NATIONAL RADIO ASTRONOMY OBSERVATORY
SOCORRO, NEW MEXICO
VERY LARGE ARRAY PROGRAM

VLA ELECTRONICS MEMORANDUM NO. 211

RADIO INTERFERENCE FROM HIGH-VOLTAGE POWER LINES

A. R. Thompson

July 1984

An investigation of the existing information on corona-discharge radiation from power lines was made during 1984, as a result of the announcement by the El Paso Electric Co. of a plan to route a 345 kV power line across parts of the San Augustin Plains. This memorandum gives the most useful source of information found in the literature, and some notes on the interpretation of the data that it contains.

Radio emission from power lines is generated by two mechanisms, arcing of the conductors to parts of the support structure, and corona discharges into the atmosphere. Arcing usually results from dirt on the insulators, or hardware that is loose or damaged. It occurs on lines with voltages down to a few tens of kilovolts, which are often less well maintained than high voltage lines. Corona discharge occurs on lines with voltages of about 70 kV or greater, and is the principal concern in this case. Radiation resulting from either mechanism falls off in field strength inversely with the frequency, and the effects of the power line are therefore most severe at 75 MHz which is the lowest frequency planned for use with the VLA.

An extensive series of measurements was made on power lines in a project supported by Rome Air Development Center in the late 1960s. A summary of the work by Pakala and Chartier (1971) was the most useful reference found, and this paper is reproduced as Appendix I. Further investigation of the literature, mainly in IEEE Proceedings on Electromagnetic Compatibility and on Power Apparatus and Systems gave the impression that little on this subject had been done during the past decade. On May 17, 1984 V.L. Chartier visited the VLA site as a consultant to the BLM on the environmental impact of the power line. The following information on the data in Pakala and Chartier (1971) is based on discussions with him.

Three types of measurements are involved in the power line data: peak, quasi-peak, and rms values. The data in the Pakala and Chartier paper are peak values, and correspond to the peak levels detected during an interval of some minutes. Field-strength measuring equipment commonly used for power line measurements at the present time incorporates quasi-peak detection. Finally, the data required for estimation of interference to radio astronomy is flux density which is directly related to the rms field-strength values. Comparison of measurements made using the three types of detection indicates that, for a given rf bandwidth, the quasi-peak values are 10 dB higher than the rms values and the peak values are a further 10 dB above the quasi-peak. These relationships are believed to apply to values in most weather conditions. The rms values are 20 dB higher in steady rain than in fair weather, and the most accurate comparisons are those made during rain. The variation of the signal with rf bandwidth is also different for the three types of measurements. The rms field strength values are proportional to the square root of the bandwidth, but the peak and quasi-peak field strength values are directly proportional to the bandwidth. The latter relationship is largely empirical, but believed to be accurate. It was used by Pakala and Chartier in converting their measurements to the 1 MHz-bandwidth values that they give in their paper. Figure 10 of Pakala and Chartier shows the general spread of values for corona radiation. The two lines in this figure marked 1/f indicate a general spread of values of $\pm$ 20 dB.

As part of his study for the El Paso Electric Company's line, V. L. Chartier computed the radiation from the proposed line using a computer program based on relationships given in Chartier (1983), which is reproduced as Appendix II of this memorandum. The results are given in the letter from V. L. Chartier to A. R. Thompson in Appendix III. The value for the median of the three conductor sizes considered is a quasi-peak figure of 18.5 dB μVm^{-1} (120 KHz)$^{-1}$ at 75 MHz and 200 ft. from the conductor. (The 120 KHz bandwidth corresponds to the bandwidth of a quasi-peak instrument used for these measurements). To convert this result to a value relative to $1 \mu Vm^{-1}$ Hz^{-1} (rms) we subtract 10 dB for quasi-peak to rms conversion and 10 log (1.2×10^5) dB for the bandwidth factor. The result is -42.5 dB μVm^{-1} Hz^{-1}, or -188.5 dB Wm^{-2} Hz^{-1}. Note that $1 \mu vm^{-1}$ Hz^{-1} -146 dB $Wm-^{2}$ $Hz-^{1}$, and in the above calculation we have followed (in reverse) the steps used by Chartier in the first page of his letter in Appendix 3. The figure just derived is for 7000 ft. elevation, and the corresponding value for sea level (-195.5 dB Wm^{-2} Hz^{-1}) is used to define a line with 1/f slope in Fig. 1. This plot may be useful as a general indication of radiation from a several-hundred kilovolt line. Values obtained from Fig. 1 should be decreased by 20 dB for fair weather, increased by 4 dB for heavy rain, and increased by 1 dB for every 1000 ft. of elevation above sea level.

The remaining problem in interference calculations is the variation of flux density with distance from the line. Parkala and Chartier used an equation by Norton described in their paper, and the resulting lateral attenuation curves for frequencies above 25 MHz are given in their Fig. 14. The field strength decreases at a rate between $(\text{distance})^{-1}$ and $(\text{distance})^{-2}$, and therefore falls off more rapidly than for free space propagation. Chartier stated that data obtained since Parkala and Chartier (1972) was written generally supports the theory used.

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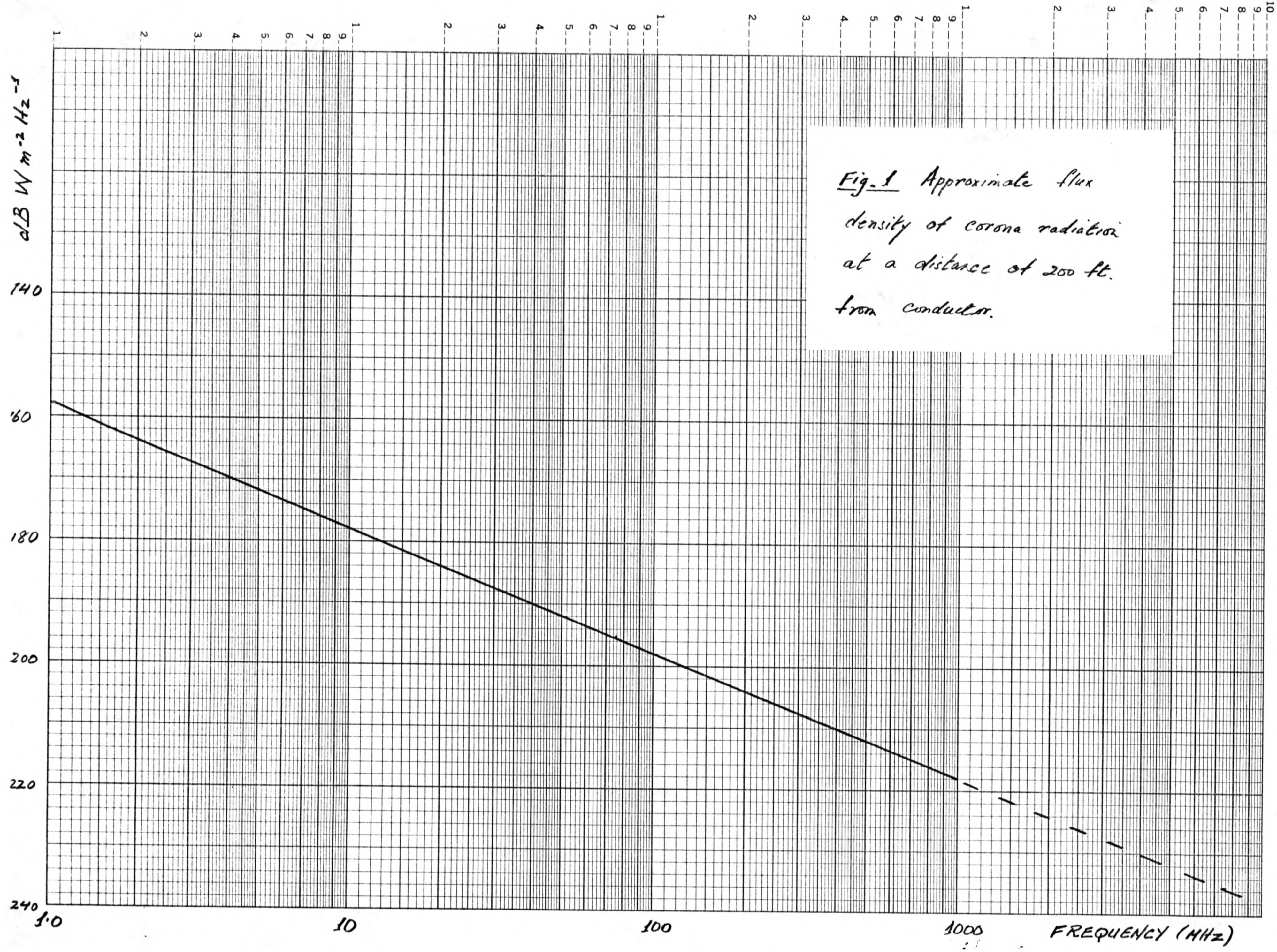

Fig. 1 Approximate flux density of corona radiation at a distance of 200 ft. from conductor.

IEEE TRANS. POWER APPARATUS AND SYSTEMS, VOL PAS-90, MAY/JUNE 1971.

Appendix I

RADIO NOISE MEASUREMENTS ON OVERHEAD POWER LINES FROM 2.4 TO 800 KV

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ABSTRACT

This paper presents radio noise measurements made near overhead power lines from 2.4 to 345 kV in the frequency range of 60 Hz to 1 GHz and on radio noise measurements made on 7.2, 345, 525, 735, and 765-kV ac lines and on an 800-kV dc test line up to 10 GHz. The measurements and their analysis show the important radio noise factors involved in the development and use of prediction techniques for the evaluation of communication site performance in the vicinity of overhead power lines.

INTRODUCTION

The measurements were made under contract with RADC, Air Force Systems Command, Griffiss Air Force Base, New York [1, 2]. A brief summary of reference 1 has been published [3].

With respect to radio noise, power lines are considered in two classes: (1) lines below 70 kV and (2) lines above 110 kV. These classes are based on the fact that all lines below 70 kV are generally free of conductor corona-type radio noise, and only gap-type discharges may be present. Gap-type discharges are described later. On higher voltage lines, especially EHV (extra-high voltage) lines, radio noise is principally due to conductor corona.

The purpose of the measurements and analysis described was: (1) to determine the radio noise levels and factors for overhead power lines and (2) to develop a technique for estimating the radio noise ground wave propagation from existing or proposed overhead power lines to significant lateral distances. The frequency range covered is .015 MHz to 10 GHz.

The radio noise field strengths in the vicinity of lines were measured under three conditions. These were (1) under normal conditions, (2) with natural gap on the line, and (3) with an artificial gap connected to one phase conductor. The artificial gap was used to increase the radio noise level from a line so that the field strength could be measured at relatively large lateral distances and at the higher frequencies with the instrumentation available. Measurements were made manually, with an X-Y recorder, and with a spectrum analyzer. Very good agreement was found between the semiautomatic and manual methods of measurement.

The measured field strength decreases laterally from the line approximately inversely as the first, second, or third power of the distance from the line depending on both the frequency and the distance from the line. The field strength was not necessarily the same on both sides of the line when the antenna was not too far longitudinally from a local source, such as a natural or an artificial gap. As the antenna was moved along the line the field strength on the two sides of the line became more symmetrical, as would be expected. Radio noise could be detected over the frequency range of 0.015 MHz to 10 GHz. Calculations of the lateral attenuation were made for the 0.015 MHz to 10 GHz range.

Paper 70 TP 632-PWR recommended and approved by the Transmission and Distribution Committee of the IEEE Power Group for presentation at the IEEE Summer Power Meeting and EHV Conference, Los Angeles, Calif., July 12-17, 1970. Manuscript submitted February 16, 1970; made available for printing May 8, 1970.

GENERATION OF RADIO NOISE BY TRANSMISSION LINES

Radio noise on transmission lines is caused by (1) partial electrical discharges, such as corona and (2) by electrical discharges across small gaps. These gap-type sources can occur in insulators, at tie wires, between hardware parts, by excessive electric stress across wood, at corroded joints, between metal parts, at small gaps between neutral wires or ground wires and hardware, and in electrical apparatus that is defective, damaged, or improperly designed or installed.

With the advent of EHV lines it was soon found that conductor corona formed at conductor gradients well below the theoretical critical gradient because of conductor surface burrs, conductor contamination, rain, snow, etc., and that EHV line design would require the consideration of radio noise generation by conductor corona.

Electrical Characteristics of Gap-Type Discharges

The gap-type radio noise source is a complete electrical discharge rather than a partial discharge such as corona. This type of discharge generates radio noise and permits very low 60-Hz currents to flow, since one or both of the electrodes forming the gap have a high 60-Hz impedance to line conductors or to ground. These gap-type discharges occur singly or are distributed along a line and are usually located on a line pole or tower. They are the principal cause of radio noise on the lower voltage lines; that is, lines below 70 kV. The artificial gap-type radio noise generator, Fig. 1, used for some of the measurements described, had an electrode spacing of 5/16 inches and was used on most of the lines above 110 kV. One electrode of this gap was connected to the line conductor, and the other electrode was left floating. This gap-type radio noise generator will produce broadband radio noise, curve (a) of Fig. 2, which can be measured up to and beyond 1 GHz. The frequency spectra of this gap and of a gap between two suspension insulators as measured in the laboratory are shown in Fig. 2. Gap-type sources can and do occur on EHV lines; however, they can be found and eliminated when necessary.

Electrical Characteristics of the Corona Discharge

The generation of radio noise by conductor corona is by means of the electrical discharge, usually called corona, occurring at or near the conductor surface. Corona is defined as "a luminous discharge due to ionization of the air surrounding a conductor around which exists a voltage gradient exceeding a certain critical value". Many aspects of corona discharges on lines are unknown, undefined, and a calculation of the radio noise magnitude with conductors in corona is not possible with the present state of knowledge. The basic physical process is that of electron multiplication or avalanche formation. The electric gradient in the vicinity of the line conductor is the highest gradient, and if this gradient or electric stress is sufficiently high, any electrons in the air around the conductor will ionize the gas molecules, and electrons produced by this ionization will produce an avalanche. If an additional electron is formed in this gradient by some process from the original electron avalanche, a new avalanche is formed by this secondary process and the corona discharge is developed.

In the case of the transmission line conductor, it is believed that the important secondary process is the ejection of electrons from gas molecules by high energy ultraviolet light (photoionization) generated

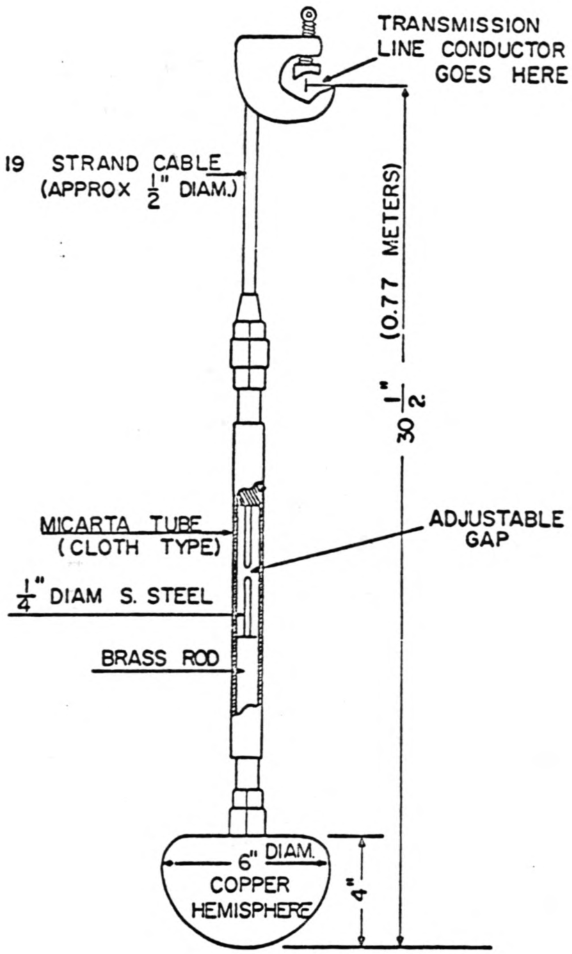

Fig. 1. Artificial Gap-Type Radio Noise Generator. 18-kV RMS Breakdown Voltage, (Floating).

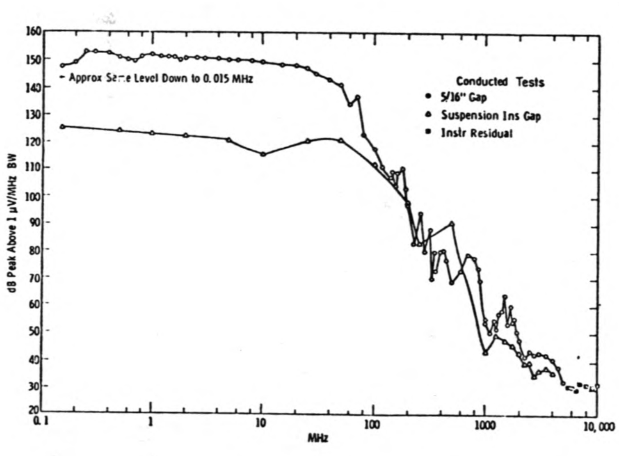

Fig. 2. Frequency Spectrum in the Laboratory for the 5/16-Inch Gap and for a Suspension Insulator Gap with 60-kV NEMA 107-1964 Circuit.

by the original avalanche. It has been found by several investigators that the radio noise generated when the conductor is at positive potential is significantly greater than it is with the conductor at negative potential. In the case of a positive overhead line conductor, the cathode is so far away that cathode emission is of no consequence, and the secondary process existing in this case is photoionization of the gas.

When streamer corona forms at a "point" on the conductor two pulse fields will exist. Near the streamer a localized or direct field is formed, and along the line the indirect field is developed due to the pulses traveling down the line. For design of EHV lines only the indirect field is considered significant, and the most useful measurements are made at some distance from the streamer locations on the line conductor.

INSTRUMENTATION

The instruments used were seven radio noise meters covering the frequency range from 60 Hz to 10 GHz. For frequencies above 30 MHz, tunable preamplifiers with a gain of 24 dB were used. Readings were always made without the preamplifiers to prevent overloading of the radio noise meters. The antennas used were 1- and 2-meter vertical antennas from 10 kHz to 25 MHz, and dipole, biconical, bi-triangle, horn, and parabolic reflector antennas above 30 MHz. A spectrum analyzer was also used with appropriate antennas for the frequency range under investigation. These instruments and accessories were carried in a 7-1/2 ton van.

The instruments were calibrated with signal generators and impulse generators. In this paper the data is given in dB peak above 1 μV/m/MHz bandwidth. The over-all general accuracy of measurements is estimated to be ±2 dB up to 25 MHz and ±3 dB from 25 to 1000 MHz.

METHODS OF MEASUREMENT

In the frequency range up to 25 MHz measurements of the field strength were made with the receivers on the ground and the antenna on the receiver or on a metal ground plane. Above 25 MHz up to 1000 MHz practically all measurements were made with receivers inside the van and the antenna on the van roof bringing the antenna 20.5 feet above ground level. For the 1 to 10 GHz range, the horn antennas were 15 feet above ground level. As many as three receivers were used at the same time at different distances from the line under test. All receivers were monitored by headphones, and readings were taken even if only the meter residual was present. This was done in order to make sure that at the specific test location radio noise from the line could not be measured or heard in the headphones with the instrument used. The headphones were also used to distinguish gap-type noise from corona noise and to distinguish these line noises from spurious noise sources such as vehicle ignition.

All directional antennas were rotated for maximum signal with the aid of a remote indicating meter available with instruments. Dipole antennas were set true vertical and horizontal with the horizontal dipole rotated for maximum, and the horn antennas were tilted for maximum.

The antennas were at distances of 50 and/or 200 feet laterally from nearest phase conductor. Other distances used were 300, 400, 500, 800, 1200, and 1600 feet. For one case distances between 3500 to 20,000 feet were also used. The locations farther away were in sight of the line and were chosen depending on accessibility, trees cultivation, other lines, density of auto and truck traffic, and on permission of the land owner.

When the X-Y recorder or the spectrum analyzer were connected to the radio noise meter the 41-inch vertical antenna was used from 0.015 to 30 MHz; a vertical dipole tuned to 60 MHz was used from 30 to 100 MHz, and the broadband antennas were used above 100 MHz.

MEASUREMENTS

Twenty-two ac overhead power lines, both single circuit and double circuit, and rated from 2.4 to 735 kV ac and an 800-kV dc test line were measured for radio noise. The artificial gap-type radio noise generator was used on 110, 161, 244, 345, 525-kV ac lines and on the 800-kV dc line to obtain lateral attenuation data for these lines which are of different phase spacings or conductor configuration. The conductor surface voltage gradient is a most important factor with respect to corona-type radio noise and its magnitude. For the lines tested the outside phase conductor gradient varied from 0.77 to 9.11 kV rms/cm for lines below 70kV and from 12.57 to 17 kV rms/cm for ac lines from 110 to 735 kV. Laboratory measurements of conducted and radiated radio noise were made with the artificial gap connected to a conductor and with the conductor in artificial rain. Twenty of the lines tested are given on Table I with their significant parameters with respect to radio noise.

THE FREQUENCY SPECTRA

Laboratory Measurements – Artificial Gap

It is very difficult, if not impossible, to determine the true generated spectra for an electrical discharge in a high-voltage circuit. The measured spectra are affected by the test circuit or by the power line characteristics and the lateral or longitudinal distance from the source. Fig. 2 shows the conducted spectra obtained from the 5/16-inch artificial gap and a suspension insulator gap with 60-kV laboratory NEMA-1964 test circuit. This circuit was made, physically, as small as possible for the test voltage used. The spectrum obtained with the 650-kV NEMA-1964 test circuit is shown in Fig. 3. Fig. 3 also shows the radiated spectrum obtained at 20 feet from the gap. It is obvious that the two test circuits, which are much different in size, one being 60 kV and the other 650 kV, are not comparable, especially above 7 MHz. The radiation method of measurement with the 650 kV circuit is much more sensitive than the conducted method above 100 MHz, and radiation could be measured up to 10 GHz. The radiated spectrum average noise level follows the 20-dB (1/f) reduction per decade more closely than does the conducted spectrum.

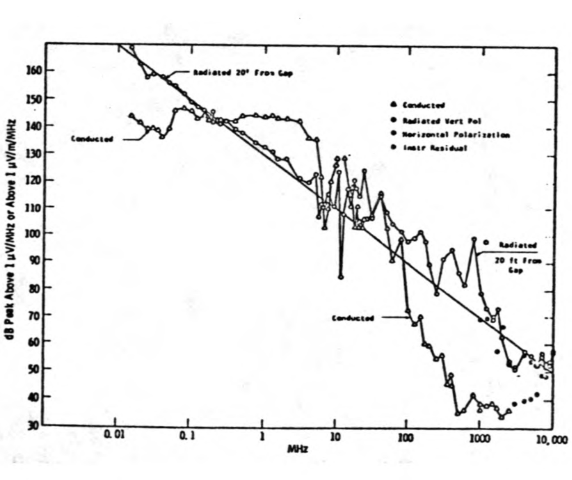

Fig. 3. Frequency Spectra in the Laboratory for 5/16-Inch Gap–650-kV 107-1964 NEMA Circuit.

Laboratory Measurements – Conductor in Rain

Radiated measurements were also made in the laboratory on a 1.65-inch diameter ACSR conductor in a bundle of two conductors, operating at 255 kV to ground, in heavy rain (0.03 inches per minute) to determine at what frequencies conductor corona-type radio noise could be measured. The maximum gradient on the bundled sub-conductors was 14.8 kV_{rms}/cm. It was possible, see Fig. 4, to measure up to 5 GHz with the instruments and pre-amplifiers available. At the higher frequencies the radiated spectrum shows the effects of the test circuit and reflections from the laboratory apparatus and walls. In making these measurements at 20 feet away from the 30-foot long conductor sample, it was necessary to place metal shields on the vertical dipole antenna tips to prevent corona formation on them due to the 60-cycle field.

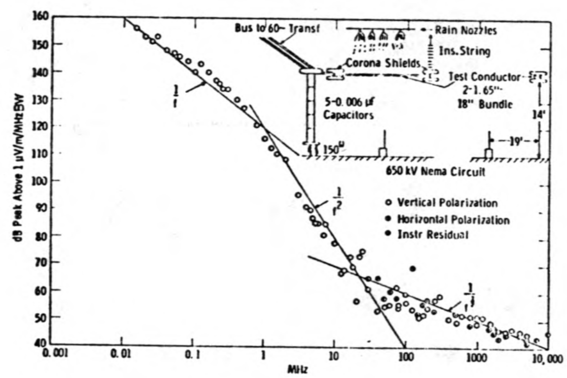

Fig. 4. Frequency Spectrum for Conductor Corona with Artificial Rain–650-kV NEMA 107-1964 Circuit.

Field Strength Measurements Near Line – Artificial Gap

Field strength measurements were made on several lines with the lines normal or with the 5/16-inch artificial gap connected to one of the phase conductors. Fig. 5 shows the frequency spectra from .015 to 1000 MHz, obtained at various distances with the 5/16-inch artificial gap on a 244-kV line. It will be noted that the form of the spectrum changes appreciably with distance from the line, especially at the low frequencies, and as would be expected from theory. See Appendix I. Attenuation for 8.23 miles of line is shown on Fig. 5 for several frequencies. The large variations over very small frequency ranges from about 2 to 8 MHz are believed to be caused by the steel tower acting as the principal radiator. At the higher frequencies the variations are believed to be due to the resultant of the direct radiation and the ground reflected radiation. The spectra obtained in the 1 to 10 GHz range from this gap on a 525-kV line is shown by Fig. 6 for vertical polarization. With horizontal polarization the magnitudes are about the same but not necessarily at the same frequencies.

The frequency spectrum from the artificial gap was measured with the gap connected to 110, 161, 244, 345, 525-kV ac lines and 800-kV dc test line. The maximums of these spectra are shown on Fig. 7. The form of the spectra is not much different and the magnitudes differed only by about 10 dB at the most. With the gap on the 800-kV dc test line negative conductor, the spectrum was about the same form as for ac lines. However, with the gap connected to the positive conductor the spectrum was of different form in that the level decreased much faster with frequency. With the gap on either conductor it was necessary to have fine corona from the sphere end of

TABLE I

Line kV and Type*	Conductor Diameter Inches	Phase Spacing Feet	Phase Conductor Height Feet	Conductor Gradient kV_{rms}/cm
2.40 HC	0.254	2.4–4.9	34.0	0.77
4.16 HC	0.316	2.4–4.9	34.0	1.13
8.00 HC	0.29–.316	3.6	33.0	2.10
12.50 HC	0.29	2.4–4.9	32.5	3.60
34.5–12.5 HC	0.316	3–6	34.0	8.85–3.11
34.50 HC	0.502	3.7	35.0	6.18
46.00 VCDC	0.447	5.0	35, 40, 45	8.52
46.00 TCSC	0.447	5.0	35, 39	–
69.00 HCWP	0.563	12.5	36.0	9.11
110.00 HCWP	0.528	15.0	39.0	15.60
138.00 HCWP	0.806	15.5	48.0	13.06
161.00 HCST	0.99	20.7	61.0	12.57
244.00 HCST	1.246	28.0	56.5	14.45
345.00 HCST	2–1.196	28.0	90.0	15.51
345.00 VCDC	1.6–1.75	–	108, 129.5, 153	17.00
345.00 HCWP	1.75	26.0	46.0	15.70
345.00 HCST	1.6	32.0	55.0	15.40
525.00 HCST	2–1.75	42.0	55, 116	15.60
735.00 HCST	4–1.38	50.0	90.0	16.00
**800.00 HCST	2.4	34.5	67.0	−22.57, +22.57
+400, −400 HCST	–	–	–	+19.40, −19.40

*In the above tabulation the abbreviations for the lines are:

HC = Horizontal configuration of line conductors
TCSC = Triangular configuration of single circuit
VCDC = Vertical configuration of double circuit
HCWP = Horizontal configuration of wood pole
HCST = Horizontal configuration of steel tower

**This is direct-current test line bipolar.
+400 and −400 are for direct-current line monopolar.

the gap in order to maintain the gap discharge. This fine corona was obtained by replacing the sphere with a ring made from wire with sharp points.

On some of the lines tested natural gap-type radio noise sources were found. Fig. 8 shows a spectrum measured on the 345-kV wood pole line at 200 feet laterally. In this case the gap discharge was

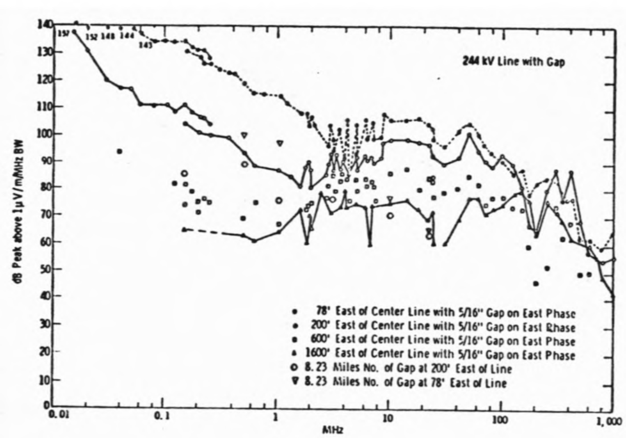

Fig. 5. Frequency Spectra for 5/16-Inch Gap at Several Distances from Outside Phase of 244-kV Horizontal Configuration Steel Tower Line.

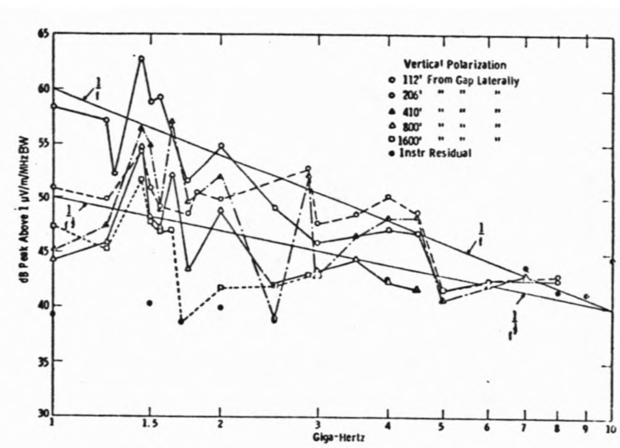

Fig. 6. Frequency Spectra for 5/16-Inch Gap at Several Distances from Outside Phase of 525-kV Horizontal Configuration Steel Tower Line.

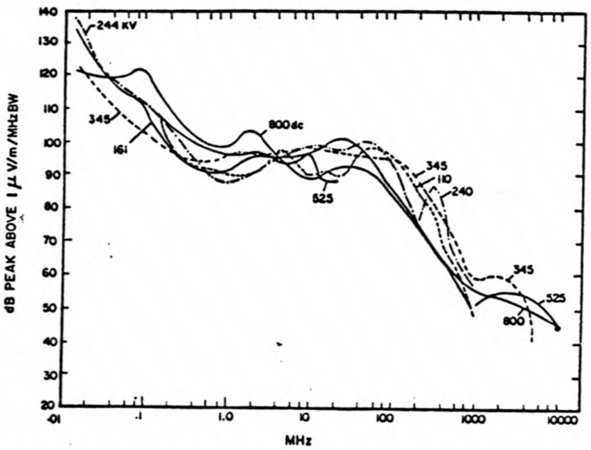

Fig. 7. Frequency Spectra Envelopes for 5/16-Inch Gap at 200 Feet from Outside Phase of 110, 244, 345, and 525-kV ac Lines and from the Negative Pole of the 800-kV dc Line.

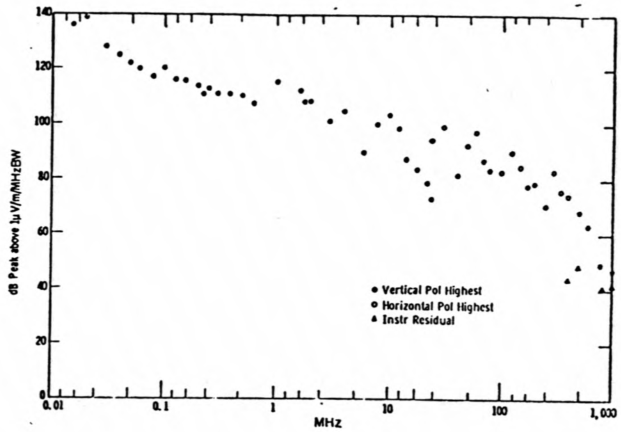

Fig. 9. Frequency Spectrum for a Natural Gap on a 12.5-34.5 kV Dual-Circuit Wood Pole Line. Measurements Made 50 Feet from Outside Phase.

between the vertical ground wire on the wood pole and cross-brace floating hardware. This natural gap source gave field strength magnitudes almost the same as the 5/16-inch artificial gap. Also there were similar large variations in the field strength over very small frequency ranges in the 2 to 8 MHz range. Fig. 9 shows a spectrum obtained on a 12.5 to 34.5 kV dual line. In this case the sources were on the 12.5-kV hardware and between the pole guy and neutral. It is evident that low-voltage lines can generate about as much gap-type radio noise as a 345-kV line.

Field Measurement – Conductor Corona

The frequency spectra obtained on lines with conductor corona sources, see Fig. 10, are considerably different from spectra obtained from gap sources, as can be seen by comparing Figs. 8 and 10. For conductor corona at a distance of 200 feet laterally from the outside conductor the corona source spectrum follows, quite closely, a 20-dB change per frequency decade in terms of dB above 1 μV/m/MHz bandwidth. The change in magnitude per decade is not the same at all distances from the line as can be seen from the curves of Fig. 5 and as expected from theory.

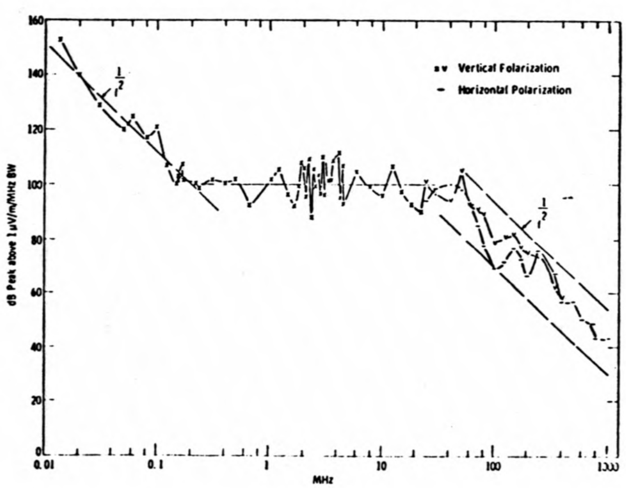

Fig. 8. Frequency Spectrum for a Natural Gap on the Wood Tower of a 345-kV Horizontal Configuration Line. Measurements Made 200 Feet from Outside Phase at Tower.

The frequency spectrum obtained with the quasi-peak detectors in the radio noise meters is considerably different and not as uniform because of large bandwidth changes in the instruments used over the frequency range of 0.015 MHz to 10 GHz. Fig. 10 is intended to show only the form of the spectra at 200 feet. Since the measurements are for fair weather and were taken only once, they should be used with care for comparison of these lines with each other or for comparison with other lines. The spectrum for the 735-kV line is shown in Fig. 11 to indicate more clearly the 20-dB change per frequency decade in the magnitude. Fig. 11 also shows the differences in vertical and horizontal polarization.

Measurements were made on some lines in the rain and with snow and sleet. The frequency spectra are similar in that they change in magnitude about 20 dB per frequency decade.

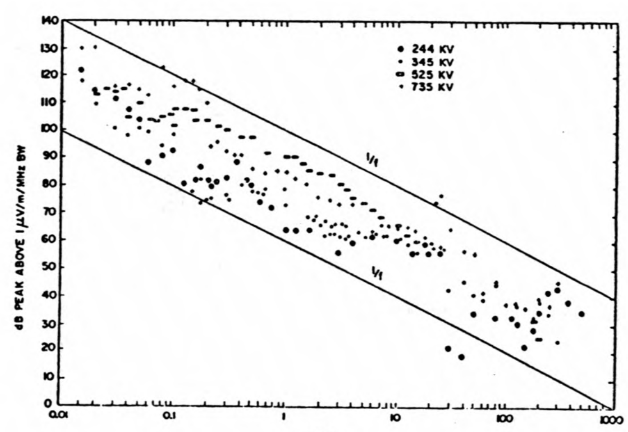

Fig. 10. Frequency Spectra for Conductor Corona (Fair Weather) at 200 Feet from Outside Phase of 244, 345, 525, and 735-kV ac Lines.

LATERAL ATTENUATION

In order to estimate the radio noise field strength near the ground surface at some distance from an overhead power line, it is necessary to have lateral attenuation formulas or curves which are referred to some distance near the line, e.g. 50 or 200 feet, where measurements have been made or can most easily be made.

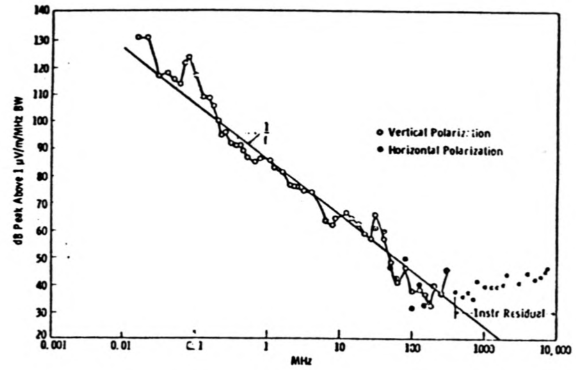

Fig. 11. Frequency Spectrum for Conductor Corona (Fair Weather) at 200 Feet Laterally from Outside Phase of 735-kV ac Line.

The problem of radiation of electromagnetic waves above earth having finite conductivity was originally solved by Sommerfield for vertical antennas [4]. Norton simplified these complex equations into forms that can be used in engineering work [5, 6]. Norton's equations were developed for dipole and loop transmitting and receiving antennas. By proper analysis and comparison with field data, a modified version of Norton's equation has been developed which assumes the transmission line is a linear radiating source. The development of this equation is given in Appendix I.

The lateral attenuation curves of Figs. 12, 13, and 14 referred to 200 feet were calculated using the equations of Appendix I for vertical polarization. The effects of the sky or the curvature of the earth are not considered, since for radio noise from power lines, the lateral distances required for practically all cases are expected to be within 10,000 feet.

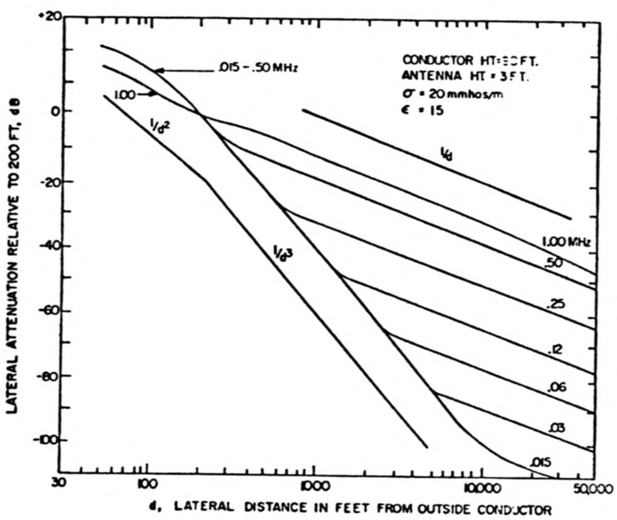

Fig. 12. Calculated Relative Lateral Attenuation, .015 to 1.00 MHz.

A conductor height of 90 feet was chosen as a typical height for EHV lines at the tower. The antenna heights are those that are used with present day radio noise meters. Since ground conductivity for any one location is not exactly known, a relatively high conductivity of 20 mmhos/m was chosen from a conservative standpoint. The dielectric constant of the earth is also not generally known; therefore a commonly used value of 15 was chosen [7].

The effects of ground reflections are clearly shown by the experimental curve in Fig. 15. This curve was obtained by strip chart recording of the quasi-peak field strength as the receiver antenna was

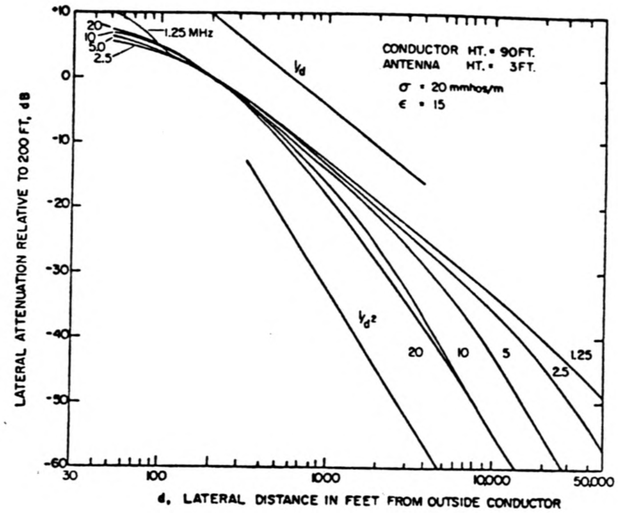

Fig. 13. Calculated Relative Lateral Attenuation, 1.25 to 20 MHz.

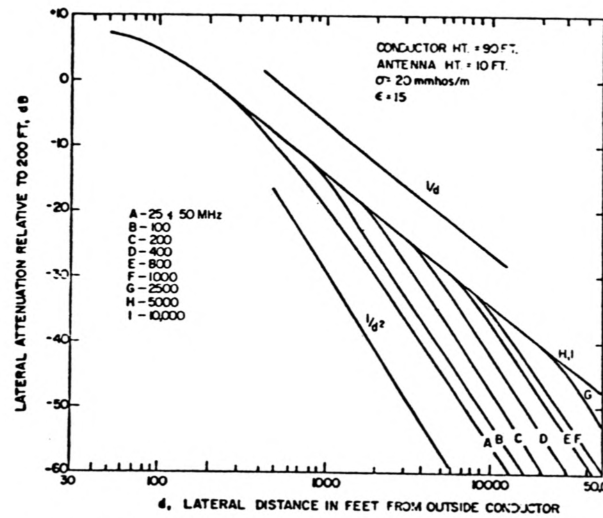

Fig. 14. Calculated Relative Lateral Attenuation, 25 to 10,000 MHz, 10-Foot Vertical Dipole Antenna.

moved away from the power line. The calculated curves of Figs. 13 and 14 do not show such variations because they follow the maximum and therefore the most significant values of the variations which are actually occurring. These maximum values are the important ones and are used to obtain the lateral attenuation required to reach the "quiet" distance in the estimation of radio noise from overhead lines.

Figs. 12, 13, and 14 show that the field strength decreases as $1/d^3$, $1/d^2$, or $1/d$ depending upon the frequency and the distance from the line. Calculated curves for some frequencies and some measured points for some of the lines tested are shown in Figs. 16, 17, and 18. The measured points follow the calculated curves of Fig. 16 quite well. However, for the frequencies of 10 and 20 MHz the measured values are scattered over a range of several dB as shown in Fig. 17, and it was necessary to adjust the ground conductivity in the calculations to better match the measured points.

If the ground conductivity were known and the uneven terrain could be factored into the equations for each of the test locations, the measured and calculated attenuation curves would probably be close to each other. Whenever the lateral attenuation is required for a specific case it is necessary to determine the attenuation and the effect of conductor and antenna height.

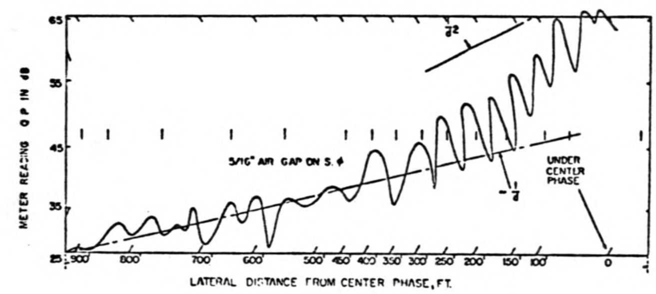

Fig. 15. Lateral Attenuation with 5/16-Inch Gap Made with Chart Recorder at 30 MHz. Gap on Outside Phase.

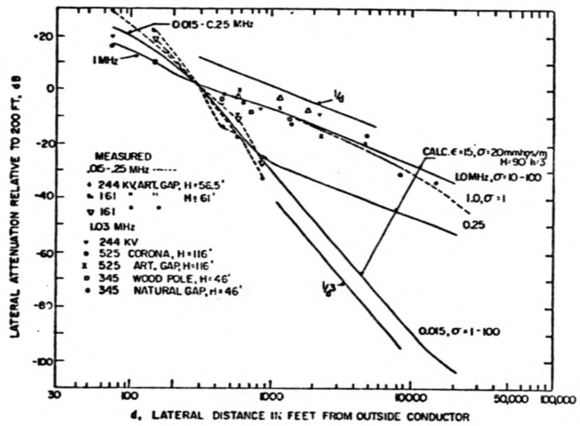

Fig. 16. Comparison of Calculated and Measured Peak Field Strength Readings Referred to Levels at a Lateral Distance of 200 Feet.

ESTIMATION OF TRANSMISSION LINE RADIO NOISE

In the estimation of radio noise due to conductor corona the magnitude is based on a comparison method [8]. The reference line is taken as a typical operating line for which long-term fair weather data is available. It is good practice, and it may be necessary to consider data obtained in heavy rain to obtain communications service protection under the worst conditions. With the reference line data available and applied to the spectrum curve of 20 dB per decade, the estimation is continued by making corrections for differences in conductor gradient, diameter, and height. [8] After these corrections are made, the calculated lateral attenuation curves, such as Figs. 12, 13, and 14, are used with the appropriate antenna height for the communication service being protected.

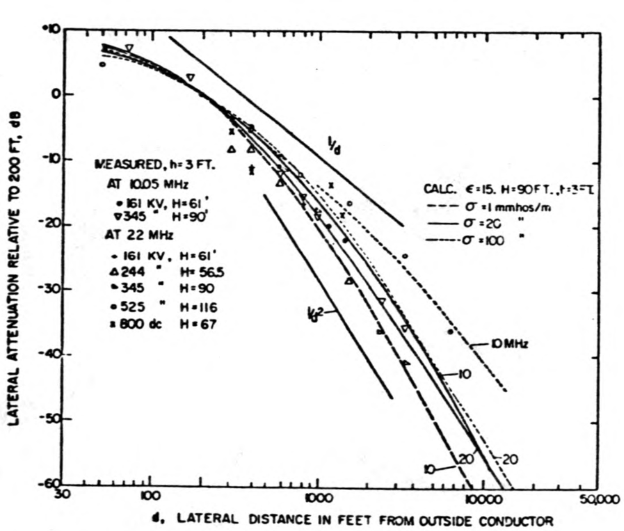

Fig. 17. Comparison of Calculated and Measured Peak Field Strength Readings Referred to Levels at a Lateral Distance of 200 Feet.

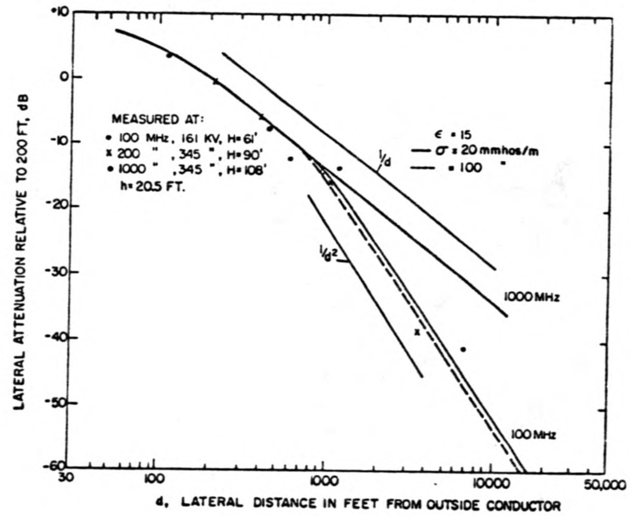

Fig. 18. Comparison of Calculated and Measured Peak Field Strength Readings Referred to Levels at a Lateral Distance of 200 Feet.

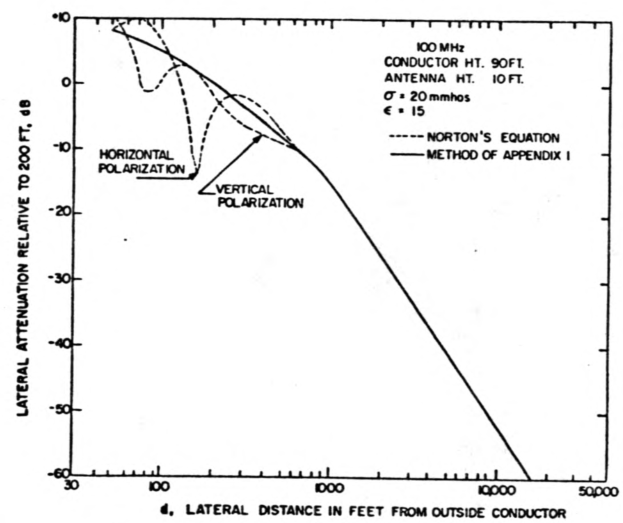

Fig. 19. Comparison of Lateral Attenuation at 100 MHz Using Norton's Equation and Modified Method of Appendix I.

In some cases it may be necessary to make field strength measurements near a chosen line in order to more accurately determine the field strength at the communications site. These measurements may be worthwhile especially at or near the frequencies where the ground conductivity significantly affects the attenuation between the line and the antenna.

CONCLUSIONS

1. This paper presents results of radio noise measurements on 12.5- to 735-kV ac lines and an 800-kV dc test line over the frequency range of .015 MHz to 10 GHz.

2. The analysis of the measurements shows the important radio noise factors involved in the development and use of these factors for the estimation of the radio noise level in the vicinity of overhead power lines.

3. Radio noise could be detected from the 12.5 to 735-kV ac lines and from the 800-kV dc test line.

4. For the lines below 70 kV only gap-type radio noise sources were significant. For the lines above 110 kV either conductor corona radio noise or gap-type radio noise was significant.

5. Radio noise on some lines could be detected in dry weather up to 1.5 GHz (source unknown – antenna pointing toward spacer) and up to 2.5 GHz with gap-type sources at 90 and 60 feet, respectively. At 60 feet from the nearest substation apparatus and other items, radio noise was detected up to 6 GHz. With heavy rain (0.3 inches/hour), the radio noise level increased by 17 dB over the average long-term fair weather value. However, for adequate protection of critical communication services, it is necessary to add as much as 24 dB to the average long-term fair weather value.

6. Horizontal polarization of dipole antennas gave higher readings than vertical polarization for about 60 per cent of the measurements. The difference between values for the two polarizations were from 0 to 10 dB.

7. The form of the frequency spectrum on power lines changes both laterally and longitudinally. The longitudinal changes are useful in locating local sources, especially at the higher frequencies, when using radio noise meters with directional antennas.

8. On lines 110 kV and higher with a gap-type source the radio noise level is not always the same close to the line on both sides of the tower. This effect is most noticeable in the vicinity of the source and is mainly because of the larger phase spacing of lines above 110 kV.

9. There is a definite tower effect on the form of the field strength spectrum from a gap source, especially in the 2 to 8-MHz range. With a loop antenna large changes will also occur in magnitude with loop orientation.

10. Because of ground reflections at the higher frequencies it is necessary to take readings at several frequencies near the frequency of interest or to move the antenna to obtain the maximum value.

11. The frequency spectrum of conductor corona radio noise follows approximately a 20-dB change per frequency decade in terms of dB above 1 μv/m peak per MHz bandwidth.

APPENDIX I

ATTENUATION OF ELECTROMAGNETIC WAVES

In order to estimate the radio noise at some distance from an overhead power line, it is necessary to have lateral attenuation formulas or curves which are referred to some distance near the line where measurements can be made. Norton, in a 1937 IRE paper, [5] published several equations for propagation of waves from dipole and loop antennas. These equations are intended for the calculation of the ground wave field strength over a finitely conducting plane earth. Included in these equations are terms for the space wave (which consists of a direct and ground-reflected wave), the surface wave, the induction field, and the electrostatic field. However, these equations are quite complex and do not simulate a power line which looks more like a linear radiator.

Below 10 MHz the following equation has been found adequate up to distances of ten miles.

$$\frac{E}{E_0} = \left[\frac{f(\rho)}{kr_1} - \frac{1}{(kr_1)^3} + j\frac{1}{(kr_1)^2}\right] \tag{1}$$

where E is the field strength at distance r_1

E_0 is the field strength at reference distance

r_1 is the radial distance from the antenna to the line conductor

k is $2\pi/\lambda$

λ is the wavelength

The term $f(\rho)$ is van der Pol's empirical relationship for the surface wave.

$$f(\rho) = \frac{2 + 0.3\,\rho}{2 + \rho + 0.6\,\rho^2} \tag{2}$$

where

$$\rho = \frac{16d}{\sigma\lambda^2} \tag{3}$$

where d is the lateral distance in feet

λ is the wavelength in meters

σ is the ground conductivity in mmho/meter

For frequencies above 10 MHz equation (1) is not sufficient. Norton's equation (1) of reference (6) was compared to measured data. As frequency is increased the interaction between the direct and ground reflected waves becomes more pronounced so that prominent minimum and maximum points appear in the curve as indicated by Fig. 19 which was calculated using Norton's equation. For prediction purposes, a trend line along the crests can be used.

Above 10 MHz, Norton's equation can be modified to more closely simulate a linear radiation by setting the cosine cubed terms equal to one since they are the result of the transmitting antenna being either a vertical electric doublet for vertical polarization or a vertical magnetic doublet for horizontal polarization. However, between the lateral distances of 50 and 200 feet from the outside phase, Norton's equation may be simplified to

$$50 < d < 200$$

$$\frac{E}{E_0} = \frac{1}{r_1} \tag{4}$$

$$f > 10\,\text{MHz}$$

The curves of Figs. 12 and 13 up to 10 MHz were developed using equation (1). The curves from 20 MHz to 10 GHz on Figs. 13 and 14 were developed using equation (4) for the distances betweer 50 and 200 feet and Norton's equation from 200 to 50,000 feet. Th lateral attenuation curves are plotted in dB taken in every case as 20 $\log_{10}\frac{E}{E_0}$.

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Discussion

J. Reichman (Hydro-Electric Power Commission of Ontario, Toronto 18, Ont., Canada): The authors have published a summary of field data on RI levels of different hv lines. In order to properly interpret these results, however, it would be necessary to know the instruments used and their respective band widths. Would the authors care to provide further information on the latter subject?

I would also like to point out that although some lines with a combination of different noise sources, such as conductor and hardware corona, insulator surface leakage corona and various spark sources, will produce fair-weather noise spectra as shown, the statement of being able to estimate the noise performance of a y line at any frequency by applying a correction factor of 20 db per decade appears to be an oversimplification of a complex problem. Let us, for example, consider foul-weather corona noise on EHV lines. Tests on one of our 230-kV lines operated at a relatively high gradient of 24 kV_{rms}/cm on 477 MCM conductors showed a reduction of 70 db in noise levels as the frequency was increased from 1 MHz to 100 MHz, using Stoddart meters and applying band-width corrections. Thus there is about 90/1 difference between our measurements and the authors' method. Our measurements are supported by the spectrum analysis of the corona pulse shape, i.e. for frequencies above the broadcast band the noise will vary as $1/f^2$ rather than 1/f as predicted by the authors. Similar results are obtained when using reported values of 1800 μV/m (1 MHz, 5 kHz bw assumed) and 30 μV/m (75 MHz and 220 kHz bw) for foul-weather corona/1/. This results in a discrepancy of 30/1 between actual field measurements and the authors' method. A somewhat smaller error in this case is explained by the difference in lateral attenuations since our measurements were carried out at a distance of 50 feet, whereas the latter tests were made at 200 feet. As shown by figures 12 and 14 of the paper, vhf frequencies attenuate less than these in the broadcast band. The authors' comments on foul-weather corona noise will be appreciated.

I agree with the authors that NEMA circuit measurements have little meaning for frequencies above 7 MHz.

Manuscript received July 23, 1970.

REFERENCE

[1] C. F. Clark and M. O. Loftness, IEEE 70 TP 104-PWR, "Some Observations of Foul Weather EHV Television Interference", presented at the Winter General Meeting 1970, New York.

F. W. Warburton (Route 2, Box 54, Westboro, Mass. 01581): The authors, from field measurements, have refined and extended means for determining lateral decrement (lateral attenuation perpendicular to the line) of radio noise sources both innate to transmission and by means of a Stone spark-gap hung on conductors. Their efforts particularly enrich knowledge of noise attributes by providing frequency characteristics above the broadcast band and by illuminating the need of nearly instant acquisition of noise measurements in large quantity. It gives the industry improved means to avoid and resolve interference with others. The authors' findings are greatly valued by the discusser.

A study of the report did raise questions. In the second paragraph of Introduction occurs the statement, "On higher voltage lines, especially EHV lines, radio noise is principally due to conductor corona." The discusser concurs but considers that Figs. 4 and 10 may then confuse the reader by stipulating high values of corona noise above 15 MHz. Historically, significant corona interference to others has essentially ended by 15 MHz. To interpret Fig. 4 and explain foul weather EHV noise levels above 15 MHz, investigators [1], [2], [3] have proposed that significant discharges between (1) water masses ejected incident to spray pluming, raindrops and snow particles, and (2) the nearby, but air-gap separated, conductor or conductor protruberances, are probably microsparks or in milder cases retrograde streamers. Here the term microspark is used only to differentiate between the spark having two metal electrodes and the similar phenomenon where at least one electrode is other than metal. Actually, some microsparks are more intense than some sparks as noisemakers, but the normal 70 MHz noise level of EHV lines is far below 1 MHz observations, Fig. 1 of [3], even when measured with far greater bandwidths. Fig. 4 shows a $1/f^2$ characteristic which according to [4] is the generated characteristic for corona. In Fig. 4 this $1/f^2$ characteristic is attributed to impingement and spray plumes and these are coronas. The measured points of $1/f^{0.5}$ slope are attributed to microsparks, not corona.

If the discussers are correct in their interpretation of Fig. 10 its publication and its implications above 15 MHz are unfortunate. At 70 MHz, Channel 4 region in television, the fair-weather noise is identified by caption as corona. The magnitudes are abnormally high and alarming. To the contrary, the discusser at 70 MHz has always found EHV coronas to be unmeasureable as any occurences present were buried in the ambient. Furthermore, EHV-TVI complaints since the late 1940s were always traced to sparks or microsparks not normal to line construction, and correctible. The designation "unfortunate" applied to Fig. 10 is made because EHV corona noise can seldom be eliminated and the Fig. 10 caption of "corona" above 15 MHz can be cited to the detriment of the industry. Consider the findings of others which dispute Fig. 10 above 15 MHz.

At 70 MHz the median value of Fig. 10 is 42 dB. This is 130 μV/m of peak measured noise on the basis of using a 1 MHz bandwidth (BW) meter. Correspondingly, the authors of [3] and [5] using their 0.22 MHz BW peak meter would measure but 0.22/1 × 130 = 29 μV/m. Actually and in comparison, using this same 0.22 MHz BW meter, less than 1 μV/m was measured 200 feet from their Bonneville Power Authority 500-kV line. See Fig. 1 of [3]. This value of <1 μV/m was undoubtedly the ambient. The author of [5] operated a television receiver under a 500-kV line with a 350 μV/m signal from Channel 5. Satisfactory operation resulted indicating less than 3.5 μV/m of line noise, but again this noise was probably in the ambient. The discusser operated a TV set under a 230-kV line with a Channel 4 signal strength near 100 μV/m and with no noise showing. The authors of [6] report TVI contributed by a 500-kV line (at an indicated 50 feet) was buried in an ambient of 1 or 2 μV/m. They also report operation of a TV receiver with but 50 μV/m and measurements made with a Stoddart NM 30. In conclusion, 42 dB of noise, 1 MHz BW at 200 feet from EHV lines would flood utilities with television complaints, a condition most untrue, in fact.

In Fig. 10 the erratic action of the 244-kV line above 15 MHz

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favors spark rather than corona action. The 525-kV line mostly dominated to 10 MHz, then its 1/f characteristic changed while the other lines were less affected. Do the authors have comments?

The authors stated that earphones... "were used to distinguish gap-type noise from corona ..." This statement is ambiguous because many coronas occur in gaps on EHV lines and moreover these same coronas will occur on protuberances. Here the discusser interprets gap-type to mean significant sparks or microsparks. The main point, however, is that identification by ear, particularly on EHV lines, can be precarious, and more precise methods should have been used considering the importance of Fig. 10. Please see Table I of [2]. Referring back to Fig. 10, did the authors believe that they identified specific cornonas near 70 MHz and if so what were they? Were any ear identifications near 70 MHz confirmed by locating their sources? Would the authors kindly comment on the identification of sources by analyzing sound recordings of noise for signatures and by the use of CRO's.

Under "Electrical Characteristics of Gap-Type Discharges" the last sentence states that these "can be found and eliminated when necessary." This may be mostly true for significant sources of sparks and microsparks in fair weather, but, although of low intensity, the microsparks of foul weather from precipitant particles to a large high-voltage conductor cannot be economically eliminated on EHV lines. They can be reduced.

In "Electrical Characteristics of Corona Discharge," the most outstanding corona mechanism is not discussed. Thus, in this paper, practically all if not all of the corona radio noise reported below 15 MHz and from "normal" EHV lines was undoubtedly caused by either streamers successively repeated or in plume form. For an EHV plume it is the streamer pulse which rises outward from the conductor protuberance that causes the radio noise. Lacking documentation by measurements, estimation [1] is that a strong six-inch plume streamer will have a current of perhaps >0.1 ampere, an initial rise time of some 10^{-8} sec., and the streamer tip near the protuberance will have a velocity outward of some 10^{8} cm/sec. The plume is the overriding EHV noise maker and fortunately lacking from it are the higher di/dt^{5} of the spark.

"Vertical antennas were used from 10 kHz to 25 MHz." Is not the use of rod antenna at 25 MHz suspect? Mr. H. Charbonneau of Hydro-Quebec and the discusser made quasi-peak measurements under insect plumes on a 735-kV line. The Stoddart NM 25T loop-to-rod measurements approached a 3 to 1 ratio at 10 MHz when the water table was near the ground surface. The standard grounding plate was used for rod support. The error increased with frequency but measurements were not acceptable above 10 MHz. Whether peak, quasi-peak, average or rms devices are used, a rod at 25 MHz on many earth surfaces would appear to be unacceptable. Long dipoles are also suspect.

The non-specialist reader should recognize the limitations of peak instrument measurements of corona and spark noise. He should also know that the quasi-peak meter above some 200 pps gives nearly the same peak indications as a peak meter of the same bandwidth [7]. Thus for most sparks where 200 pps are usual, the peak and quasi-peak meters are good detectors but poor quantitative indicators of interference to television receivers, most communication receivers above the broadcast band, and to the masers with integraters of radio telescopes. The average type meter gave much improved evaluation of television noise[8] and for many radio communication systems [7]. Unfortunately, and theoretically, only near-peak measurements of corona noise can be presented on a per unit bandwidth basis with acceptable accuracy.

The Stone spark gap as originally constructed was subject to variations in output. Was this characteristic monitored during test runs, and also was it improved for the authors' investigation?

Not duplicated in Fig. 8 and similar graphs are large noise-intensity variations frequently encountered by the discusser in the television regions. This has often been attributed to hardware or accessory dimensions matching certain wave lengths. Also the 244-kV characteristics of Fig. 5 and Fig. 7 are not alike. Would the authors kindly comment.

Some readers may be apprehensive about the import of the high-frequency measurements. Although spark energy is sometimes radiated above 100 MHz in measureable quantities, these radiations have apparently and to this date caused negligible trouble. One New England utility has supplied 60 Hz energy to five radio-astronomy telescopes for some 65 telescope-use years. Station frequencies were between 200 and 1420 MHz with sensitivities as low as 10^{-9} V/m. No complaints of interference have occurred. This is attributed to low spark radiation intensities above 200 MHz, to antennas normally pointed above the horizon, and to other earth "temperatures" overriding spark "temperatures." In 1961, in a test where the discusser was a participant, a radio astronomy telescope antenna directed at a Stone spark gap a quarter mile distant, gave no positive detection of noise at 1420 MHz. Fortunately all appreciable size sparks on lines can be eliminated. However, there is no assurance that other sensitive devices will not appear in the future and spark incidences, whether from design or construction causes and whether they occur in fair or foul weather, should be reduced.

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W. E. Pakala and **V. L. Chartier**: We appreciate receiving the two discussions of this paper. We will try to answer the questions with the hope that they will clarify and add to the completeness of the paper.

Mr. Warburton contends the $1/f^{0.5}$ slope of Fig. 4 is due to what he defines as microsparks and not corona. This may or may not be true. At this time we believe it is due to corona. If Mr. Warburton has evidence that the noise in this part of the frequency spectrum is due to "microsparks" we would be very interested in seeing these data.

Mr. Warburton is concerned about the high levels measured at 70 MHz as shown in Fig. 10. It is very important to realize that these measurements were taken with the peak detector (which was the important one for these investigations) using the well known slide-back method. However, it may be that this method and the result is not as well known as we assumed in writing the paper. This peak value as measured has a low repetition rate of the order of one pulse per second. Actually a better and more informative method for most types of impulse noise would be to measure the number of pulses exceeding different levels of peak value. This method we leave to the next generation of radio noise meters. Since the repetition rate is low for these maximum peak values, the interpretation of the data with respect to interference effects require care. Therefore, we do not believe that our peak values at 70 MHz can be compared with data obtained with the meter used in references (3) and (5) of Mr. Warburton's discussion. Also, we do not expect any TVI from the EHV lines shown on Fig. 10.

We do not know at this time whether the data in this paper can be used to determine the amount of TVI. The purpose of this investigation was to determine the peak noise spectrums of a large number of overhead power lines and not their effect on communication receivers. Mr. Warburton's attempts at using these data to determine the amount of TVI from power lines is commendable but premature. A single method for measuring TVI from power lines has not been established at this time. Whether this method will require the use of a peak, quasi-peak, or some other detector is not known at this time.

We state in the paper concerning Fig. 10 that "they (fair weather measurements) should be used with care for comparison of these lines with each other or for comparison with other lines." The measure-

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TABLE II

INSTRUMENTS AND IMPULSE BANDWIDTHS

Manufacturer	Model No.	Frequency Coverage	Impulse Bandwidth
Stoddart	NM10A	14 - 250 KHz	203 - 560 Hz
Stoddart	NM20C	150 KHz - 25 MHz	2.27 - 7.3 KHz
Stoddart	NM30A	20 - 400 MHz	200 KHz
Stoddart	NM52A	375 - 1000 MHz	530 KHz
Polarad	FIM-L	1.0 - 2.24 GHz	1 MHz
Polarad	FIM-S	2.14 - 4.34 GHz	1 MHz
Polarad	FIM-M	4.2 - 7.74 GHz	1 MHz
Polarad	FIM-X	7.36 - 10 GHz	1 MHz

ment of radio noise from power lines involves taking readings at several frequencies or scanning over the frequency range of interest in order to obtain the maximum and significant peak values. This is necessary because the radiation pattern from a line changes with frequency and because of reflections from towers, etc. and the ground plane. These effects produce maximum and minimum values in the frequency spectrum. The envelope of maximum values are considered in determining the spectrum.

It is necessary to monitor the radio noise meter with head phones so that ignition noise, stations, and other sources will not be measured and that gap-type sources will be measured as such. In fact, all the gap-type sources found on these lines could be detected at or near 70 MHz and many other frequencies. However, most of these sources were located and eliminated. In some cases we did not locate the sources because of lack of time, and it was also not necessary.

Mr. Warburton states that in the paper under "Electrical Characteristics of Corona Discharge" the most outstanding corona mechanism is not discussed. We fail to find from his discussion what this mechanism is that we omitted.

The use of vertical antennas at 25 MHz is questioned by Mr. Warburton. The loop antenna supplied with the Stoddart NM25T is about 10 dB less sensitive than the 41" rod antenna. Also, the vertical antenna is required for spectrum analyzer measurements. Measurements made under a line and near a corona source with loop and vertical antennas will not give the same comparison as measurements made 200 feet from the outside phase conductor. A local source produces a radial current from the conductor. With the loop under the line this radial current affects the desired measurement; that is, the current in conductor.

The gap-type generator we used was constructed with best grade of supporting insulation. We found that in rain the gap would cease to operate. However, in dry weather the magnitude of peak radio noise was very nearly the same each time the gap output was checked.

We do not agree with Mr. Warburton that Fig. 8 and similar graphs do not have large variations in the television regions. The reason, in our opinion, for the variations has been discussed previously. Figures 5 and 7 are not exactly alike since the curves on Fig. 7 are for the envelope (most important for prediction) which follows the maximum values. With this method the gap data for several lines can be easily compared since the large variations are eliminated.

We agree that radiations above 1000 MHz can be measured from power lines, and we also agree that these radiations have been of little, if any, consequence.

Mr. Reichman is making the same error as Mr. Warburton in trying to compare the peak measurements in this paper with other detectors. We assume the measurements made by Mr. Reichman on the 230-kV line were made with the quasi-peak detector, and we agree with his results. However, the difference between the peak and quasi-peak measurements on the lines in this paper increased with increasing frequency. For example, at 1 MHz this difference was about 6 dB, whereas at 70 MHz this difference was 13 to 17 dB. These differences are those obtained at the receiver bandwidths. Mr. Reichman claims his measurements are supported by the spectrum analysis of the corona pulse shape. However, the spectrum he is referring to is the corona generation on the conductor and this spectrum drastically changes its shape because of change with frequency of the radiation as the antenna is moved away from the conductors as is shown in Fig. 5 of the paper.

Mr. Reichman questions the 20 dB per decade frequency spectrum. As is shown in Fig. 10 every EHV line we measured generally had this frequency spectrum, and we can assure the discussor that all these lines did not have gap-type sources. Again, this 20 dB per decade frequency spectrum is related to the peak detector; the quasi-peak detector would have a completely different form for the frequency spectrum.

The receivers used for these measurements and their respective bandwidths are shown in Table II.

Foul weather corona noise over a large frequency spectrum is difficult to obtain with manual instruments since the weather will change faster than the measurements can be made. The data we have shows that during rain the radio noise increases over the entire frequency spectrum. Spectrum analyzers are preferred for this type of measurement. A paper showing such measurements has been prepared for the IEEE 1971 Winter Power Meeting.

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Mr. Pakala is U.S. National Committee Technical Adviser for the International Special Committee on Radio Interference and a Registered Professional Engineer in the Commonwealth of Pennsylvania.

V. L. Chartier (S'62-M'64) was born in Fort Morgan, Colo., on February 14, 1939. He received the B.S. degrees in electrical engineering and in business from the University of Colorado, Boulder, in 1963.

In 1963 he joined Westinghouse Electric Corporation on the Graduate Student Course. He then joined the Electric Utility Engineering Department as an Assistant Sponsor Engineer, where he worked on problems involving planning, design, and operation of electric utility systems. In 1964 he was appointed Field Research Engineer in Electric Utility Engineering where he was Engineer-in-Charge of the Apple Grove Project, with responsibility for planning, instrumentation, installation, maintenance, analysis, and results. In 1969 he became a Research and Development Engineer, Power Systems Planning Department, Westinghouse Electric Corporation. Other research interests have included studies on radio noise, audible noise, corona loss, and electrostatic induction.

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EMPIRICAL EXPRESSIONS FOR CALCULATING HIGH VOLTAGE TRANSMISSION CORONA PHENOMENA

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INTRODUCTION

The Bonneville Power Administration (BPA) engineers over the past 10 years have been developing empirical expressions for calculating corona phenomena associated with a-c and d-c high voltage transmission lines. The majority of these empirical expressions were developed from data obtained from BPA operating lines or test lines (The Dalles DC Test Line, Lyons 1200-kV Test Line) in conjunction with data that was in the technical literature, such as from the Apple Grove 750-kV Project and from Project UHV. Up until 1977, no single Division within BPA had the primary authority for developing these empirical expressions; therefore, such equations were being produced by System Engineering, Transmission Engineering, and the Laboratories. However, in 1977 the Chief Engineer assigned the responsibility for the development and maintenance of the empirical equations for calculating audible noise (AN), radio interference (RI), television interference (TVI), corona losses (CL), and ozone (Oz) to the Division of Laboratories.

As a result of this directive from the Chief Engineer, in 1977 Bob Larson and Vern Chartier produced a report that not only described the recommended equations for calculating corona phenomena for a-c lines, but also described a computer program written for the CDC 6600 that could make calculations for any a-c line. The initial computer program was limited to a-c lines. In addition, the line(s) could have no more than six phases and four overhead ground wires. That original computer program and the associated equations are described in BPA Division of Laboratories' Technical Report Number ERJ-77-167 [1].

Over the past 4 years the Laboratories has been updating that original computer program (called COMBINE) so that it could make all the corona phenomena calculations associated with both a-c and d-c lines. Subroutines for calculating electric and magnetic fields were also added. The original program was called COMBINE since it combined all the individual corona phenomena programs into one program and calculated the electric field at the surface of the conductor using a technique developed by Markt-Mengele [2, 3].

The purpose of this report is to describe the latest equations that are being used at BPA to make corona and field effect calculations. At this time, the program calculates the lateral profiles of AN, RI, TVI, electric field, and magnetic field. Lateral profile printouts of these sets of phenomena can be requested individually or collectively. If an individual printout is requested for audible noise and/or TVI, the noise contribution from each phase/pole plus the total is printed out. For RI, a frequency spectrum as a function of lateral distance is printed out. The individual printout for ozone gives both a vertical and a horizontal profile of O_3 concentration. The individual printouts for electric and magnetic fields give the maximum field and its electrical angle, and the maximum horizontal and vertical component and their appropriate electrical angles. A separate printout for corona loss can be requested which gives the total corona losses, the corona loss for each phase/pole as a function of rain intensity, and the average rain and average fair weather losses.

The user has the option of inputting values for conductor surface voltage gradients (previously calculated from some other source), or he may have the program compute them using the equation developed by Markt-Mengele [2, 3].

The user has the option of inputting and outputting values in either Metric or English units.

The program can handle a combination of 50 phases or poles and overhead ground wires. At this time the program cannot make calculations for a hybrid line (a-c and d-c lines in close proximity).

All the analytical expressions in this program are state-of-the-art. The Division of Laboratories makes an attempt to conduct measurement programs on BPA's existing transmission system and at the Lyons 1200-kV test facility to verify or update the analytical expressions. The Laboratories also tries to keep abreast of the R&D work being conducted all over the world on corona and field effects. Some of the data coming from other countries is sometimes used in conjunction with data from North America to update existing equations.

EFFECT OF ALTITUDE

Altitude has a very definite effect on the production of corona, as has been shown at the Leadville High Voltage Project operated by the Public Service Company of Colorado and Westinghouse in the 1950's [4, 5]. Obviously, the development of empirical expressions for the effect of altitude is difficult, since the only data in the literature is either from lines at sea level or the test line at Leadville (3400 m above sea level). Westinghouse engineers used the Leadville data to develop a term for correcting RI calculations made at sea level to other altitudes [6]. Reference 6 also contains an Italian formula for the effect of altitude on RI. These two equations are compared in Figure 1. The agreement is quite good. The Westinghouse formula requires the user to know what the average relative air density is for each altitude, whereas the Italian formula only requires a knowledge of the altitude.

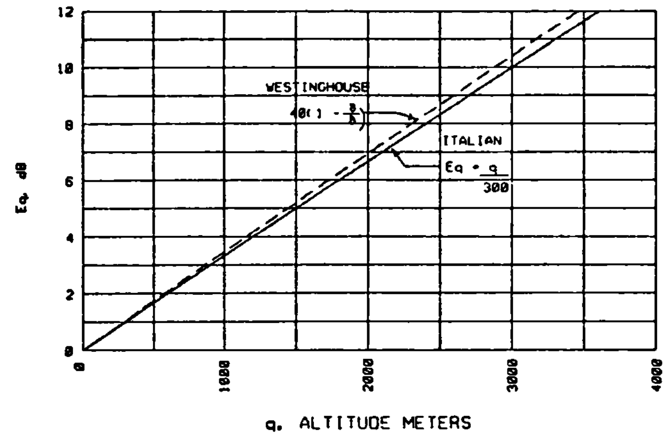


Figure 1: Effect of Altitude on Corona Phenomena

For calculating corona phenomena, the Italian correction term for altitude has been applied in the computer program for not only RI, but also for TVI, AN, and CL. It obviously has not been verified for either TVI or AN, and only partially verified for CL. However, it is better to have a correction term for all these corona phenomena rather than no term. After all, if RI and CL, which are the result of increased corona activity, increase with altitude so too must AN and TVI.

The use of this term for correcting CL needs further verification. A careful study of the Leadville [4] and Tidd [7] papers gives some indication that it might be valid for rain. However, the Leadville weather and the Tidd weather are very dissimilar. Foul weather at Leadville consists primarily of dry snow in the winter and very little rain, whereas foul weather at Tidd consists of mostly rain and wet snow; even the dry snow at Tidd is much wetter than Leadville snow. Heavy snow seems to produce higher corona losses than heavy rain or wet snow. This data indicates that dry snow produces a different type of corona (possibly ultra-corona) which may produce different levels of AN, RI, and TVI than either rain or wet snow.

Therefore, at this time, calculations using this altitude correction for determining corona loss should be made with a great deal of caution, especially for snowy weather.

AUDIBLE NOISE

The method of calculating A-weighted AN for a-c and d-c lines is based upon empirical expressions developed by V. L. Chartier and R. D. Stearns. Those equations and how they were developed are thoroughly described in an IEEE paper [8].

The equation for calculating the AN during rainy weather for each phase of an a-c line is:

$$SLA = -170.46 + 120 \log E + 55 \log deq - 11.4 \log D$$

where:

E = average maximum surface gradient kVrms/cm
deq = equivalent diameter of the bundle from an AN standpoint
$deq = d$ for $n < 3$
$= (0.58d)n^{0.48}$ for $n \geq 3$
d = subconductor diameter, mm
n = number of subconductors in the bundle
D = radial distance between conductor and microphone, m

The formula for calculating the L_{50} A-weighted AN per positive pole for fair weather (the negative pole produces negligible AN) is:

$$SLA = -133.4 + 86 \log E + 40 \log deq - 11.4 \log D$$

$$deq = d \text{ for } n = 1,2$$
$$= (0.66d)\, n^{0.64} \quad n > 2$$

The equations calculate the L_{50} rainy weather AN for a-c lines and the L_{50} fair weather AN for d-c lines. The L_{50} fair weather AN for a-c lines is calculated by subtracting 25 dB from the L_{50} rainy weather AN. The L_5 AN for rain for a-c lines is calculated by adding 3.5 dB to the L_{50} rainy weather AN.

For d-c lines, the L_5 fair weather AN is calculated by adding 3.5 dB to the L_{50} fair weather AN, whereas the L_{50} AN during rainy weather is calculated by subtracting 6 dB from the L_{50} fair weather AN. Only the positive pole produces measurable AN for d-c lines; therefore, -999.9 is printed out for the negative pole.

For the effect of altitude, the previously discussed term

$$AN = \frac{ALTIT}{300}$$

is used. However, its use below 300 m is not recommended since the data used to develop the empirical formulas was taken at altitudes primarily between 0 and 300 m. There has been some question about how to use this term around 300 m. It is strongly recommended by the Laboratories that until further data is collected the equations be used just as they are written, but that 1 dB be added for each 300 m above sea level.

RADIO NOISE

The methods of calculating RI for both a-c and d-c lines over the frequency range of 100 KHz to 20 MHz has evolved over the last 10 years. There is no single reference which describes the equations that are used by BPA. Reference 9 describes the general a-c equation that is used in the AM broadcast band and at distances within 60 m of the outside phase of

Table I: Prediction Formulas - DC Lines

	Ref.	Formula
BPA Reiner Gehrig	[10]	$E = 51 + 1.5(g - 20.9) + 10 \log \frac{n}{2} + 40 \log \frac{d}{4.577} - 33 \log \frac{f}{0.834} - 40 \log \frac{D}{13.6}$
BPA Capon	[11]	$E = 214 \log \frac{g}{14} - 278 \left[\log(\frac{g}{14})\right]^2 + 40 \log \frac{d}{2} - 27 \log \frac{f}{0.834} - 40 \log \frac{D}{30.5}$
BPA Gehrig	[12]	$E = 1.6\, g + 40 \log \frac{d}{2} - 40 \log \frac{D}{30.5}$
BPA Perry	[13]	$E = E_o + 80 \log \frac{g}{g_o} + 10 \log \frac{n}{n_o} + 40 \log \frac{d}{d_o} + 40 \log \frac{D_o}{D}$
Germany	[14]	$E = E_o + K^*(g-g_o) + 40 \log \frac{d}{d_o} + 20 \log \frac{1+f_o^2}{1+f^2} + 29.4 \log \frac{D_o}{D}$
IREQ	[15] [16]	$\Gamma = \Gamma_o + 1.71(g-g_o) + 40 \log \frac{d}{d_o} + 30.8 \frac{n}{n_o}$
Sweden	[17]	$E = E_o + 10 \log n + 20 \log r + 1.5(g-g_o) - 40 \log \frac{D}{D_o}$

the line. BPA engineers have developed several equations for calculating d-c RI as can be seen in Table I. The only difference between all these BPA d-c equations is the effect of conductor surface gradient on RI.

AC EQUATION

The RI/phase at a horizontal distance of 15 m from the phase is given by:

$$RI = 48.0 + 120 \log \frac{E}{17.56} + 40 \log \frac{d}{35.1} + 10\,(1-(\log\,(10f))^2) + \frac{q}{300} - C_1 + C_2$$

where:

- E = average maximum conductor surface gradient, kVrms/cm
- d = conductor diameter, mm
- f = frequency, MHz
- q = altitude, m

All the constants in this equation came from the Apple Grove A-line, where excellent long-term RI data was collected over several years [18]. The constants C_1 and C_2 adjust the RI calculated at 15 m to other lateral distances from the line. The equations for these terms are based upon the work of Pakala and Chartier [19]. C_1 is a constant for the reference line at the particular distance conductor height, antenna height, and frequency for which the RI is being calculated. Therefore, C_2 is based upon the input data. The difference between C_1 and C_2 is added to the RI/phase calculations at 15 m.

The values of C_1 and C_2 are derived from the following equations:

$$C = 10 \log\,(DW^2 + ESU^2 + EIND^2)$$

where:

DW is the direct wave component
ESU is the surface wave component
EIND is the induction field component

$$DW = \frac{\lambda\ Hc}{2\,\pi\,D} = \frac{47.7\ Hc}{fD}$$

when: $D < \frac{(12)\ Hc\ Ha}{\lambda}$

where:

- Hc is height of conductors, m
- D is radial distance between conductors and antenna, m
- f is frequency, MHz
- λ is wavelength, m
- Ha is height of antenna, m

when $D > \frac{12\ Hc\ Ha}{\lambda}$

$$DW = \frac{(47.7\ Hc)}{(f\ D)} \cdot \frac{(12\ Hc\ Ha)}{(D)}$$

$$= \frac{1.908\ (Hc)2\ Ha}{\lambda\,D^2}$$

$$ESU = \frac{f(\rho)\ Hc}{KD}$$

where:

$f(\rho)$ is Van de Pol's empirical relationship for the surface wave

$$K = \frac{2\pi}{\lambda}$$

$$f(\rho) = \frac{2 + 0.3\rho}{2 + \rho + 0.6\rho^2}$$

$$\rho = \frac{52.5D}{\delta\lambda^2}$$

δ = ground conductivity, m mho/m

$$EIND = \frac{Hc}{(KD)^2}$$

The reference parameters for calculating C_1

$$DW_1 = \frac{(47.75)\ (13.7)}{f(21.0)} = \frac{31.2}{f}$$

$$EIND_1 = \frac{13.7}{\left(\frac{300\ D^2}{2\pi f}\right)} = \frac{0.006009}{D^2}$$

$$\rho_1 = \frac{(52.5)\ (21.0)}{4\ (\lambda)^2} = \frac{276.16}{2\lambda^2}$$

$$f(\rho)_1 = \frac{2 + 0.3\rho_1}{2 + \rho_1 + 0.6\rho_1^2}$$

$$ESU_1 = f(\rho)_1\ \frac{31.1}{f}$$

DC EQUATION

The RI/positive pole at a horizontal distance of 15 m from the positive pole is given by:

$$RI = 60.5 + 86 \log \frac{E}{27.5} + 40 \log \frac{d}{46.2} + 10(1-(\log(10f)^2\ ) + \frac{q}{300} - C_1 + C_2$$

This equation calculates the average fair weather. All the constants in this equation come from the most recent RI tests at The Dalles d-c test site [20].

Data from IREQ [16] suggests that for d-c lines RI during average rain conditions is 3 dB less than average fair weather levels; whereas heavy rain RI is 6 dB less.

TELEVISION INTERFERENCE

The method for calculating TVI for a-c lines during rainy weather is based upon an equation developed by V. L. Chartier. The empirical terms used for calculating the propagation of TVI were developed from data in References 20 and 21.

The per phase TVI level in dB μV/m is given by:

$$TVI = 10.0 + 120 \log E/16.3 + 30.0 \log (D/30.4) + 20 \log (75.0/f) + C$$

where:

E = Conductor surface voltage gradient, kVrms/cm
D = Diameter of a subconductor in the bundle, mm
f = Frequency at which TVI is to be calculated

The constants in this equation come from a 345-kV line in New York where excellent TVI during steady rain was obtained [22]. Measurements of TVI from BPA lines have agreed quite well with calculated levels using this equation.

C is the correction factor to calculate the TVI at the radial distance from each phase. It can be determined from the Pakala-Chartier paper. C can also be determined by considering the four distinct cases shown in Table II.

No significant TVI has ever been measured from d-c lines during fair or foul weather. As a result, no attempt has been made to develop equations for calculating TVI from d-c lines.

CORONA LOSS

There are a number of methods that exist for calculating corona losses for both a-c and d-c lines. Most of these methods are not very easy to understand or use; therefore, in the Laboratories we decided to develop empirical equations similar to the equations for other corona phenomena [23].

AC LINES

The CL/phase in dB above 1 w/m is calculated using the following equation:

$$CL = 14.2 + 65 \log \frac{E}{18.8} + 40 \log \frac{d}{35.1} + K_1 \log \frac{n}{4} + K_2 + \frac{q}{300}$$

where:

n = number of subconductors

K_1 = 13 for $n < 4$
= 19 for $n > 4$

K_2 is a term that adjusts corona loss for rain intensity.

$$K_2 = 10 \log \frac{I}{1.676} \quad \text{for } I < 3.6$$

$$= 3.3 + 3.5 \log \frac{I}{3.6} \quad \text{for } I > 3.6$$

To calculate the losses in w/m or kW/km, the antilog of CL must be taken or:

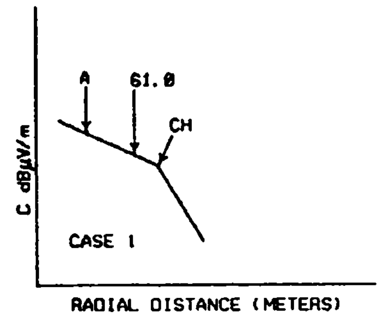
Table II

CASE 1: Do $<$ CH
A $<$ CH

Both the reference point and the measuring point lie on the 20 dB/decade slope of the curve.

The value of C is therefore determined by:

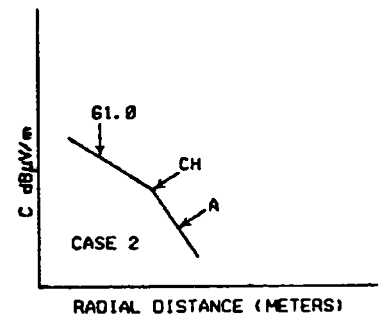
$$C = 20 \log_{10}(Do/A)$$



CASE 2: Do $<$ CH
A $>$ CH

If Do $<$ CH and A $>$ CH, we must move from the reference point down to the measuring point. Therefore:

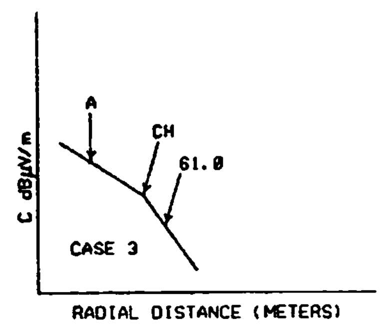
$$C = 20.0 \log_{10}(Do/CH) + 40.0 \log_{10}(CH/A)$$



CASE 3: Do $>$ CH
A $<$ CH

In this case we must move up from the reference point to the measuring point.

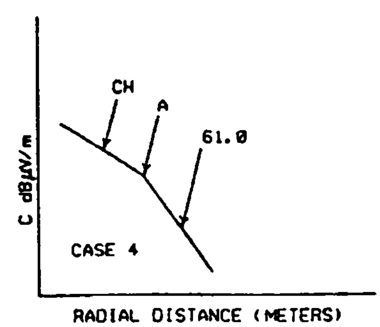
$$C = 20.0 \log_{10}(CH/A) + 40.0 \log_{10}(Do/CH)$$



CASE 4: 61 $>$ CH
A $>$ CH

In this case both points lie on the 40 dB/decade portion of the curve. Therefore:

$$C = 40.0 \log_{10}(Do/A)$$



$$CL\ (W/m) = \text{antilog}\ \frac{CL(dB\ w/m)}{10}$$

The total losses for a line, of course, are:

$$CL\ (\text{Total}) = \quad CL(i)\ \ w/m$$

To calculate the average levels during rainy weather, the computer program assumes an average rain intensity of 1.676 mm/hr (this, of course, will vary from region to region). To calculate the average fair weather losses, the program subtracts 17 dB from the calculated average rainy weather losses. This difference of 17 dB was obtained from the Apple Grove test data [18] where carefully controlled fair weather measurements were made.

DC LINES

IREQ has conducted the most extensive corona loss measurements in all kinds of fair, rainy, and snowy weather. Consequently, until a better analysis of all the available corona loss data can be conducted, the Division of Laboratories has adopted the IREQ corona loss formula [16]. We have modified that formula so it calculates the average corona loss for each pole in rain, which assumes the corona losses are the same for the negative and positive poles of a d-c bipole line.

$$CL = 16.9 + 0.73\ (E - 25) + 20 \log \frac{d}{40.7} + 8 \log \frac{n}{6} + K_2 + q/300 - 3.0$$

To obtain average fair weather corona loss, 5 dB is subtracted from the average rainy weather calculation. At this time, we are assuming that the change in corona loss on d-c lines as a function of rain intensity is the same as for a-c lines; therefore, K_2 in the d-c formula is the same as for the a c formula.

OZONE CONCENTRATION

The method of calculating theoretical estimates of ozone concentrations is based on a method developed by V. L. Chartier and J. F. Roach [24].

For the case of a wind normal to the line, the lateral profile is estimated by (MKS units):

$$C(X,Z) = \sum_{i=1}^{3} \frac{\overline{Si}}{U \sigma_z \sqrt{2\pi}} \left\{ \exp\left[-\frac{(Z-H)^2}{2\sigma_z 2}\right] + \exp\left[-\frac{(Z+H)^2}{2\sigma_z 2}\right]\right\}$$

Where:

Si is the source strength of the i-th line
U is the wind speed
H is the average height of the line above ground
Z is the ozone sensor height
σz is the spreading coefficient in the Z direction

The spreading coefficient is approximated by (MKS units):

$$z = .0315\ [23/U + 4.75(100/H)^{.25}]\ (X-X_i)^{.86}$$

Where X_i is the X coordinate of the i-th line source.

The source strength S_i for a-c lines is given by:

$$S_i = 1.260 \times 10^{-7}\ (P_i)(G_i)^2$$

and for d-c lines, it is:

$$S_i = 1.260 \times 10^{-9}\ P_i$$

for the negative pole, and:

$$S_i = 0.380 \times 10^{-9}\ P_i$$

for the positive pole.

DISCUSSION

1. Effect of altitude on corona phenomena is based upon radio noise and corona loss data obtained at Leadville, Colorado, in the 1950's.

   It is obvious that AN data is especially needed at higher altitudes, and it would be desirable to obtain additional RI and TVI data at higher altitudes. A test station will be installed on the Garrison-Hot Springs double-circuit 500-kV lines at an altitude of about 1800 m, which will provide some of this additional data.

2. The empirical expressions for calculating corona losses are primarily developed from rain data on both a-c and d-c lines. There is some indication that corona losses may be higher during dry snow conditions than during rainy weather. Dry snow being a sharp pointed object may be going into a form of ultra-corona which is known to be very lossy. The Leadville and other data needs to be examined in detail to determine if an additional correction factor for dry snow should be developed and added to existing CL formulas.

3. Most of the better radio noise formulas give about the same calculations for RI at the reference distance of 15 m from the outer phase. However, the agreement falls apart when a comparison of calculated lateral profiles is made. An example of this disagreement can be seen in Figure 2 where a comparison is shown between the calculated RI levels using the BPA empirical formula, and the General Electric analytical formula for the 500-kV base case delta-configurated line shown in Figure 5.4.22 of the "Red Book." Also shown on this curve is a calculated lateral profile, assuming the 1 MHz field produced by corona would have the same lateral profile as the 60 Hz field. Many analytical approaches have used this assumption for making RI calculations.

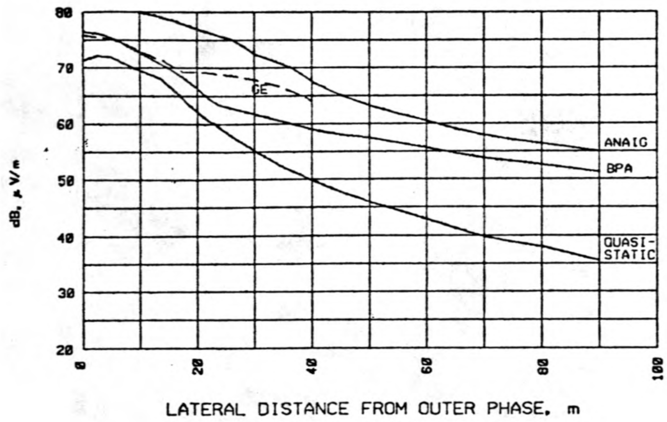


Figure 2: Comparison of Shapes of Radio Noise LateralAttenuation Profiles at 1 MHz

4. The difference between fair weather and foul weather AN is assumed to be 25 dB based upon data obtained on the Marion-Alvey and Marion-Lane 500-kV lines. Data from other lines in and outside of BPA territory indicates that this difference is a function of conductor surface gradient and possibly other line parameters. Therefore, additional data is needed to verify this assumption.

5. The formula for calculating TVI for a-c lines is quite similar to the RI formula, and like the RI formula, it assumes the TVI is primarily generated by conductor corona. Some data from the Apple Grove 750-kV project and the Lyons 1200-kV test facility indicate that TVI is independent of conductor configuration. This data suggests the primary source of the TVI might be the corona off the insulators or the tower hardware where the electric fields are stronger because of the proximity of the tower.

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V. L. Chartier was born in Fort Morgan, Colorado, on February 14, 1939. He received B.S. degrees in Electrical Engineering and Business from the University of Colorado in 1963. From 1963 to 1975 he was with the Advanced Systems Technology Department of the Westinghouse Electric Corporation, where he was engineer-in-charge of the Apple Grove 750-kV Project and was a principal consultant to the utility industry on the effects of corona and electric fields of high voltage transmission lines. In 1975 he joined the Bonneville Power Administration's Division of Laboratories, where he has been assoicated with the Lyons 1200-kV Project and other high-voltage projects. He is presently BPA's Chief High Voltage Phenomena Engineer.

Mr. Chartier is a member of the USNC of IEC; Technical Advisior to the USNC of IEC on matters pertaining to CISPR Subcommittee C on High-Voltage Lines and Traction Systems; past Chairman of the IEEE/PES Corona and Field Effects Subcommittee; past member of the Board of Directors of the IEEE Electromagnetic Compatibility Society; Secretary of IEEE/PES Transmission and Distribution Committee; member of ANSI C63 Committee (Radio Electrical Coordination); Chairman of Subcommittee 4 (High Voltage Apparatus and Power Lines) of ANSI C63· Expert Advisor to CIGRE Study Committee No. 36 (Interference); member of CIGRE; and member of the Acoustical Society of America.

Department of Energy
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P.O. Box 491
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In reply refer to: ER

May 25, 1984

Dr. A. Richard Thompson
National Radio Astronomy Observatory
Associated Universities, Inc.
P.O. Box O
Socorro, NM 87801

Dear Dick:

Enclosed are the computer results of calculating the EMI from the proposed EL Paso Electric Company 345-kV line at 75 MHz. The computer program calculates all the corona phenomena and also the 60 Hz electric and magnetic field. The 75 MHz calculation is called "TVI" on the computer output, and it is a QP calculation whose units are dBµV/m/120 kHz.

As I mentioned on the telephone, I converted your limit of -260 dBw/m^2/Hz to the same units as are calculated by our computer program in the following manner:

$$P = -260 \text{ dBw/m}^2 \text{ (telescope limit @ 75 MHz)}$$

$$= 10^{-26} \text{ w/m}^2\text{/Hz}$$

$$E_{rms}^2 = PZ = 377 \times 10^{-26} \text{ w/m}^2\text{/Hz}$$

$$E_{rms} = 1.94 \times 10^{-12} \text{ V/m/Hz}$$

$$= 1.94 \times 10^{-6} \ \mu\text{V/m/Hz}$$

For a 120 kHz bandwidth

$$E_{rms} = (1.94 \times 10^{-6})\ (120{,}000)^{1/2}$$

$$= 6.73 \times 10^{-4} \ \mu\text{V/m/120 KHz}$$

$$E_{rms} = -63.4 \text{ dB}\mu\text{V/m/120 kHz}$$

A QP detector gives about a 10 dB higher measurement than an rms detector for corona noise; therefore,

$$E_{QP} = -53.4 \text{ dB}\mu\text{V/m/120 kHz}$$

Now, this limit of -53.4 dBμV/m/120 kHz can be compared with the computer calculations, and we find that level occurs at about:

37,000 ft	for the	2 -1.108"	conductor
33,000 ft	for the	2 -1.196"	conductor
28,000 ft	for the	2 -1.345"	conductor

These calculations are an average level during steady rain. Our measurements have shown that a heavy rain increases the EMI for conductor corona about 4 dB over average rain. Our measurements have also shown that average fair weather EMI levels are about 20 dB lower than average steady rain levels.

The calculations are also for a voltage of 362 kV which is the maximum voltage for the line, whereas 345 kV is the nominal voltage. Most power companies operate their lines somewhere between the nominal and the maximum voltage, and I have asked Darwin Jensen if he could determine the normal voltage at which El Paso Electric operates their 345-kV transmission system.

So you can compare these calculations with ones in the Pakala/Chartier paper, let's convert the computer calculated levels at 200 ft to dBuV/m/MHz Peak.

Conductor	QP Level @ 200' from Computer	Peak Level @ 200'	
	dBμV/m/120 kHz	dBμV/m/120 kHz	dBμV/m/MHz
2 -1.108"	20.4	30.4	48.8
2 -1.196"	18.5	28.5	46.9
2 -1.345"	15.5	25.5	43.9

The conversion is made by adding 10 dB to convert QP to Peak for the same bandwidth. This 10 dB addition is based upon both short- and long-term measurements. The correction for bandwidth for Peak detector is:

$$dB = 20 \log (1000/120)$$

This conversion term for bandwidth is how the data in the Pakala/Chartier paper was normalized to a 1 MHz bandwidth. We have obtained additional data since that paper was written that provides additional support for this correction for bandwidth. By making these corrections for both the Peak detector and the bandwidth, you can see that the EMI levels for the El Paso Electric line expressed in dBμV/m/MHz (Peak) are in the same ball park as shown in Fig. 10 of the Pakala/Chartier paper. The numbers are actually a little bit higher than most of the data points at 75 MHz in Fig. 10. The 10 dB correction from QP to Peak may be a little large, but I've never seen this difference to be less than 6 dB.

It was a pleasure meeting you and your colleagues last week, and I really appreciated the opportunity to tour the VLA. I now have a greater appreciation for how valuable this facility is to future of radio astronomy, not only here in the U.S.A. but for the entire world.

If you have any questions on the enclosed, please feel free to call me at any time.

Sincerely,

V. L. Chartier

V. L. Chartier
Chief High Voltage Phenomena Engineer

2 Enclosures:
Graph
Computer printout

cc:
Jack Edwards - BLM (with enclosures)
Darwin Jensen - El Paso Electric Co. (with enclosures)

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