ASSESSMENT OF ELECTROMAGNETIC NOISE MEASUREMENTS TAKEN BY BUREAU OF MINES CONTRACTORS

technical memorandum report to

U. S. BUREAU OF MINES
PITTSBURGH MINING AND SAFETY RESEARCH CENTER

JANUARY 1972

Arthur D. Little, Inc.

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TECHNICAL MEMORANDUM REPORT

TO

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PITTSBURGH MINING AND SAFETY RESEARCH CENTER
PITTSBURGH, PENNSYLVANIA 15213

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I. INTRODUCTION

As part of its research and development activities concerning coal mine operational/emergency communications systems, the Bureau of Mines commissioned several contractors to conduct electromagnetic (EM) noise studies and measurements that would aid the development of improved coal mine operational/emergency communications systems. The bulk of the noise studies and measurements were conducted in 1971. The Pittsburgh Mining and Safety Research Center (PMSRC) inherited the responsibility for monitoring the electromagnetic noise activities by mid-to-late 1971, and initiated a review and evaluation of the current and planned electromagnetic noise work. Arthur D. Little, Inc., (ADL) was asked by PMSRC to assist it in performing this review and evaluation by placing stronger emphasis on certain tasks of existing Contract No. H0122026.

This technical memorandum report presents the findings, conclusions, and recommendations of our review and evaluation of the electromagnetic noise measurements of the five contractors we were asked to examine. Our review and evaluation effort included meetings and telephone discussions with technical staff of each contractor; serving as Technical Discussion Leader of a "Contractor's Round Table Meeting on EM Noise, Surface and Subsurface, Operating and Non-Operating Mines" called by the Bureau of Mines; examination and discussion of contractor reports and relevant open literature; sample verification calculations; and the documentation of our findings, conclusions, and recommendations by this report.

The report is organized so that contractors are treated in alphabetical order, and each contractor's electromagnetic noise work is discussed according to the following format:

SUMMARY
FINDINGS
Noise Measurements and Instrumentation
Units and Sensors
Data Analysis and Presentation

II. COLORADO SCHOOL OF MINES (CSM)

A. SUMMARY

Colorado School of Mines (CSM) is the only contractor that has taken extensive EM noise data on the surface above the working sections and faces of operating coal mines. The data cover a variety of mines from the Mid-West to the East, a wide frequency band (20 Hz-10kHz), and times spanning work shifts and 24-hour periods. As such the data may prove valuable in spite of some deficiencies.

The noise measurements, sensors, and data analysis are not the most appropriate for characterizing noise environments dominated by discrete frequency components such as the power frequency harmonics found in and around coal mines. The CSM instrumentation and measurements are more suited to geophysical measurements and to environments with broadband random or impulsive noise of modest dynamic range. However, in spite of several deficiencies, it may be possible to analyze and recast some of the data in a more useful presentation format; a format that will help to provide more insight into the nature of the levels and diurnal variations of man-made EM noise experienced on the surface as a result of mining activities. Only order of magnitude estimates can be expected, and the utility of the data for statistical analyses will be limited.

We recommend that this instrumentation not be used to gather additional mine site noise data, until a more effective utilization of its potential is determined. We recommend that a limited effort be made to re-analyze and recast a modest amount of the present CSM data as suggested in our findings. The objective would be to see if more useful information could be captured from the data, particularly with respect to diurnal man-made EM noise variations on the surface caused by subsurface mine activity, or other sources on the surface such as power lines.

B. FINDINGS

1. Noise Measurements and Instrumentation

The Colorado School of Mines has made measurements of the horizontal electric field and the vertical magnetic field components of noise, on the surface at a number of operating mines in Colorado, Illinois, and West Virginia. Locations above the working faces were chosen, which is good. Measurements have also been made near a power station. The frequency band from 20Hz to 10kHz was examined. This band was further divided into eight secondary bands each an octave wide, with the exception of the lowest band from 20-80Hz which covered two octaves. The noise in each of these bands was examined by selecting the upper and lower bandpass cut-off frequencies of a Rockland analog filter to coincide with each of the octave band limits. The noise waveform from this filter went to a 13-bit A-D converter, where it was sampled, digitized and fed into a Nova Model 4001 minicomputer that computed noise histograms. Eleven bits of the A-D converter were used to accommodate a variable 2000-to-1 (66db) amplitude dynamic range, subdivided into 6db increments.

The following noise measurements were made. Once an hour, approximately on the hour during a workday, 10,000 noise samples from each sensor (whip and loop) were taken in each of the eight-octave frequency bands chosen. Some measurements spanned 24-hour periods to examine diurnal variations over the course of a full day. The noise in each band and from each sensor was measured in sequence, not simultaneously. Each band of data represents from about 1 second to 1 minute of data-taking time, depending on the sampling rate, which was adjusted to prevent data aliasing errors. The absolute value of the instantaneous voltage in each one of the octave bands is the quantity sampled and digitized. From these samples, noise histograms were computed by the field minicomputer. The histogram values were printed out by a teletype terminal hooked up to the computer, and later plotted by CSM staff. The histograms indicate the percentage of time that the noise waveform spent in each of the eleven 6db voltage increments, over a 2000-to-1 (66db) dynamic range, for each of the time segments analyzed.

No noise power measurements were made, and no analog tape recordings were taken of any of the noise waveforms. Direct digital analysis in the field was chosen, over analog magnetic tape recordings of noise waveforms, on the basis of potential dynamic-range limitations imposed by single-channel tape recordings. Noise recordings by the National Bureau of Standards (NBS) in operating-mine, high-noise environments illustrate that the normal broadband-noise dynamic range of a single-channel analog tape recording is not the limiting dynamic range when the noise is characterized primarily by discrete line spectra. However, even under broadband impulsive noise conditions, wide dynamic ranges can still be accommodated if proper precautions are taken by using multiple-channel, split-gain techniques.

The choice of octave-bandwidth intervals for data acquisition was an arbitrary one based on a desire to avoid dominance by a single power harmonic in any measurement band. The choice of 6db voltage amplitude increments was also an arbitrary choice, prompted perhaps by the choice typically made for taking atmospheric noise measurements. In retrospect, both choices turned out to not be the most appropriate ones, given the presently known harmonic character of the noise. If one wanted to choose a wide bandwidth over which to analyze the noise in the manner of CSM, a 500Hz to 3000Hz band for voice would have been a more appropriate choice. Then the results could have been more easily related to reliability of voice-signal reception in the presence of the noise measured. By using octave bands, there is also little in the way of noise diagnostics that can be accomplished, particularly when the noise is dominated by closely spaced line-frequency components of different amplitudes. For instance, there is no way of positively identifying the amplitude and frequency components of specific noise sources from the CSM measurements, unless only one is dominant in the octave band of interest.

2. Units and Sensors

The field-strength units used to present the noise data were "millivolts/kilometer" for the long-wire/electrode sensor, and "gamma/second" for the loop sensor. Both are units frequently used in geophysics, but are not particularly convenient terms for communications system analysis. The millivolts/kilometer unit is related to the electric-field horizontal component in this case, and is derived from the voltage measured across the electrodes. The gamma/second unit is a unit related to magnetic field. In the case of the CSM noise measurements, it describes the open-circuit voltage induced in the measurement loop by the noise vertical component of magnetic field for the octave of interest, normalized to a loop of unit area. However, since the measurement loop and long-wire/electrode sensors used are so large, these results cannot be extrapolated to smaller sensors without potentially significant errors.

Both sensors were much larger than would be used for reception in a communications link. The E-field sensor was a wire greater than 1,000 feet long terminated in grounded electrodes, and the H-field sensor was a 1,000-foot perimeter loop laid on the ground. As such, the sensor sizes become comparable to and larger than a skin depth for typical ground conductivities at the higher frequencies examined. They are also large compared to physical dimensions in the mines, such as the widths of entries and haulageways. Sensors of such size will tend to average out or mask spatial variations of the fields that are quite likely to occur over distances of this order. Since the fields are not likely to be uniform over the above large sensors, the utility of standard calibration methods must also be questioned. The method of calibration was not described in any of the reports we examined.

3. Data Analysis and Presentation

Examination of the histograms of the instantaneous absolute values of the noise waveforms produced by CSM reveals shapes that are characteristic of histograms for sinusoidal waveforms, as opposed to random Gaussian or impulsive noise. The leveling off at low field values reflects the lower limit of the 2000-to-1 A-D converter dynamic range utilized and not the external noise. CSM and other investigators have observed that the noise in the vicinity of mines consists mainly of harmonics of 60Hz and 360Hz, supporting the conclusion regarding the shapes of the histograms. When the dominant noise consists of discrete frequency components, histograms and/or amplitude probability distributions (APD's) are not the best ways to characterize the noise (although they still can be useful as described later). In such cases, the noise is most usefully described by high-resolution power spectra.

If the noise had been random or impulsive, a number of samples significantly larger than 10,000 would have been necessary, to produce reliable histogram or APD estimates for those noise waveform values which occur the smallest percent of the time. These percentages represent the highest and lowest noise levels in the histogram distributions. In the case of harmonic-dominated, man-made noise that is also non-stationary - as mine produced noise is very likely to be - a greater sampling of the noise processes will eventually be required, to place tighter bounds on the expected variability of the noise environment.

In some of the CSM reports, some noise histogram-type curves have been labelled "probability density functions." These are not probability density functions, but simply smoothed versions of the histograms. They were produced by drawing a smooth line through the mid-point of the top of the bars of the histograms. To convert histograms to probability density functions, one has to normalize properly, which includes division of each histogram value by the corresponding voltage interval. CSM agrees, and has discontinued using the probability density function description.

In spite of some of the above-mentioned deficiencies and preferences, the histograms in hand can be used to obtain approximate estimates of the noise power in each of the octave bands measured. For those octaves exhibiting strong dominance by a single harmonic, assume that all the power is, in fact, contributed by that harmonic. Thus, the peak amplitude value V_p of that harmonic will be simply related to the field-strength 6db amplitude interval with the highest percentage on the corresponding histogram, giving an rms value estimate $V_{rms} = V_p/\sqrt{2}$. The single-harmonic characteristic shape is quite evident in the CSM data, particularly for those octaves containing the dominant power frequencies of 60 and 360Hz. For those octaves not exhibiting single harmonic dominance, a slightly more time-consuming statistical method for estimating the rms field value can be used; compute

$V_{rms} = \left(\sum_{i=1}^{N} V_i^2 f_i \right)^{1/2}$, where V_i is the geometric mean noise level in the histogram i^{th} noise level band; f_i is the histogram fraction of time the i^{th} band is occupied; and N is the total number of bands spanning the dynamic range.

CSM has also presented its noise data in the form of contour plots of field strength (plotted versus frequency and time of day) in an attempt to portray in a graphic manner the variability of the noise with underground mining activity. This is a good idea, but the present method of plotting and interpolating the data is misleading and therefore not acceptable. In particular, the contours are drawn on the basis of a 6x8 grid of points, spaced every four hours on the time scale, and at the center frequency of each of the octave bands on the frequency scale. The field strength values chosen for the 48 grid points are those for the field-strength intervals with the maximum percentage of time occupancy on the histogram, typically falling between 30% and 50%. There is no basis for interpolating field amplitudes versus frequency or time to the fineness shown in the CSM graphs; especially when the dominant noise occurs at specific harmonic frequencies, as opposed to a smooth broadband spectrum, and was measured at widely separated times.

We recommend that these contours not be drawn. Instead, either the 30% to 50% field values chosen for each grid point or the rms field value in each octave should be plotted to form a three-dimensional perspective plot. The 30% to 50% field or rms field values can be plotted as bars spanning each frequency octave at each of the hourly periods that data was recorded. Such three-dimensional bar plots should give valuable physical insight into the diurnal variation of the man-made EM noise in each octave, and also identify the octaves containing the strongest harmonics. A limited number of the above-mentioned rms field calculations and 3-D bar plots should be made to see if they are useful enough to justify analyzing a larger amount of the CSM data in this manner.

III. INSTITUTE FOR TELECOMMUNICATIONS SCIENCES (ITS)

A. SUMMARY

The noise-measurement effort of the Institute for Telecommunications Sciences (ITS) for the Bureau of Mines was primarily aimed at characterizing the long-term behavior of both atmospheric and man-made electromagnetic noise in the band from 20Hz to 20kHz. Some limited, short-term, narrowband spectral analyses have also been made. However, the ITS noise measurement program appears to have been largely a disorganized effort that has produced few tangible results to date. It also appears that considerable expertise in, and instrumentation for, conducting man-made and atmospheric noise measurements is resident at ITS, but was not utilized for this noise-measurement program.

The noise measurements, with one exception, have not been made at coal mine locations, but mainly in Lafayette and Boulder, Colorado. The primary field components measured were not the most appropriate for emergency/operational mine communications, but apparently those components ITS has measured routinely in the past on other programs. The long-term, time-averaged measurements made are not appropriate for characterizing mine noise environments dominated by power harmonics, nor for broadband noise environments either. The shorter-term, narrowband, swept-frequency measurements may be marginally useful.

Documentation of measurement activities and data has been spotty and incomplete. Although there are rumors of much unprocessed data existing, including that from a limited set of in-mine measurements, it remains to be seen whether this data will ever appear in a readily comprehensible form. However, in spite of the deficiencies in its long-term, time-averaged measurements, ITS has assembled and exercised narrowband swept-frequency instrumentation which may be useful for select measurements in the field. An existing in-house, real-time wave analyzer may also be useful for quick-look processing of analog tape recordings. However, this may prove to be of marginal utility because of the dynamic range limitations of the output display.

The potential importance of Whistler and solar Hiss noise to mine communications in the voice band has been cited by ITS. Agreement as to the severity and frequency of occurrence of these forms of noise in the voice band of interest has not been reached. The more severe of the two is claimed to be the solar Hiss, with high energy content in the band between 500Hz and 6kHz when it occurs during high sunspot activity. The urgency of immediate investigatory measurements was agreed to be low for the time being.

We believe some small value may be obtained from the data that ITS has presented to date, but only if select data are properly documented. The data also are only of limited value for making statistical analyses, and with perhaps a few exceptions bear little or no relation to coal mine noise environments.

We recommend that the broadband and narrowband time-averaging instrumentation not be used to gather additional noise data, either in Boulder or at mine sites. The narrowband swept data to date may have some marginal utility, so we recommend that it be obtained from ITS with adequate documentation. These data may help in defining the location and depth of the variable null found in atmospheric noise spectra between 1 and 4kHz. The data may also help estimate some surface man-made noise levels in suburban areas such as Boulder, and in similar-sized cities over and near coal mines. However, we believe this will provide only coarse order-of-magnitude estimates. We doubt that much information of significance to emergency/operational mine communications will be gained from it, if most of it is for the vertical component of electric field. The narrowband, automatically swept, wave analyzer and analog tape-recording instrumentation purchased for this program may be of use to future Bureau of Mines noise-measurement programs. Expertise, mobile instrumentation, and experience in making measurements of man-made noise above 10kHz apparently is available in a different group at ITS. We recommend that consideration be given to exploring the suitability of this ITS resource for obtaining in-mine noise data relevant to carrier-type communications systems for the 10kHz to 400kHz band.

B. FINDINGS

1. Noise Measurements and Instrumentation

The Institute of Telecommunications Sciences (ITS) has made measurements primarily of the vertical electric-field component of EM noise, on the surface at two fixed field sites in Colorado. Limited magnetic-field measurements have also been made at these sites. The vertical electric field is the least important field component for emergency mine communications. Three components of noise magnetic field were measured in an operating mine on only one occasion, on a joint field trip with Bureau of Standards staff.

The surface measurement data fall into two categories: long-term averaged data and narrowband frequency-swept data. The frequency band from 20Hz to 20kHz was examined. The long-term, time-averaged measurements were of two types--broadband and narrowband. The widest broadband measurements utilized a filter that applied about 4db/octave roll-off above 10kHz and about 10db/octave roll-off below 5kHz. After the filter, the voltage waveform was full-wave-rectified, averaged by an integrator, and recorded on a strip-chart recorder.

A second broadband measurement divided the 20Hz-to-20kHz band into three secondary bands (low, middle, and high) with filters. The noise waveforms were then subjected to full-wave rectification and averaging as in the first broadband measurement. The narrowband time-averaged measurement was made by centering a 100Hz narrowband filter on the frequency 5.22kHz, and then subjecting the output of this filter to full-wave rectification and integration as above.

The narrowband swept-frequency measurements utilized a Hewlett-Packard 3590A wave analyzer purchased for this program. The instrument was programmed to automatically sweep the 20Hz-to-20KHz band with a 10Hz-bandwidth filter, taking approximately one hour to complete the sweep. The output of the wave analyzer was recorded on an analog strip chart recorder, and later hand digitized for input to computer plotting software. The automatic sweeping unit for the analyzer was fabricated by ITS, since the one available from Hewlett-Packard was claimed to be inadequate. An analog tape recorder has also been purchased for this program. Because of its late arrival, it was not used for surface noise measurements, but only on the one field trip made to an operating coal mine.

The long-term, time-averaged broadband and narrowband measurements were conducted on a continuous basis, spanning several days in many instances, to monitor diurnal variations. The vertical electric field was the principal field component measured. The output quantity in the time-averaged measurements was the average value of the full-wave rectified filter output, not average power. Noise average power and APD measurements were not made, nor were analog tape recordings taken of the noise waveforms during these long-term measurements. Measurement of average voltage without corresponding APD or average power measurements provides no means for subsequent statistical analyses of the data. The method of calibration was not described in any of the reports we examined.

The broadband time-averaged data taken are not appropriate to the needs of designing emergency mine communications. ITS agrees and has abandoned these measurements. No spectral diagnostics can be made from such broadband averaged measurements, since all the noise spectral structure of interest to a communications system designer was averaged and filtered out. For example, the broadband filter severely attenuated the principal man-made noise components. The subsequent time averaging, without an analog recording of the waveform before averaging, then prevented the possibility of identifying and quantifying the power levels of the principal noise sources in the original 20Hz-to-20kHz band. The weighting filter was included so that no one source of noise would dominate in the measurements. But this procedure has value only when waveform recordings are made <u>before</u> averaging, so that subsequent analysis can reveal the nature and strength of the attenuated noise components.

Fortunately, very few measurements were made with the 20Hz-to-20kHz band divided into high, middle, and low bands, since these measurements also have little or no merit. The narrowband, time-averaged measurements centered on 5.22kHz were conducted in parallel with the principal broadband measurements. 5.22kHz was chosen because a 100Hz-bandwidth filter centered on this frequency was available from another program, and since this frequency is the 87th harmonic of 60Hz. Therefore, expectations were that this frequency might be a meaningful indicator of expected diurnal variations of man-made noise. Average power was not measured, only the average rectified voltage from the filter. These measurements have also revealed themselves to be of little value, and have been abandoned.

After examining some of the respectable published work of D. Spaulding and R. Disney of ITS with regard to both man-made and atmospheric surface noise measurements, we were quite surprised at the deficiencies in the ITS noise-gathering effort for the Bureau of Mines. In fact, ITS has a complete calibrated mobile facility for taking higher frequency radio noise measurements, housed in a cab-pulled "low-boy" trailer. It is unfortunate that the above resources were not utilized for the ITS noise measurement effort.

The narrowband swept-frequency instrumentation and measurements appear to be the most useful contributions of ITS. The instrumentation is well suited to measuring noise environments dominated by line spectra, since it can easily resolve each of the components with its 10Hz bandwidth. Its main deficiency is the length of time (about one hour) it takes to sweep the 20Hz-to-20kHz band chosen by ITS. If the time taken to sweep through a frequency range of interest is long compared to times when gross variations can occur in conditions of the noise sources, noise components measured at one end of the spectrum are unlikely to be related to noise components measured at the other end of the spectrum. This is particularly true in the case of man-made sources that are subject to nearby intermittent operation or gross load changes, as in mines. Ideally, noise measurements should be made across the entire spectrum of interest simultaneously, though in practice this is not always possible. The HP 3590A wave analyzer is a good instrument and can be used for spectrum analyses up to 620kHz, in a manual sweep mode, and at faster auto-sweep rates with an HP plug-in unit. As such, this instrument may be useful as a quick-look diagnostic device in the field at both high- and low-frequency bands of interest to the Bureau of Mines. A battery-operated, portable oscilloscope is still perhaps the most efficient and convenient quick-look instrument to have in the field, though.

2. Units and Sensors

The field-strength units used to present the noise field-strength data were the standard db relative to one microvolt-per-meter for electric fields, and db relative to one microam-per-meter for magnetic fields. Only the vertical component of the electric field was measured, and this was done with a standard one-meter monopole above a ground plane at Lafayette, Colorado, and a two-meter monopole above a ground plane on the Radio Building in Boulder. These antennas would be acceptable for surface measurements if the vertical electric field was an important quantity to measure for mine communications.

We do not have details on the loops used for magnetic field measurements, but it appears that separate loops were used to measure all three components. Since we do not know what size and type loops were used to make the measurements, we cannot comment on how these measurements can be related to loops of interest for mine communications. Calibration details have not been found in reports or discussed. However, this information should be easily obtainable from ITS.

With regard to the long-term, time-averaged measurements, the plotted average field strength data in db re 1μv/m are of little value, because they are not related to power. Secondly, there is no way of converting the data at the recorded bandwidth to other bandwidths of interest without knowledge of the average power or the character of the noise. The units are appropriate for the narrowband swept-frequency measurements of the harmonic noise components, since they can be related to power, and to other communication bandwidths of interest in a straightforward standard manner.

3. Data Analysis and Presentation

The broadband and narrowband time-averaged data are not useful for designing mine communications, and ITS agrees with this finding. The swept-frequency narrowband noise-spectrum plots obtained from the HP 3590A wave analyzer may have some marginal utility. These plots are computer generated from data obtained from the analyzer analog strip-chart recordings. The strip chart values were read and digitized manually for subsequent inputs into the computer; this allows spectrum plots to be plotted to any amplitude and frequency scale, and allows convenient superimposition of several spectrum plots on the same graph. However, the manual transfer of data points from the strip charts hardly sounds like an attractive feature.

Computer software was developed to produce the above plots, and apparently is now finally debugged. If so, it may be an asset. For instance, by superimposing spectrum plots obtained over the course of a day or week, a better understanding of the size and type of noise variations over the band of interest may be obtained. However, the nonstationarity of man-made noise, and mine-related noise in particular, will preclude relating the noise levels obtained at one point in the spectrum with noise levels obtained in another part of the spectrum because of the one-hour sweep times. A more desirable way to obtain such spectrum plots, when the upper frequency of the band is not excessive, is via real-time direct computer analysis, or wideband tape recordings and subsequent computer analysis, as done by Westinghouse and NBS, respectively.

Magnetic field strength plots have also been presented of eight one-hour-long traces of the frequency spectrum taken with the HP wave analyzer over the course of a day, placed one under the other on an 8-1/2 x 11 page. However, this type of presentation requires that the vertical amplitude scales be compressed by an inordinate degree, which makes it difficult to quantitatively examine the plots.

Frequency versus time noise plots have been prepared by ITS, in which time runs along the horizontal axis and frequency along the vertical axis, and the strength of the noise component at a particular frequency is represented by the darkness of the lines traced across the plot as a function of time. These plots were obtained by passing noise waveforms (recorded on analog magnetic tape in an operating mine) through a Rayspan real-time frequency analyzer made by Raytheon. The Rayspan analyzer is coupled to a special strip-chart recorder. The instrument has 440 comb filters of bandwidths ranging from 10Hz to 50Hz. A DC voltage proportional to the intensity of the noise output of each of these filters determines the darkness of the lines traced on the strip chart at each of the frequencies containing noise above some level. We have been assured that the originals of the Rayspan plots are of better quality than the Xerox copies obtained at the December meeting.

Despite the poor Xerox copies, one could easily see the discrete frequency components of several noise sources, together with broadband impulsive bursts, apparent frequency fluctuations of harmonics, and the sudden turning on and off of equipment. Such plots can be good for gaining insight into the characteristic noise constituents, and their variations with time. However, since the dynamic range of the strip chart paper is limited to 10 to 12db, for the most part, the typical intensity variations between frequency components will not be noticeable, thereby limiting the utility of the plots.

Initially we thought the Rayspan equipment might be useful for obtaining quick looks at noise data at mine sites to get quick signature identifications of the most dominant noise sources. Unfortunately, the equipment is not portable because of its considerable volume and weight when the paper drive output is included. Another device, more portable in size, and with greater dynamic range (30-40db) may be available at ITS to provide a similar function. It is called a Saicor, and reportedly computes a power spectrum estimate via an FFT calculation every 40ms, and displays it on an A-scope type display in a three-dimensional format. This information needs to be verified.

The potential importance of Whistlers and solar-produced Hiss noise to emergency mine communications has been cited by ITS. The more severe of these phenomena, when it occurs, appears to be the solar Hiss. Its noise power generally occupies the 500Hz to 6kHz band, with peak field strength levels approaching 300 millivolts/meter around 3kHz. This noise is strongly dependent on the solar sunspot cycle. Since we are at a low level in the sunspot cycle, and will be for several more years, ITS agrees that this type of noise does not deserve a high priority for field investigations at this time. However, since this source of noise will return during the next peak of sunspot activity, it should be kept in mind and appropriate preparations made. The lightning-produced Whistler noise has also been relegated to a lower priority temporarily. Both Whistlers and solar Hiss have received considerable attention by other investigators. Therefore, examination of the considerable existing literature on these noise sources is a logical first step toward obtaining estimates of the potential restrictions these noise sources may impose on operational/emergency mine communications.

The ITS noise-measurement program appears to have been a disorganized, poorly executed effort which has so far produced few tangible results for the Bureau of Mines program. This appears to be due in part to the several reorganizations that occurred during the last year or so at ITS, which in turn resulted in four or five changes in leadership and responsibility for the Bureau of Mines EM noise work. Of all the ITS noise measurements, the narrowband swept-frequency noise measurements may still yield some marginal results as stated above, but only if the data and measurements are properly documented. The associated computer software for obtaining the computer-generated plots may also be of some value, but again only if it has been completely debugged and documented.

Some of the instrumentation purchased and modified for this Bureau of Mines program may be useful to future Bureau of Mines noise program work. In particular, the Hewlett-Packard 3590A wave analyzer and a new analog tape recorder. We recommend that as a minimum, ITS collect and present in a manner that can be understood and used by others, the narrowband swept-frequency data it has taken. It should also document the calibration and measurement procedures used for this instrumentation, and the corresponding data-processing computer software.

IV. NATIONAL BUREAU OF STANDARDS (NBS)

A. SUMMARY

The National Bureau of Standards (NBS) has produced by far the most relevant and useful instrumentation, data, and data-analysis methods for characterizing electromagnetic noise environments in and around operating coal mines. The noise-measurement system as a whole represents a totally integrated approach. It reflects the simplicity desired in a field-transportable system for use in operating coal mines, and technical correctness and efficiency in its implementation and utilization. The measurement system has been calibrated as a complete system, starting with input field sensor up to and including the computer-driven graphical display output. The NBS approach is centered on wideband (40Hz to 10kHz) direct recording of magnetic field noise waveforms on analog magnetic tape in the field, and subsequent sampling, A/D conversion, and computer spectrum and statistical analysis of these waveforms back at the laboratory. The NBS noise measurements, instrumentation, and processed data are the best documented in the Bureau of Mines EM noise program.

Electromagnetic noise has been recorded and processed from inside and outside three operating coal mines in Colorado. The data represents a small, but good sample of coal-mine noise situations. In-mine situations include quiet times and locations, together with extremely noisy conditions encountered in the vicinity of DC trolley lines, electrically powered locomotives, and entrances to AC electric power boreholes. No data was taken at the working faces. Surface measurements were made over mines, usually in the vicinity of AC power lines, but not necessarily over working sections. The bulk of the data has been processed to produce highly desirable, high-resolution, noise power spectra. These spectra illustrate both the high harmonic content and impulsive character of in-mine magnetic noise, revealing in some cases spectrum signatures that may be characteristic of specific mine equipment. The computer software also allows preparation of three-dimensional spectrum plots revealing the variability of the noise environment over short time periods.

Since the noise waveforms have been recorded on tape, they are available for further computer and analog processing, or for laboratory simulation of mine noise environments for testing the effectiveness of receivers and/or noise-cancellation techniques. The NBS instrumentation, data-processing system, and noise data provide a good starting point for the preliminary characterization of coal mine noise environments, and for the accumulation of a more statistically significant noise data base, from which emergency/operational mine communication systems can be designed and tested.

We recommend that this instrumentation and data processing system be used to accumulate a wider sampling of both in-mine and on-the-surface electromagnetic noise environments, particularly in the working face areas. Only small refinements, such as battery operation of the tape recorder, are suggested to make the system more portable. We recommend that strong consideration be given to engaging the proven NBS measurement team to conduct all or part of the noise measurements. We recommend that the currently published NBS noise data be used to guide the design of experimental mine operational/emergency communication systems, and for estimating and testing the performance of a variety of candidate systems under representative noise conditions. Access should also be gained to the rest of the NBS unpublished (but processed) mine noise data, and duplicates obtained of the noise analog tape recordings for further analysis and possible noise environment simulations.

B. FINDINGS

1. Noise Measurements and Instrumentation

The National Bureau of Standards has measured the vertical and two orthogonal horizontal components of the noise magnetic field, underground and on the surface, at three operating coal mines in Colorado. Measurements were made in the vicinity of suspected major noise sources and in quiet locations, which is good. Magnetic-field noise waveforms were sensed by a loop antenna, amplified, low-pass filtered to exclude frequency components above 10kHz, and subsequently recorded on analog magnetic tape. The tape recorder was AC powered. Both visual and aural monitors, in the form of a battery-powered oscilloscope and an audio amplifier with speaker, were used as diagnostic and alerting tools.

The noise waveforms recorded in the field were subsequently analyzed by computer back at the laboratory. The tapes were played back into a sharp-cutoff, low-pass filter, then sampled, A/D converted, and re-recorded on digital magnetic tape for subsequent computer processing. The recorder playback speeds and the low-pass filter cutoff frequency were adjusted properly to provide faithful data analysis without aliasing errors, while operating within the maximum sampling-rate limit (16kHz) of the 12-bit A/D converter. Though this scheme allows noise analyses to be made up to the full 10kHz recorded bandwidth, only 3000Hz of the bandwidth was utilized for the present NBS noise analyses. The digital noise tapes were processed by a large digital computer. Highly desirable, high-resolution power spectrum plots were produced, using the direct-segment power-spectrum estimation technique and a Fast Fourier Transform (FFT) computational algorithm. The computed power spectra are equivalent to those obtained by analyzing the noise waveforms with analog bandpass filters, with bandwidths equivalent to the 2Hz and 8Hz resolution windows used for the 750Hz and 3000Hz band analyses, respectively.

The NBS measurement system represents a nearly optimum approach to the in-mine noise measurement problem. Wideband analog recording of noise waveforms was chosen because: the frequency band of interest was low enough to be easily accommodated by analog tape recordings; the exact nature of the noise was unknown, so the maximum possible noise information was required; the necessary computer data-processing software was available; and it was the most rapid and simple way of obtaining the noise data with minimum disturbance to mine operations.

The above instrumentation and data-processing system was assembled from equipment and software that existed at NBS, ITS, and NOAA, requiring at most minor modifications. The effort revealed the value of internal cooperation. As a result, NBS produced an effective and well-defined measurement system, both in terms of its components and in terms of system operation and calibration as a whole. Individual component and overall system responses and correction factors were ascertained from measurements, and the limits of the data-processing errors defined. The system parameters measured included frequency response, aliasing error, intermodulation and harmonic distortion, and overall absolute gain from the antenna to the final graphic output. Absolute calibration was made on the measurement data-processing system as a whole, by immersing the antenna sensor in a standard known magnetic field generated at the NBS Calibration Facility, and measuring the system response as a function of frequency right through to the computer processed graphical output. All of the instrumentation, measurements, and error estimates are carefully documented in the NBS report, entitled "Coal Mine ELF Electromagnetic Noise Measurements," by W.D. Bensema.

The following measurements were made. Surface measurements were conducted over mines, but not necessarily over the working sections or faces. AC power lines were usually present within a hundred feet or so of the sensor location, and their presence was apparent in the processed power spectra. No attempt was made to correlate surface noise recordings with subsurface activity in the mine. On the surface, all three components of magnetic field (vertical and two horizontal) were measured, in addition to that for the loop oriented for minimum noise pickup. These components were measured in sequence, not simultaneously. Three mines were sampled on the surface; two mines underground. No underground measurements were made in the working face areas. The underground measurements were typically made in the vicinity of DC trolley lines, near a locomotive pulling a loaded train, at the entrance to a power borehole, and near other selected mine machinery. Measurements were taken under both quiet and obviously noisy mine conditions, thereby giving a small but good sample of both quiet and perhaps some of the noisiest conditions in the mine. Instrumentation system noise checks were also made, both underground and on the surface, by recording the system noise pickup with the antenna terminals short circuited.

The measurement team was generally on-site for several hours at a time and recorded noise situations that appeared important. The recording times ranged anywhere from fractions of a minute to several minutes, as opposed to continuous uninterrupted recordings. Surface measurements were made during and after work-shifts, depending on the mine, but generally not both for the same mine. In mines, measurements were made during the work-shifts, and in one mine during the lunch hour. Though these measurements are good and important, they are not extensive enough to set tight bounds on the variations expected during a work-shift, with respect to activities, locations, times, and machinery. However, as a result of the many situations that were recorded, a reasonable estimate of the extremes that mine noise environments may encounter is available, for estimating the transmitter power requirements of candidate communications systems.

2. Units and Sensors

The field-strength units used were db relative to 1 ampere per meter for the magnetic field strength, the only field measured. It is presently considered the most important field quantity for operational/emergency communications. For discrete frequency components on the spectral plot, the value of the peak response at the frequency in question represents the rms value in amp/m of the field strength at that frequency. For broadband noise levels between the discrete component peaks, the levels represent the rms noise field strength in amp/m as seen at the output of a narrow bandpass filter equivalent to the 2Hz or 8Hz resolution band used to analyze the noise waveform.

The sensor used is a standard Stoddart 11-turn electrostatically shielded 30" diameter loop. This loop, and its impedance transforming balun, are used with Stoddart ELF-VLF field-strength meters to cover the 30Hz-to-15kHz frequency band. The size is not too large to be inconvenient for in-mine field measurements, and is small enough to relate the results to man-pack receiver loop sizes without gross errors. The size of the loop may be too large to measure the noise field variations very close to specific equipments. At short ranges the noise field can experience large changes over distances comparable to the loop diameter. For conducting additional in-mine measurements, a standardized 12" diameter loop is preferred, if an acceptable one is available.

3. Data Analysis and Presentation

NBS used a high-speed digital computer to produce high-resolution power spectra of the sampled and digitized noise waveforms. The power spectra were computed by the direct-segment (modified periodogram) method of spectrum analysis, assisted by a Fast Fourier Transform (FFT) computational algorithm. The direct-segment method and FFT enables power-spectrum calculations to be made at considerable savings in computer time. This is a good way to analyze the data if done properly, which it was.

The NBS power spectrum analysis of a waveform is accomplished by: taking a finite time block of the sampled and digitized waveform; subdividing it into N equal time segments; taking the Fourier transform of each time segment; using the transform to compute a power spectrum estimate for each time segment; and finally averaging a large number of the individual time-segment power spectra together, to obtain a stable statistical estimate for the power spectrum. Each of the individual spectrum estimates based on single time segments is a random variable subject to a high degree of variability; so it is necessary to average many of them together to reduce the estimate uncertainty.

The number of time segments that need to be averaged together is generally chosen according to criteria for stationary Gaussian random noise. Although ELF and man-made noise are non-Gaussian and largely non-stationary, stationary Gaussian noise criteria are usually still the only practical ones to use. The minimum number of time segments one should be comfortable with when estimating broadband noise spectrum levels is about 17, representing 34 degrees of freedom. NBS has exceeded this with 20 segments for its two-dimensional spectrum plots. Estimates based on averaging the spectra of 20 segments (40 degrees of freedom) give a 90% confidence limit that the error will be within $\pm$ 1.6db of the true spectrum level, for the broadband part of the noise. The discrete frequency harmonic components are subject to a different estimation error discussed later. Other ELF noise investigators, MIT Lincoln Laboratory and Westinghouse, have used 50 and 300-segment averages (100 and 600 degrees of freedom, respectively) in their work to achieve somewhat smaller error bounds; or to perhaps "hedge their bets" a little bit more since the noise is non-Gaussian and non-stationary. Above about twenty time segments the error reduces at a slower rate, and the choice typically depends on the application and the accuracy appropriate to it. It might be instructive to see how much the NBS broadband spectrum estimates vary as the number of segments averaged is increased above twenty. Since the mine man-made noise is highly non-stationary, it must be kept in mind that each of these spectrum estimates may be representative of only a small fraction of the noise conditions that may occur in an operational mine.

Most of the power spectrum plots produced by NBS are based on the twenty-segment analysis and have been presented in a two-dimensional format. The rms magnetic field strength is plotted on the vertical axis versus frequency on the horizontal axis. The system and data presentation software have been calibrated so that the peaks of the harmonics can be read off the vertical scale directly as rms field strength in db relative to 1 amp/meter. For the broadband noise levels between the harmonics, the vertical scale readings represent the rms field strength levels seen at the output of a narrow bandpass filter equivalent to the 2Hz or 8Hz resolution bandwidths used to analyze the noise waveform. To convert these levels to levels in a 1Hz bandwidth, a number of db equal to $10 \log_{10} B$, where B is the resolution bandwidth, must be subtracted from the plotted field strength db values, 3db for the 2Hz bandwidth and 9db for the 8Hz bandwidth.

The tape-recorded noise waveforms were subjected to two 20-segment analyses, one extending up to 3000Hz and a second expanded-scale version extending only up to 750Hz. The 750Hz spectra were produced from 20, 1/2-second contiguous time segments, whereas the 3000Hz spectra were produced from 20, 1/8-second contiguous time segments. It was convenient to keep the number of data samples per time segment (2048) constant for the existing computer-analysis software. To accommodate the factor-of-four increase in the data-sampling rate required to analyze the 3000Hz band versus the 750Hz band, without increasing the number of data samples per segment, it was necessary to reduce the size of each time segment by a factor of four, from 1/2-second for the 750Hz to 1/8-second for the 3000Hz band. This reduction in time-segment length is the reason why the resolution bandwidth increased from 2Hz for the 750Hz spectra to 8Hz for the 3000Hz spectra.

The variability of both the harmonic and broadband noise over short time periods has also been graphically illustrated by providing three-dimensional spectrum plots that exhibit the changes in power spectrum levels as a function of time. Spectrum level versus frequency is plotted as in the two-dimensional spectrum plots, but time is now plotted along the third orthogonal axis. Vertical scales are missing, but will be provided in the final version of the report. In this 3-D analysis the spectrum levels computed for plotting versus time are formed from a sliding or running average of only four time segments, as opposed to 20 time segments. Therefore, the 90% confidence limit error estimate increases from $\pm$ 1.6db for the 20-segment average to $\pm$ 3.8db, for the 4-segment average. So, the broadband noise values cannot be considered very reliable in these 3-D plots, because much of the variation in the fine structure is due to statistical estimation error. However, the plots are still extremely useful for giving one a feel for how both the harmonic and broadband noise can change over short periods of time in mines. It also reinforces the need to obtain a wider exposure to the mine noise environments to establish tighter bounds on the expected variations of the noise produced by specific equipment and the mine environment in general.

The computer-based analyses were carried out in a competent manner, but some minor points of clarification are necessary with respect to the NBS Preliminary Report, to avoid confusion. NBS has agreed with these points, and they will be included in the final version of the report. First, in the description of the data-processing software, the error in estimating the harmonic peak levels is stated as $\pm$ 1.5db of the actual value. This should read 0db to -3db relative to the actual value. (The error always produces a lower apparent level.)

Second, in the 3000Hz-band spectral plots, the analysis bandwidth is a nominal 8Hz wide, and the noise level between harmonics appears to just run up and down the skirts of the analysis resolution filter, without ever reaching the actual broadband noise floor in some of the plots. In the 750Hz-band spectral plots, the resolution filter is a nominal 2Hz wide, and it is possible to reach the broadband noise floor between harmonics. On those graphs where the noise level appears to be running up and down the analysis filter skirts, the broadband noise floor level cannot be determined. This behavior can be attributed to the out-of-band response of the analysis filter, and can generally be improved by applying an appropriate weighting function across the data samples of the time segments, or narrowing the resolution bandwidth by using longer time segments.

Third, in comparing the 750Hz band and 3000Hz band analyses of the same piece of recorded noise data, a 6db difference should exist between the plotted broadband noise levels for each case. This reflects the 6db difference in noise power passed by the 2Hz and 8Hz analysis bandwidths. In Figures 32 and 33 discussed in the text of the NBS report, this difference is greater than the expected 6db. The present NBS data analysis routine uses about 10 seconds of data for the 750Hz-band analysis, but about 2.5 seconds of data for the 3000Hz-band analysis. Since the noise power level can and sometimes does change over even this short period of time, the spectral estimates that average 10 seconds worth of time segments can differ from estimates that average only 2.5 seconds of the above 10 seconds worth of time segments. We and NBS have jointly concluded that an actual change in field strength probably occurred during the 10-second time block; and that this caused the unexpected difference in computed spectrum levels, as opposed to the reasons given in the report. This problem could be avoided by utilizing the full 10 seconds for the 3000Hz band analysis too.

Fourth, the predigitizer filter roll-off frequencies are 375Hz and 1500Hz, instead of the 750Hz and 3000Hz mistakenly typed in the report. These lower frequencies correspond to the 750Hz and 3000Hz analysis bands, because the tapes were played back at half speed.

Fifth, NBS stated that it was necessary to make display density corrections, dependent on resolution bandwidth, to the power spectrum analysis computer software to change the output from spectrum power density to spectrum power. Since the NBS Preliminary Report description of this is somewhat confusing, NBS plans to provide clarification in the final version. However, this point of clarification is not essential to understanding and using the results of the report.

Three-dimensional cumulative (rank ordering) distributions of the rms field-strength spectrum estimates over short time periods have been prepared. RMS field strength is plotted on the vertical axis and frequency on the horizontal axis as in the other 3-D plots, but the third axis now represents percentage of time an rms field value is exceeded at each frequency. The sample populations from which the rms values are obtained are the four-segment running averages for the same time blocks used to prepare the 3-D power spectrum plots. Therefore, these plots are not to be construed as, or mistaken for, conventional amplitude probability distributions (APD). No documentation has been given on these plots, but NBS plans to explain them in the final version of their report; so further speculation on their utility will not be made at this time.

We view the high-resolution power spectra prepared by NBS to be extremely useful. First they provide a preliminary identification of some potentially troublesome noise sources and frequencies inside coal mines, and to a more limited extent outside of coal mines. Although the data are far from being considered the final word in characterizing in-mine harmonic and broadband magnetic noise levels and their frequency of occurrence, they provide a good starting point. We recommend that this spectral data be used to advantage: for making performance estimates for existing receiver designs and transmitter powers; for testing noise reduction techniques that may be devised for receivers; for conceiving new operational/emergency communications systems to combat this type of noise environment; and for planning future in-mine and above-mine noise-measurement strategies. We recommend that consideration be given to engaging the proven NBS measurement team to help in the accumulation of additional noise measurements in and above mines at frequencies below 10kHz, and particularly at the working-face areas.

V. WESTINGHOUSE GEORESEARCH LABORATORY (WGL)

A. SUMMARY

Westinghouse Georesearch Laboratory (WGL) has collected a modest amount of electromagnetic noise data in the frequency band between 20Hz and 5kHz at several non-operating and some operating coal mines. These data have been collected as part of the field-test program to exercise the CMR&SS electromagnetic and seismic emergency communications subsystems in a wide variety of mines under simulated emergency conditions. WGL's main objective has been to gather data under the relatively quiet non-operational electromagnetic conditions that are likely to exist several hours after a disaster. Documentation of measurement activities and collected data has been spotty and incomplete to date.

A limited sampling of surface and subsurface noise data from four coal mines principally in the Mid-West has been obtained. No analog tape recordings were made, no data were taken in the vicinity of working faces, and some of the data may not be calibrated. A few discrete harmonic spectra were obtained with a manually tuned wave analyzer in two operating mines. Most of the limited noise measurements were made by sensing the noise waveforms and subjecting them to direct digital processing in the field, producing moderate-resolution noise power spectra. The field minicomputer data-processing system originally intended for the processing of seismic signals was conveniently used for this purpose. This field computational capability offers the considerable advantage of quick-look analyses of the noise environment while at the mine site. It can be a valuable tool for rapidly identifying and classifying specific mine and surface equipment noise signatures, both during field measurement trips and actual emergencies.

A second thrust of the WGL EM noise measurement program has been to develop and assemble a fixed-site, noise data-acquisition system, to study long-term narrow-bandwidth characteristics of cultural and atmospheric noise in the frequency band from 20Hz to 5kHz in the vicinity of Boulder, Colorado. These long-term noise measurements are somewhat similar in character to those previously taken by WGL for other Government agencies. The previous data were taken to aid the design of reliable narrowband code communications, not voice communications systems. Hence, those results of the intended fixed-site noise measurements that may be useful will be applicable to the uplink reception of narrowband code signals for mine emergency communications and/or location. Sequential narrowband measurements of the noise envelope characteristics for all six magnetic and electric-field noise components at 24 frequencies across the band have been recommended, requiring 12 hours for each complete measurement cycle. The means of utilizing the data and the forms of data presentation have not been well documented.

These long-term measurements are not appropriate for characterizing the surface man-made noise in this band, which is dominated by power line harmonics at both suburban and coal mine sites. All or some of these measurements may also be neither necessary nor appropriate for characterizing the atmospheric noise environments that emergency mine communications are likely to encounter; particularly in view of past noise measurements in this band by WGL and others, and the findings and current plans of the Bureau of Mines. Bureau of Mines uplink-beacon code communication and location experience to date has revealed magnetic-field sensing systems and operating frequencies below 300Hz to be of high promise, and therefore worthy of greatest emphasis at this time. Therefore, some of the original field components suggested for long-term narrowband measurement by WGL are not applicable, the 20Hz-to-5kHz frequency band is perhaps wider than necessary, and good and suitable noise data appear to be already available in the lower band of current interest.

Lack of complete and proper documentation has prevented a definitive evaluation of the value of the WGL effort, plans, and limited noise data taken to date. We recommend that documentation be obtained from WGL for the field minicomputer data-processing system, including the data analysis and presentation software and methods of operation. An understandable, coherent summary of the mine-site EM noise data taken by WGL should also be acquired, together with detailed calibration and measurement procedures.

Some of the WGL mine-site data will then be more useful for making preliminary communication system performance estimates. We recommend that any future CMR&SS mine-site noise measurements by WGL include operating mine conditions of interest to the Bureau of Mines, and that these measurements commence only after present instrumentation and documentation problems and uncertainties are resolved. A wideband data-acquisition system centered on analog tape recordings of noise waveforms, that also includes a field minicomputer data-analysis facility similar to that of WGL's, should be considered for future coal mine EM noise measurements by the Bureau of Mines. Since it appears that some or all of the long-term narrowband noise measurements at the WGL Boulder facility may not be appropriate or necessary, we recommend that this program activity be seriously reviewed and modified accordingly.

B. FINDINGS

1. Noise Measurements and Instrumentation

The Westinghouse Georesearch Laboratory (WGL) electromagnetic noise measurements to date have been only a small part of its field test and evaluation program for the CMR&SS EM and seismic emergency communications subsystems in a wide variety of hard-rock and coal mines throughout the U.S. Eight mines in the Mid-West have been visited to date, but only about half of these have been coal mines. The documentation of the WGL noise measurement effort to date has been spotty and incomplete, making it difficult to evaluate the full potential of their limited noise measurements. However, we believe that a very small but useful sample of EM noise data has been obtained for relatively quiet, non-operating mines; a sample that perhaps may be representative of conditions that could exist several hours after a disaster.

WGL has made noise measurements at about four coal mines, mostly under non-operating conditions. The vertical component of noise magnetic field was measured on the surface, while the horizontal component of noise magnetic field was measured in the mines. These components correspond to those sensed by the CRM&SS surface and subsurface communication receiving systems, respectively. The objective was to obtain quiet-mine data. Measurements were generally scheduled when mining activities were shut down or minimal, with all but the absolutely necessary mine equipment such as fans, etc., turned off. In addition, quiet locations in the mine were chosen away from working sections,power boreholes, telephone lines, and specific equipment. Surface noise measurements generally displayed the presence of the 60Hz power frequency and its harmonics, and in one case, measurements were made under a power line going to a radar station. A few operating mine measurements were made, but no measurements were made over or at working faces. It appears that only very few samples of magnetic field noise were obtained for each mine, one on the surface and one in the mine, unless WGL has other data it has not released. No attempt was made to correlate surface EM noise recordings with subsurface activity in the mine, but penetration into the mine of 60Hz fields from surface lines was noticed.

Mine-site noise measurements were made in two ways. The first utilized the 24-inch square, 1000-turn beacon receive antenna feeding a manually tuned, Quantek 304 wave analyzer with a 10Hz bandwidth. The frequency band from 60Hz to 5kHz was examined by manually recording the rms field strength at each harmonic encountered in this band. In some cases noise levels between harmonics were estimated. These measurements were made in mines under operational conditions, once at the Geneva Mine and once at the Clyde Mine. Though such a wave analyzer is good for measuring harmonic noise components, a time on the order of two hours was required to cover the frequency band and about four hours to later reduce and plot the data. The two-hour measurement time is not only excessive operationally, but also prevents correlation of harmonic levels in different parts of the spectrum. Calibration details for this system have not been discussed or reviewed. The excessive measurement and processing time required with the wave analyzer led WGL to the use of a more efficient and useful measurement method that produced real-time wideband analyses of the noise waveforms on-site.

The second mine-site measurement method senses the magnetic field noise with one of several loop antennas, preamplifies it, and applies compensation before sending it up 3,000 feet of balanced and shielded cable to the surface, typically via a water borehole. At the surface the noise waveform is amplified again and low-pass filtered (with a 3kHz or 5kHz cut-off frequency and 24db/octave roll-off) in order to avoid data aliasing errors, while operating within the maximum sampling rate (10kHz) of the subsequent 10-bit A/D conversion. The 10kHz sampling rate limits real-time spectrum analyses to frequencies below about 3kHz.

The sampled and digitized noise waveforms are used to compute real-time, moderate-resolution power spectrum plots by means of the field mini-computer data acquisition and analysis system. The field data acquisition and analysis system is the one supplied by Computer Signal Processors, Inc., originally for CMR&SS seismic signal analysis. The system, designed around a Varian 620 series minicomputer that serves as the system central processing unit (CPU), is able to output noise power spectrum plots via a Hewlett-Packard Model 7500 plotter in approximately three minutes, as compared to the hours required via the manual wave analyzer method. The plotted noise spectra are equivalent to those obtainable by analyzing the noise waveforms with analog filters of bandwidths equivalent to the 20Hz and 10Hz resolution windows used. From what we can ascertain, the power spectrum computational routine appears to be similar to that used by NBS. Though the field minicomputer will demonstrate analytical limitations when compared with the large, high-speed digital computer utilized by NBS, its convenient on-site analysis capability is extremely valuable. The noise data can always be subjected to a more refined and detailed analysis later, on a large machine if analog tape recordings are taken of the original noise waveforms. No analog tape recordings were made by WGL.

The measurement configurations were changed several times in obtaining the data presently available, as data acquisition problems were identified and solved. Since these changes have not been reported and well documented, confidence in the WGL data has been impaired accordingly.

WGL should be able to restore this confidence by proper documentation. For instance, all the recorded noise data has not been presented together in a unified, coherent, understandable manner. Secondly, some of the magnetic field noise measurements were made with the beacon receive air-core loop antenna, while others were made with a 1-foot diameter air-core loop or with a ferrite-core loop, so that some are calibrated and some are not. Thirdly, some measurements were made with a seismic matching transformer present, which introduced undesirable system frequency response artifacts and required subsequent graphical corrections on the power spectrum plots. The latest noise measurements have been made without this transformer, and include signal conditioning to compensate for the 6db per octave rise of the loop frequency response, thereby producing a more desirable preamp output response which is relatively flat between 100Hz and 5kHz, and directly proportional to the noise magnetic field.

Subsystem calibrations have apparently been made in some instances, together with frequency response measurements of selected components. The ferrite loop-stick antenna with its compensated preamplifier was calibrated as a complete unit in a known field in Boulder. A complete calibration from the antenna sensor through to the graphical output was not made. System noise levels were checked in some instances by shorting the preamplifier input, but not at mine-sites to check whether the system including the 3,000-foot cable was picking up unwanted noise from the environment. The A/D converter also experienced dynamic range limitations when in the presence of strong 60Hz power line components. This should be examined further and resolved, if possible.

A limited number of the wideband, real-time noise power spectra appear to be useful if the instrumentation, methods of measurement, calibration and data analysis can be adequately documented. However, in spite of the condition of the present set of data, the field-portable van-mounted minicomputer data acquisition and power spectrum analysis system can and should be a valuable measurement tool for future Bureau of Mines noise measurements. It could well serve as the quick-look analysis device desired for probing the EM noise environment for conditions and equipment deserving more extensive and careful noise recording and analysis. Therefore, the system's adaptability and utility for examining operational coal mine environments should be ascertained.

A fixed-site instrumentation system is also being assembled by WGL to monitor and characterize the long-term narrow-bandwidth characteristics of natural and man-made noise as a function of time, frequency, and EM field components at the WGL Boulder, Colorado, site. The noise measurements and instrumentation are somewhat similar to those conducted in the past by WGL for other Government agencies. The previously taken noise data were for aiding the design of reliable narrowband code communications, not voice communications systems.

This fixed instrumentation system was designed to obtain narrowband (6Hz) noise statistics over the 20Hz to 5kHz band. The measurements are to include the average and peak values of the detected noise envelope (not the rms value), together with time and amplitude probability distributions (TPD's and APD's) of this envelope. All six EM noise field components, three for the electric field and three for the magnetic field, at each of 24 frequencies selected across the 20Hz to 5kHz frequency band are to be measured sequentially. Twelve hours will be required for each complete measurement cycle at the sequencing rate of five minutes per field component per frequency. The instrumentation has been designed around a Hewlett-Packard 302A wave analyzer of 6Hz bandwidth and 60db dynamic range, which has been programmed to step through the desired frequency band and/or sensors in five-minute steps.

Measurement of the most useful noise parameter, the rms value of the detected envelope, was not included in order to avoid somewhat increased instrumentation costs, since the rms value can be computed from the APD. The cost or inconvenience of having to compute the rms values was not discussed. The 6Hz bandwidth is not fundamental but happens to be a convenient one used in the past by WGL to gather noise data with the 6Hz bandwidth HP 302A. Wider bandwidth measurements of atmospheric noise have since been found to be more useful for some receiver applications. The APD analyzer spans a dynamic range of 120db (in twenty 6db steps) characteristic of that expected for ELF atmospheric noise, but the data acquisition system will be limited by the HP 302A 60db dynamic range. WGL plans to alleviate this shortcoming by examining only the upper 60db of the noise dynamic range that contains most of the noise power. This will require somewhat greater diligence in the adjustment of system gain with ambient noise conditions to ensure efficient use of the limited dynamic range while preventing saturation. If such long-term narrowband noise measurements become necessary, a modified version of this system might provide a potentially moderate cost method of obtaining a limited set of data. This should be confirmed if the need arises.

The planned long-term noise measurement effort at Boulder in its original form will be of questionable utility to the Bureau of Mines emergency/operational mine communication and location program, and should receive careful review and redirection for several reasons. The sequential measurements across the frequency band will take two hours for each sensor (12 hours for six sensors) which precludes relating spectrum levels observed at one point in the frequency band to those at another, or relating the levels observed by different sensors. Since the man-made noise in the voice band at coal mine and suburban locations will be dominated by harmonics of the power frequencies such as 60 and 360Hz, the instrumentation is inappropriate for characterizing this type of man-made noise. The long-term narrowband measurements over the voice band will not be useful for predicting the performance of voice communications systems. They will have some value for narrowband code systems for up-link communication or EM location; however, restriction of the measurements to the Boulder site will most likely not provide atmospheric noise results representative of the entire country and coal mining regions in particular.

More importantly, the Bureau of Mines and WGL have identified magnetic field sensing systems, at frequencies between about 20Hz and 300Hz, to be the most promising for EM code and location systems. These findings are based on the extreme attenuation experienced by 2.7kHz beacon signals in deep mines with higher-than-expected overburden conductivities, and the potential field distortion effects caused by non-homogenous overburdens at the higher frequencies. Consequently, many of the original field components to be measured are no longer applicable (the electric field measurements have already been de-emphasized by WGL), the original 20 to 5kHz measurement band is perhaps wider than necessary, and good and suitable data appear to be already available for the field components and frequencies of greatest interest.

In particular, a wealth of calibrated and well-documented horizontal component magnetic field atmospheric noise data has been recorded wideband and analyzed by the MIT Lincoln Laboratory at several locations in the U.S. and around the world in the frequency band from 3Hz to 300Hz. These data, in analyzed and/or originally recorded form, can be acquired by the Bureau of Mines from Lincoln Laboratory together with documented analysis software. The horizontal magnetic field components measured are the dominant ones. They are also the most likely to restrict the location accuracy of EM location systems that depend on detecting and locating a null in the horizontal magnetic field. Curves produced by WGL indicate that the null in the horizontal component of the field can be on the order of 55db below the vertical component of the field directly above a magnetic field loop source. The vertical component of magnetic field atmospheric noise will, in fact, be weaker than the horizontal component, as a result of the source and propagation mechanisms. However, this difference should not even approach the 55db difference between the vertical field component produced by a beacon and the expected null depths for the horizontal beacon component. Orientation and dimensional errors in practical sensing loops will further limit the degree to which the vertical and horizontal noise fields can be discriminated against. Since the noise horizontal field component may in fact be the limiting noise component, the currently available Lincoln Laboratory noise data between 3Hz and 300Hz may be sufficient for designing EM location and code communication systems, and for making system performance estimates.

2. Units and Sensors

The field strength units used for all magnetic field strength measurements were db relative to one microampere/meter (μa/m), and the units for the intended electric field measurements db relative to 1 micro-volt/meter (μv/m). The manually-scanned measurements with the Quantek wave analyzer give the rms value of field strength at each of the noise harmonics measured. In the real-time power spectrum plots produced by the field minicomputer data processing system, the peak value of the response at each of the discrete harmonic components represents the rms value of the harmonic in μa/m. The broadband noise levels between the discrete harmonic peaks represent the rms noise field strength in μa/m as seen at the output of a narrow bandpass filter equivalent to the 20Hz (or 10Hz) resolution band used to analyze the noise waveforms. However, most of the broadband noise levels may not be reliable because the width of the analysis resolution band coupled with poor out-of-band response characteristics allow significant contributions from adjacent harmonic components to corrupt the broadband noise estimate.

Several antennas were used for mine-site noise measurements, only some of which were calibrated. One was the 24-inch square air-core shielded loop receive antenna; a second was a 1-foot diameter air-core loop antenna; the third a ferrite-core loop with a compensated pre-amplifier to produce a preamp output flat across the 100Hz to 5kHz band. Though the third unit was calibrated in a known field, questions still remain about it as well as the others. The sizes of the antennas are convenient for in-mine field measurements, and they are small enough to relate the results to man-pack receiver loop sizes without gross errors, if calibrated. A loop smaller than the beacon receive loop should be used to measure noise field variations very close to specific equipment, as in the case of the NBS loop. A standardized 12-inch diameter air-core shielded loop is preferred, if an acceptable one is available. One of the disadvantages of ferrite loops is that rough field handling may change the initially calibrated characteristics. This is not a problem with air-core loops, which is why they are usually preferred when taking absolute field strength measurements. Harmonic distortion problems were experienced with the ferrite-core loop antenna at those locations where 60Hz components were particularly strong.

The ferrite-core loop was used only at one mine, the Gunn Quealy. The AC power was turned off in the mine, and locations away from power lines were chosen on the surface. More documentation is needed regarding antenna description, performance and calibration.

For the fixed-site long-term noise measurements in Boulder, beacon receive antennas (24 inches square with 1000 turns) will be used to measure all magnetic field components. For measuring electric field components, a six-foot whip is intended for the vertical component; and for each of the horizontal electric field components, two probes placed in the ground 10 meters apart. Since the December meeting, emphasis has changed to include only the magnetic field measurements because of their primary importance to mine emergency communication and location systems. There have been some indications of calibration procedures existing for this Boulder system, but they have not been documented in any meaningful manner.

3. Data Analysis and Presentation

The power spectrum estimates produced by the field minicomputer data analysis system appear to be computed by the direct segment method, assisted by a Fast Fourier Transform (FFT) computational algorithm, in a manner similar to that used by NBS. However, because of the more limited capacity and speed of the field minicomputer system, some of the analysis and implementation details may in fact be different. These details should be obtainable from WGL.

As in the NBS work, WGL computed power spectrum estimates for a large number of individual time segments and averaged these together to obtain stable final spectrum estimates. WGL averaged three hundred (300) 50-millisecond time segments to produce power spectra with 20Hz resolution bandwidths. Frequencies up to 2-3kHz were analyzed. Spectra of 10Hz resolution are also claimed to be available by using 100-millisecond-long time segments, but data has not yet been presented with this resolution. Not much difference was found to exist between 100 segment and 1000 segment spectrum analyses, so the geometric mean (300) was chosen arbitrarily. This represents 15 seconds of data for the 50-millisecond segments and 30 seconds of data for the 100-millisecond segments.

All other conditions being equal, the WGL power spectrum estimates of the broadband noise between harmonics should have a smaller statistical error than those of NBS, because of the large number of segments used by WGL (300 vs. 20). However, the wider analysis resolution band combined with the worse out-of-band response used by WGL have created broadband noise estimates that are perhaps no better than the 8Hz bandwidth NBS analyses and worse than the 2Hz analyses of NBS. Examination of the Westinghouse spectra reveals the same riding up and down the filter skirt behavior observed in the 8Hz NBS analyses. In these cases the broadband noise floor cannot be determined. No weighting function was applied to the noise time samples across each time segment to improve the out-of-band response. This feature is supposedly available, and if so, could be used to advantage for future measurements. Longer time segments to reduce the analysis bandwidth should also be used if possible. Incorporation of these changes is necessary if the broadband noise levels between harmonics are to be determined.

Of the computed spectra to date, those taken at the Gunn Quealy Mine are the most conveniently presented for subsequent use. The Geneva and Somerset Mine plots require graphical interpolations between the plotted spectrum levels and superimposed reference lines representing the frequency response of the seismic preamplifier and transformer (removed after the Somerset Mine measurements). The main problem remaining in the Gunn Quealy spectra is that the broadband noise floor still cannot be determined because the poor out-of-band response does not allow the computed levels to reach the noise floor. This problem can be alleviated by the methods discussed above. In spite of some deficiencies, these real-time spectrum plots obtainable in the field can be a very important asset for quick-look characterization of mine noise environments.

The results of the manual Quantek wave analyzer measurements of discrete harmonic noise levels have been tabulated and plotted versus frequency in the form of vertical bars of length equal to the rms harmonic level measured at each harmonic frequency. These represent subsurface measurements up to 5kHz in two coal mines, the Clyde and the Geneva Mines, under operating conditions. These data may be quite useful in assessing the utility of harmonic filtering techniques for receivers, because measures of the noise levels between harmonics were also obtained. However, the two-hour period required to obtain the data prevents correlation of harmonic levels at different frequencies.

No explicit plans have been documented for the ultimate presentation and utilization of the data to be obtained from the narrowband long-term noise measurements in Boulder. It is critical that these be determined before any measurements be allowed to commence, to avoid the generation and proliferation of a lot of useless data.

In the absence of any narrowband long-term noise data measured for the Bureau of Mines, WGL has presented several graphs of narrowband noise data measured by WGL for other Government agencies in the past, much of which was published by E. Maxwell in 1967 and 1969. Some of this narrowband data may be useful for estimating the performance of narrowband up-link code or location systems, but only if they are relevant, and well documented with regard to measurement and calibration methods, methods of analysis, and significance and utility of the end results. Much of the presented magnetic field data represents estimates based on converting vertical electric field levels obtained from whip antennas to corresponding horizontal magnetic field levels by invoking the uniform plane wave relationship between the E and H fields, an assumption that is not justified at frequencies below about 5kHz. As such these results may at best be considered upper bounds on the horizontal magnetic noise field, and used only with caution unless all measurement and processing details are known. Plots of various types have been shown for several locations in the world, including Japan, Alaska, and Malta, without explanation of their significance to coal mine rescue systems. The magnetic field curves for Malta were interesting in that they at least represented actual loop data at a very low frequency of 33Hz. The Malta curves are not to be confused with amplitude probability distributions but are cumulative distributions of the rms values of atmospheric noise electric and magnetic field components during the data measurement interval in the winter of 68-69. More of these data should be available from WGL but the value of these data to mine communications and location system design has yet to be demonstrated.

The moderate-resolution real-time power spectra prepared by WGL to date are of moderate quality and limited utility unless better documented. Though the Gunn Quealy Mine noise spectra may represent a small sample of calibrated results under quiet mine conditions, the lack of proper documentation still casts some doubts on their validity and utility. The WGL real-time field data acquisition and analysis system is a potentially useful tool, if it is modified to produce better quality spectra, and its capabilities and limitations are documented carefully. We recommend that the field minicomputer data acquisition and processing system be modified accordingly for use on future field trips to characterize coal mine noise environments. It should be integrated with an analog tape recording system in order to allow more definitive analyses to be performed in the lab and for simulation work. Complete documentation and explanation of system operation and limitations should be obtained from WGL. Documentation of the measurements made with the Quantek wave analyzer should be obtained from WGL. The planned long-term narrowband noise measurements at the WGL Boulder facility are of questionable utility. We recommend that these measurements not be continued in whole or in part until it is determined that they will serve a necessary and useful purpose to the Bureau of Mines mine rescue program. We recommend that any future WGL mine-site noise measurements include relevant samplings of surface and subsurface operational mine environments.

VI. WEST VIRGINIA UNIVERSITY (WVU)

A. SUMMARY

West Virginia University (WVU) is the only contractor that has taken EM noise measurements in operating coal mines covering the frequency band extending from 2kHz to 200kHz. EM noise conditions in a wide variety of Eastern coal mines, under operating conditions, and in the vicinity of likely sources of EM noise are represented. WVU is also the only contractor that has measured conducted-noise levels on trolley and telephone lines in mines under operational conditions. As such, the WVU noise data will be of value in spite of some instrumentation and calibration deficiencies. Documentation of the mine-site measurement activities and accumulated data to date is still incomplete.

The objective of WVU's noise measurements was to obtain order-of-magnitude noise information, to aid WVU's efforts to develop a new wireless paging system for in-mine use and improve carrier-current mine telephone systems. Definitive measurements that would accurately characterize coal mine noise environments were not intended. Data from eight coal mines (including the Bruceton experimental mine) have been obtained. No analog tape recordings or average power measurements were made, no data were taken in the vicinity of working faces, and the data have yet to be calibrated on an absolute basis. The instrumentation was centered around a conveniently portable, manually tuned, frequency-selective voltmeter of moderate bandwidth; an instrument designed for measuring levels of single harmonics, carriers, and pilot-tones on commercial telephone lines. It is not the most appropriate instrument for measuring coal mine EM noise, noise that is alternately dominated by closely spaced power frequency harmonics and broadband wide-dynamic-range impulsive noise.

The accuracy and interpretation of the WVU noise data will vary considerably depending on the type of noise dominant at the times the measurements were taken and the portion of the frequency band analyzed. Harmonic-dominated noise data at frequencies below about 30kHz should be the most accurate; wide-dynamic-range impulsive noise data and all data above 30kHz should be the least reliable. In spite of deficiencies, it may be possible to analyze and recast much of this data to yield useful results with regard to noise variations as a function of frequency, equipment types, and distance from equipments. However, these data should be used with caution if applied to the design of narrowband-code paging systems or voice communications systems. We recommend that this instrumentation not be used to gather additional mine-site noise data until a more effective utilization of its potential is determined. The required calibration procedures must be performed on the instrumentation. A final assessment of the validity of the impulsive noise data and all data taken above 30kHz must be made and the findings documented. We recommend that the EM noise data taken to date be re-analyzed and recast in presentation formats that will be more instructive and revealing of pertinent environmental noise characteristics, as suggested in our findings. WVU's considerable knowledge of and general experience in operating coal mine environments can be used to the Bureau of Mine's advantage in subsequent noise measurement and communications programs.

B. FINDINGS

1. Noise Measurements and Instrumentation

West Virginia University has made measurements of the horizontal and vertical components of EM noise magnetic fields, inside seven operating coal mines in Pennsylvania and West Virginia and in the Bureau of Mines Bruceton Experimental Mine. AC and DC mines are represented. A limited number of measurements have been made on the surface at some of these mines. Conducted noise measurements were also made in these same mines on the DC trolley lines and the mine telephone lines. In-mine locations near high-voltage transmission lines and high-power mining equipment were chosen in addition to relatively quiet locations. Conducted noise measurements were generally made near the dispatcher's office on the telephone lines and near the mine entrances on the trolley lines. The frequency band from 2kHz to 200kHz was examined by sequentially measuring magnetic field components at 20 discrete frequencies with a 300Hz (or 250Hz) bandwidth instrument. The 20 frequencies were chosen to provide equally spaced data points on a logarithmically plotted frequency scale. The measurements were intended to produce order-of-magnitude noise level estimates for carrier telephone and wireless paging applications being considered by WVU.

The magnetic field components were sensed by a close-wound 50-turn, unshielded air-core loop, 1.3 square meters in area. The loop terminals were directly connected to a high input impedance (10 megohm) amplifier (40db gain), the output of which was fed into the input of a manually tuned Philco-Sierra Model 127C frequency-selective voltmeter. The 127C 3db bandwidth is given as 250Hz in the manual, but WVU has referred to a 300Hz bandwidth. This should be confirmed. Eyeball averages of the output meter readings on the 127C were recorded at each frequency examined in the band. The length of time needed to cover the frequency band was not discussed. The Philco-Sierra 127C is an instrument designed for use with telephone carrier systems to measure discrete frequency signals as carriers, pilot tones, and single-frequency RFI components, on 135 ohm and 600 ohm balanced or unbalanced lines. The 127C will give a accurate measurement of the rms voltage or average power for these types of signal and noise components but not for broadband impulsive noise. The Sierra 127C does not measure signal or noise power but the average value of the full-wave-rectified input voltage. A long time constant on the order of 500 ms is used for the averaging. No noise power measurements were made and no analog tape recordings were taken of any of the waveforms.

Measurements were made of the horizontal and vertical magnetic field components of the EM noise at the following locations; near AC and DC power centers, near high-voltage and low-voltage AC power cables, near DC trolley lines, places isolated from electrical cables and equipment, and in the vicinity of specific mine equipment such as continuous miners, rotary dumps, and high-voltage three-phase rectifiers. Measurements were taken as a function of distance from the electrical cables and machinery, and as a function of equipment operation. Frequencies and individual field components were not measured simultaneously, but sequentially, which impairs meaningful correlation of noise levels recorded at one point in the band to levels at other points in the band. No data were taken at working faces in the mines, or above the working faces on the surface. Preliminary documentation has been received on the noise measurements, together with some preliminary conclusions regarding the noise measurements. Some of these conclusions may be valid and others may have to be modified after closer scrutiny and analysis of the data and the conditions under which they were obtained.

The instrumentation system has not been calibrated by placing the sensor in a known field and relating this field to the 127C meter output for various types of noise waveform inputs. NBS has supplied WVU with a signal injection network to apply to the loop antenna in order to get an absolute system calibration for the EM noise measurements. However, for loops exhibiting self-resonance properties, like the WVU loop does near 50kHz, this signal injection calibration method is alleged to be unreliable at frequencies in the vicinity of and above such resonances. Hence, WVU believes that the EM noise data above about 30kHz may be unreliable even after the calibration.

Conducted noise measurements were made at the same frequencies as the EM noise measurements by connecting the amplifier high-impedance input across the trolley line and ground and the telephone line and ground. DC isolation was obtained by means of a high-pass capacitive coupling network (with cutoff frequency 20Hz) preceding the amplifier input. Conducted noise levels were examined in the 20Hz to 200kHz band to see if the sensitivity of present DC trolley carrier telephone systems could be improved by changing to a frequency having lower noise levels than 88kHz. Our evaluation has been centered on EM noise environments encountered by wireless mine communications, so the WVU conducted noise measurements did not receive detailed evaluation.

The Sierra 127C is not the most appropriate choice for coal mine noise environments and the voice and narrowband-code paging systems of interest to WVU. With this type of instrument in the coal mine noise environment, it is not possible to reliably extrapolate up to the approximately 2500Hz to 5000Hz bandwidths needed for single sideband or double sideband AM voice communications or to extrapolate downward to determine the broadband passband of the 127C. Some data have been normalized to a 1Hz bandwidth while others have not. The conducted-noise data on trolley lines and telephone lines have been presented as noise voltage levels seen between the lines and ground by the high input impedance amplifier, within the 127C passband. These data are not normalized to a 1Hz bandwidth.

The normalization factor used to obtain noise voltage levels in a 1Hz bandwidth is 10 $\log_{10}B$, where B is the 300Hz bandwidth. This is the correct factor for converting rms noise levels to different bandwidths when the noise spectrum is continuous and uniform across the bandwidth in question. This factor is not applicable when the noise is dominated by harmonics as it can be in coal mines; nor for levels obtained from average reading meters, unless the noise is white and Gaussian. Until the WVU data is analyzed more carefully with respect to the character of the noise, the levels measured should not be normalized to 1Hz bandwidths.

The loop voltage has not yet been referenced to units of absolute magnetic field strength at the sensors. Therefore, all WVU results have been plotted relative to an open-circuit voltage 0db reference level of 0.35 volts. Hopefully the injection calibration network supplied by NBS will allow WVU to relate the open-circuit voltage readings to magnetic field strengths expressed in amperes/meter, in the 127C passband, over those frequency ranges where this injection network will provide a valid calibration.

The WVU magnetic field sensor is a 50-turn, close-wound, unshielded air-core loop, with a 1.3 square meter area. It is a collapsible design easily transported into mines and moved around equipment. It was fabricated by WVU especially for this purpose. WVU suspects that the loop may be sensitive to electric fields, thereby introducing added uncertainty the noise levels, particularly those measured in the vicinity of specific noise sources such as power lines, trolley lines, and mining equipment. The frequency response of the 50-turn loop has been compared to that of a 1-turn loop reference and found to exhibit a self-resonance centered around 50kHz, the effects of which are apparent between 25kHz to 200kHz.

A calibration curve, which is the inverse of the loop resonance characteristic, has been measured and applied to the noise data taken above 25kHz. However, in spite of this calibration curve, three things make the results above about 30kHz less reliable than the data below 30kHz. First, WVU has found the resonance calibration curve to change when the loop is brought underground and used in coal seams. The coal itself appears sufficient to cause these changes, without assistance from rails or metallic equipment. Secondly, the NBS signal-injection calibration method supposedly does not provide valid calibrations in frequency regions where an antenna exhibits self-resonance behavior. Thirdly, the 50kHz to 200kHz part of the frequency band lies on the upper roll-off skirt of the loop self-resonance characteristic measured in the laboratory. The loop frequency response changes by on the order of 30db in this frequency range, so that large changes in compensation factor are produced by only small changes in frequency. Hence, incorrect compensation corrections of many db can result, particularly when the shape and location of the loop resonance can change as a function of location and orientation in the mine.

The size of the loop is small enough for taking convenient measurements in mines and for relating the results to small man-pack receiver loop sizes without gross errors. However, WVU agrees that a loop smaller than this should be used to measure noise field variations close to specific equipment. After calibration, WVU believes that its data should be reliable at frequencies below about 30kHz when not taken in the immediate vicinity of specific equipment. However, the EM noise data will probably remain unreliable for frequencies above about 30kHz, thereby casting doubt on the validity of the apparent noise minimum above 80kHz.

3. Data Analysis and Presentation

EM noise data taken to date by WVU have not received much detailed analysis. WVU desires direction on preferred methods of analyzing and presenting its data. With the exception of the Bruceton Mine data, the WVU data have to date been plotted in the form of composite graphs, which represent maximum and minimum noise voltage levels recorded at all mines, under all conditions, at each of the 20 frequencies measured in the 2kHz to 200kHz band. The intention of these plots was to provide an indication of the extremes over which noise voltage levels could vary under various mine conditions. The plotted parameter for the conducted noise is the open-circuit voltage measured by the 127C in its 300Hz (or 250Hz) passband. The plotted parameter for the EM noise is the loop open-circuit voltage measured by the 127C in its 300Hz (or 250Hz) passband, but normalized to a per-cycle (1Hz) bandwidth. Unfortunately, because of the frequencies chosen, the instrumentation used, and the character of the coal mine noise environment, the EM composite noise plots in their present form do not give an accurate picture of the absolute noise levels or of their relative variation with frequency. Thus they can lead to misleading interpretations. One of the main problems is that such a composite plot does not differentiate between discrete harmonic type noise and broadband impulsive noise. If the noise in the instrument passband is dominated by the harmonic type noise that is characteristic of coal mines, normalization to a 1Hz band is not appropriate, since the noise power is not distributed evenly across the passband. Such normalizations will lead to errors in noise levels in these cases, and misrepresent the character of the noise.

A DC coal mine, where noise environments are strongly dominated by harmonics of 60Hz and 360Hz, is a good case in point. In such a mine, the 300Hz (or 250Hz) passband of the Sierra 127C is very likely to be occupied by one harmonic of 360Hz and 4-5 harmonics of 60Hz as the 2kHz to 200kHz band is scanned with the 127C. The 360Hz harmonic is also likely to be the dominant one, thereby presenting a single-frequency noise source situation. A less likely situation is that the 127C 300Hz (or 250Hz) passband can be located between two 360Hz harmonics so that the 60Hz harmonics or broadband noise will be dominant. If the 127C passband is dominated by a harmonic of 360Hz, say 10db above a background of 60Hz harmonics, the 127C meter reading will probably be within about 0.5db of the true rms level of the harmonic. If the passband is dominated by several nearly-equal-strength harmonics of 60Hz, or by white Gaussian noise, a meter reading on the order of 1-2db lower than the true rms level of the resultant noise wave form occupying the passband can be expected. If the noise in the passband is dominated by wide-dynamic-range impulsive noise, the 127C readings may not be useful at all.

A quick comparison of the measurement frequencies chosen by WVU with the harmonics of 360Hz, up to about 36kHz, reveals that a harmonic of 360Hz falls within 100Hz of all but two of the chosen frequencies, and hence falls within the passband of the 127C. As a result, relatively variable noise readings can be expected at these frequencies in DC mines, high when the haulage trains are drawing power, and low when the haulage power needs are low. For two of the frequencies chosen below 36kHz, the 127C passband falls between 360Hz harmonics, which should result in lower noise level readings. Therefore, it is possible that the high and low maxima shown on the composite plots may only be reflecting the above operational and measurement conditions and coincidences.

By plotting the WVU noise data, taken in the 300Hz (or 250Hz) passband of the 127C, as a function of frequency, for each of the locations, mines and occasions that the frequency band from 2kHz to 200kHz was scanned, considerably more information should be gained regarding the characteristic behavior and components of coal mine EM noise environments. It may also be possible to then relate the WVU data to observations made by other investigators such as NBS and WGL.

WVU has a collection of noise data representing a wide variety of coal mine noise environments. These data have apparently satisfied WVU's needs. To be of more general utility to other Bureau of Mines' communications activities, several matters need to be resolved. The loop antenna and instrumentation as a whole must be calibrated as a function of frequency. The behavior of the Sierra 127C in the presence of wide-dynamic-range impulsive noise must be determined, preferably by measurements. The data obtained by WVU must be documented more completely, and should be subjected to intensive and timely analyses that will quickly reveal the most useful data. In this manner it may be possible to capture more information on coal mine noise environments than originally intended from the WVU data taken to date, if it can be done in a timely and efficient manner. We recommend that this instrumentation not be used to gather additional mine-site noise data until a more effective utilization of its potential is ascertained.

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