 \rangle - \langle v_1 \rangle^2)^{\frac{1}{2}} (\langle v_2^2 \rangle - \langle v_2 \rangle^2)^{\frac{1}{2}}} , \qquad \text{(A1)}$$

where v_1 and v_2 are the detected inputs to the two channels and $\langle \cdot \rangle$ denotes the time average. Many commercial correlators provide only the first term of the numerator. If the noise process is stationary over the proper time period (or if one has a means of continually replaying the same noise samples), the denominator can be measured and system gains set to make the denominator = 1. If the signals are also zero-mean signals, then the correlation coefficient does reduce to one term, $\langle v_1 v_2 \rangle$. Unfortunately, a radio noise envelope is neither zero-mean nor stationary over the proper time period, necessitating measurement of all of the quantities necessary to calculate (A1).

Equation (A1) may be rewritten as

$$C_{12} = \frac{\left(\frac{\langle v_1 v_2 \rangle}{\langle v_1^2 \rangle^{\frac{1}{2}} \langle v_2^2 \rangle^{\frac{1}{2}}} \right) \left(\frac{\langle v_1^2 \rangle^{\frac{1}{2}} \langle v_2^2 \rangle^{\frac{1}{2}}}{\langle v_1 \rangle \langle v_2 \rangle} \right) - 1}{\left(\frac{\langle v_1^2 \rangle}{\langle v_1 \rangle^2} - 1 \right)^{\frac{1}{2}} \left(\frac{\langle v_2^2 \rangle}{\langle v_2 \rangle^2} - 1 \right)^{\frac{1}{2}}} . \qquad \text{(A2)}$$

Putting this more explicitly in terms of the quantities which the correlator measures (fig. A3), we have

$$C_{12} = \frac{ACE - 1}{[(A^2 - 1)(E^2 - 1)]^{\frac{1}{2}}} = \frac{BCD - BD/AE}{[(B^2 - B^2/A^2)(D^2 - D^2/E^2)]^{\frac{1}{2}}} , \qquad \text{(A3)}$$

where

$$A = v_{d1} = \frac{\langle v_1^2 \rangle^{\frac{1}{2}}}{\langle v_1 \rangle} ,$$

$$B = v_{rms1} = \langle v_1^2 \rangle^{\frac{1}{2}} ,$$

$$C = \frac{\langle v_1 v_2 \rangle}{v_{rms1} v_{rms2}} , \qquad (A4)$$

$$D = v_{rms2} = \langle v_2^2 \rangle^{\frac{1}{2}} ,$$

$$E = v_{d2} = \frac{\langle v_2^2 \rangle^{\frac{1}{2}}}{\langle v_2 \rangle} .$$

Equation (A3) gives the correlation coefficient for a single 10-sec period, based on the quantities measured in that period. The correlation coefficient for any longer time period can be computed from the five values recorded each 10 sec in the following manner. The correlation coefficient, C_{12T}, for some time period, T, consisting of n 10-sec periods is

$$C_{12T} = \frac{\sum_{i=1}^{n} B_i C_i D_i - \frac{1}{n} \sum_{i=1}^{n} \frac{B_i}{A_i} \sum_{i=1}^{n} \frac{D_i}{E_i}}{\left(\left[\sum_{i=1}^{n} B_i^2 - \frac{1}{n} \left(\sum_{i=1}^{n} \frac{B_i}{A_i} \right)^2 \right] \left[\sum_{i=1}^{n} D_i^2 - \frac{1}{n} \left(\sum_{i=1}^{n} \frac{D_i}{E_i} \right)^2 \right] \right)^{\frac{1}{2}}} . \qquad (A5)$$

The calibration equipment completes the normal van installation. The primary calibration relates the rms output to F_a, the equivalent noise power spectral density available from a short, lossless antenna. All other calibrations are maintained relative to this value. The basic calibration for the rms channels consists of two steps. One step is the calibration of the system from the preamp input to the recorded output by means of a known input from a noise diode. This provides a relationship between the recorded voltage level and F_a, required at the preamp input to give the output reading. Since both the noise process and the calibration source are broad-band phenomena, the calibration with the noise diode eliminates any bandwidth problems in obtaining an accurate calibration. The second step in the basic calibration procedure is to determine the antenna circuit losses up to the preamp. This is accomplished by using a CW generator connected first to a permanently installed calibration stub antenna and then connected to the preamplifier input, where the noise diode calibration signal is injected. By knowing the relation between the two CW inputs, the self-impedance of the antenna and the calibration stub, and the mutual impedance between the two, the antenna circuit losses can be determined (Ahlbeck et al., 1958, "Instruction Book for ARN-2 Radio Noise Recorder," NBS Report 5545). The calibration of the other three moments is accomplished by setting the gains such that, for a CW signal, V_d, L_d, and Q_d are all equal to zero. The DM-2 is calibrated by relating one of the 15 levels relative to a given rms value, which in turn can be related to the available power from a lossless antenna. The same type of calibration is used on the analog tape recording system by recording a CW reference level on the tape which is related to the noise rms level.

Calibration measurements are made at the beginning and end of each run. While the recording equipment has been stabilized as much as possible, some variation in gain may occur over the measurement period. The two calibrations are averaged to find the calibration factors to be used for a block of data.

The accuracy of the recorded data will depend on the precision of the measuring/recording equipment and the calibration accuracy. The overall accuracy of the system is within ± 2 dB for the basic available power measurement. The accuracy of the other measurements is within ± 0.5 dB relative to the power measurement.

The design criteria used in establishing the sensitivity of the recording equipment was based on natural noise levels expected and the lowest values of man-made radio noise expected. A comparison of the system noise factor achieved at each frequency with the design criteria is shown on figure A4. The lowest atmospheric radio noise expected in the United States (CCIR, 1964) occurs during the winter 0800-1200 time block. This is the atmospheric noise curve shown. Also from CCIR (1964), the Galactic radio noise curve and the quiet rural curve for man-made radio noise are shown. Since we obtained this man-made noise curve from data recorded at our world-wide network of atmospheric radio noise recording stations, where each site was carefully chosen to be as free of man-made radio noise as possible, lower levels were not expected to be encountered when using the mobile noise lab. The design criteria, therefore, was the highest of these three curves at each nominal recording frequency. This was fairly well achieved except at 250 MHz, where a 7 dB noise factor was obtained. In some rural areas, the 250 MHz external man-made radio noise was found to be equal to or even less than the system noise factor.

The present radio noise measuring capability is limited in frequency range, with 250 MHz being the highest available channel. Some measurements of man-made radio noise have been made at frequencies up to 2.5 GHz (Automobile Manufacturers Association, 1969, 1970, and 1971; Anzic, 1970). A great deal of information about the various required amplitude and time statistics is needed at these higher frequencies. To date, even the most basic parameters (such as power spectral density) are little known as to variation with time and location.

Present measurement bandwidths are limited to 4 kHz by the IF band limiting in the receivers. This probably is adequate for frequencies up through the HF band. For measurements at VHF and higher frequencies, considerably wider bandwidths should be used. While the effect of bandwidth reduction on some of the noise statistics can be estimated (Spaulding et al., 1962), extrapolating radio noise statistics measured in a narrower bandwidth to those that would have been present in a wider bandwidth can be questionable since some information on the noise process is lost in bandlimiting. Therefore, bandwidths approximately equal to the widest expected bandwidth used in the various frequency ranges generally should be used for recording the radio noise information. Except for use with the correlator, only vertical monopole antennas have been used. Additional antenna configurations should be employed to obtain direction and polarization information.

Most of the data taken with the radio noise laboratory has been under mobile operating conditions. After selection of an area to be measured, a route was layed out in business or residential areas to include all streets or highways in the area if the whole area was homogeneous. If not, an attempt was made to separate the different types of areas. Once the route was layed out, at least two runs were made, if possible, with the noise laboratory going in opposite directions on the two runs. In some areas this was not possible due to the presence of one-way streets. In the rural areas, only one run was generally made over a given route.

Fixed-location measurements have been made using either self-contained power or commercial power for equipment operation. Additional precautions have been necessary when using commercial power to insure that the temporary power line is not a source of the recorded noise. When fixed-location measurements are made, the analysis of these data is separated from the analysis of the mobile data.

The choice of frequencies to be used for any given set of measurements and the choice of recordings to be made will depend upon the primary purpose of the measurements. A full set of eight frequencies is used for each measurement run unless a channel is used for the analog tape recorder or the distribution meter recordings which generally will leave only seven channels for the moment measurements. The moments always are measured simultaneously on the channel with the tape recordings or distribution recordings.

REFERENCES, APPENDIX A

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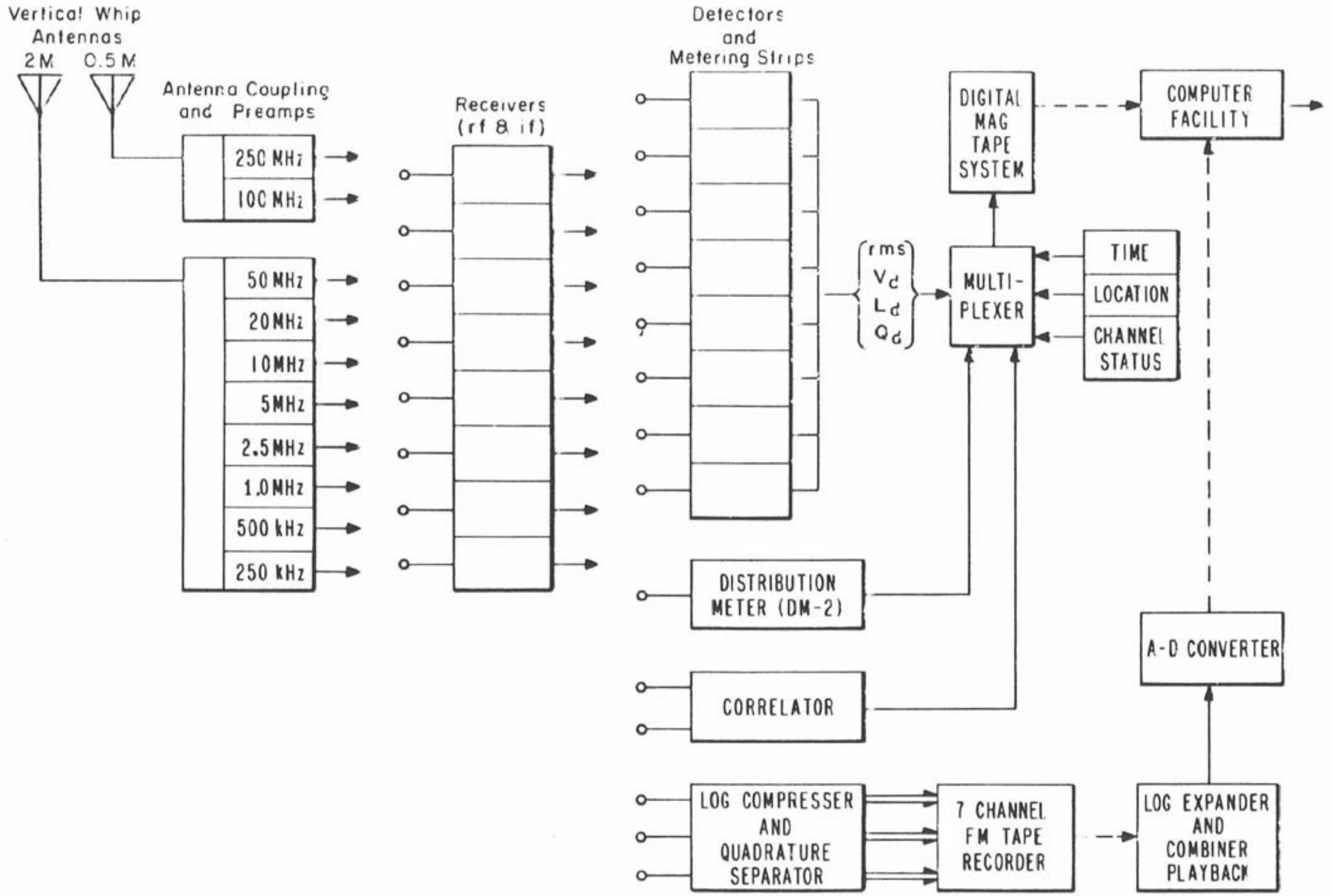

Figure A1. Block diagram of the measuring and recording facilities in the OT/ITS mobile radio noise lab.

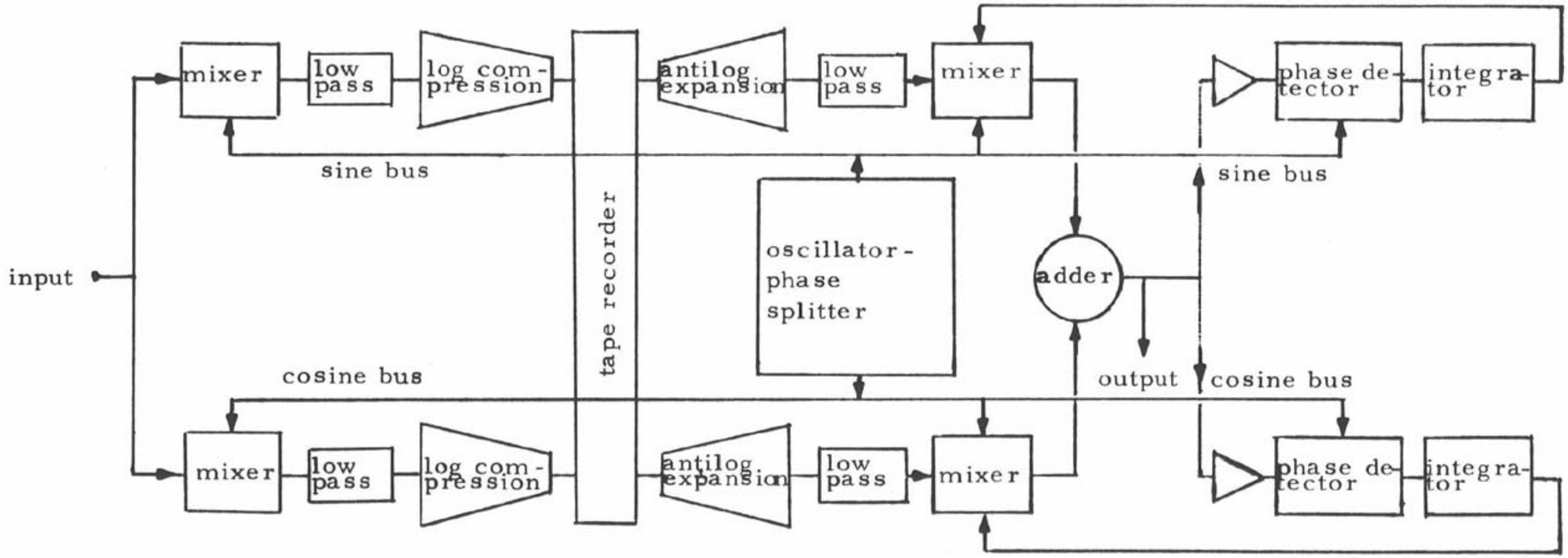

Figure A2. Block diagram of the analog recording-playback system.

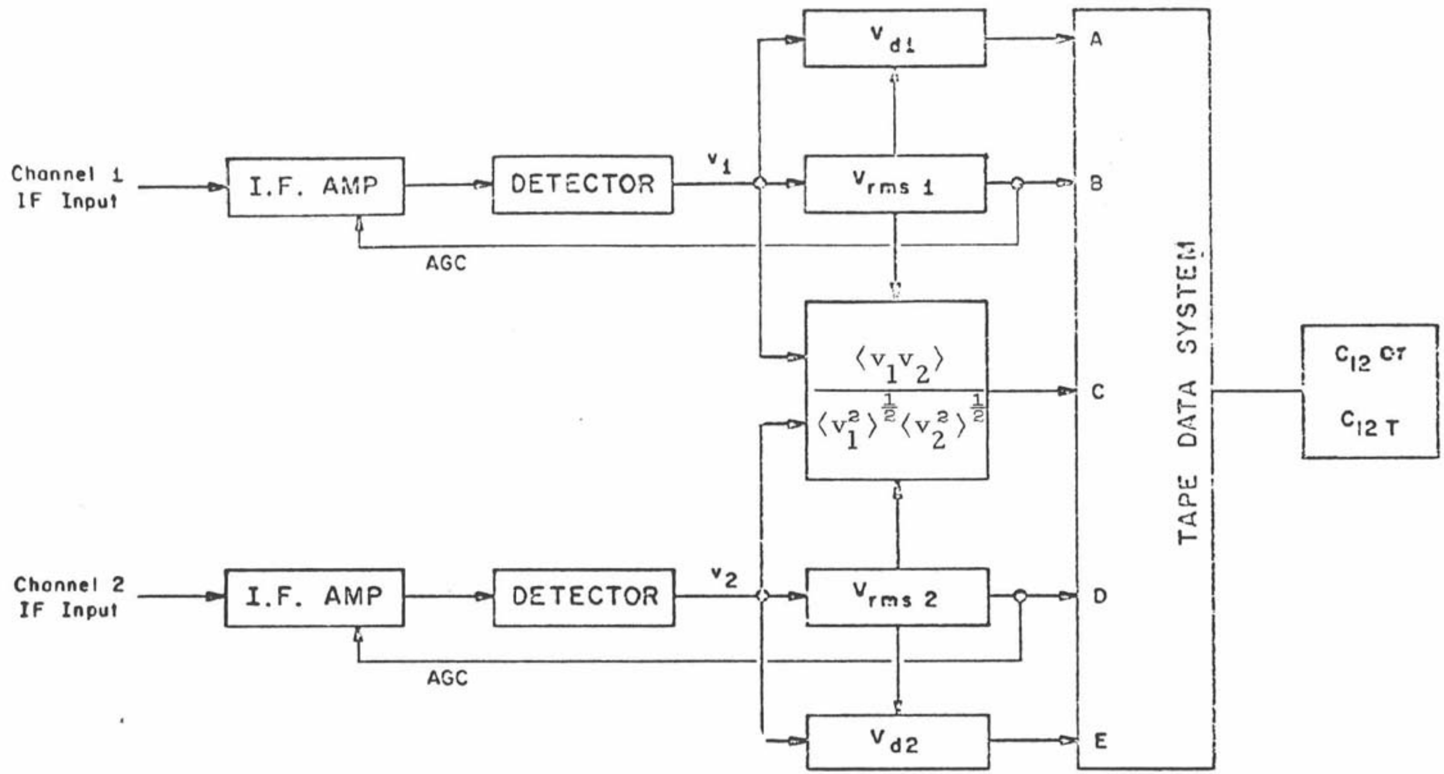

Figure A3. Block diagram of the correlation measurement system.

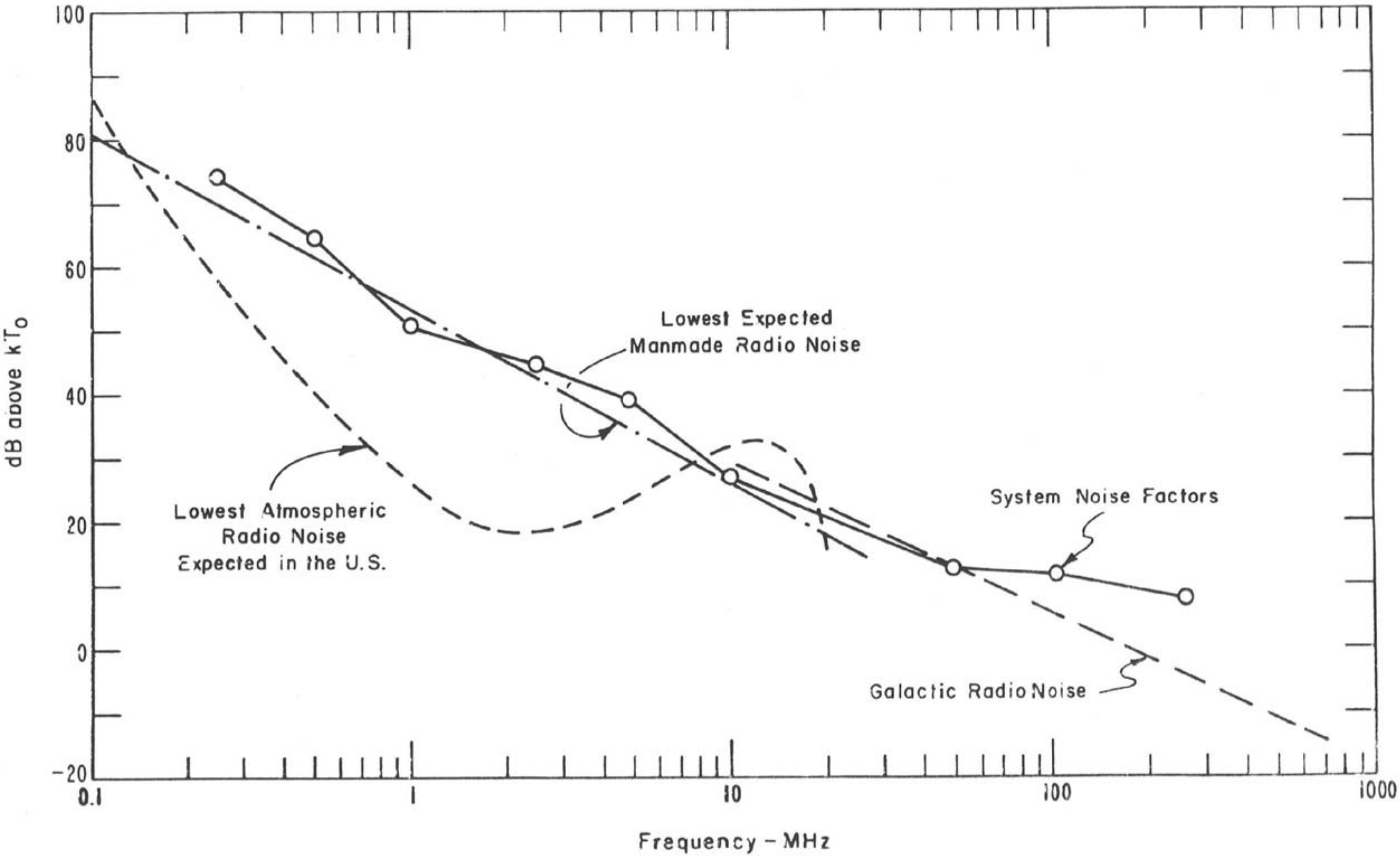

Figure A4. OT/ITS mobile radio-noise lab system noise factors.