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May 31, 1985

"Initial Assessment of Reradiation from a Power Line and Its Detuning by Tower Isolation"

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CHAPTER ONE

INTRODUCTION

1.1 Problems Considered in the Contract Period

This document is the Final Report in DOC/CRC Contract No. OST83-00290, covering the period October, 1983 to May, 1985, and continues the sequence of Final Reports of Refs.(1), (2), (3) and (4). Those reports presented a computer model for a power line, and used it to investigate the resonant behaviour of power lines, which is reviewed in Chapter 2 of this report. Detuning measures for power lines were considered in Ref. (3). In this contract period, reradiation from the power lines near CHFA was re-evaluated using the "as-built" designs for the power lines, resulting in an Interim Report entitled "The Radiation Pattern of CHFA, Edmonton near the As-Built North and Southeast Power Lines, and Their Detuning by Isolating Towers"(5), which is presented in Chapter 4 of this report. A systematic procedure for choosing towers for isolation from the skywire in order to "detune" a power line was developed and applied to the power lines near CHFA, resulting in the Interim Report entitled "Analysis and Procedures for Detuning the Power Lines near CHFA, Edmonton, by Isolating Towers", Ref. (6), and the method is presented in this Report in Chapter 5. The recommended towers were isolated from the skywire by Trans-Alta, and achieved a satisfactory reduction in the measured tower base currents on the power line(7).

The problem of "initial assessment" of potential reradiation from a proposed power line was reconsidered in this contract period. The general case of a power line with non-uniformly spaced towers was considered, where, at the "proposal" stage, only the nominal tower height and tower separation or "span length" is known, and the actual span lengths are expected to be "normally" distributed about the nominal value. A statistical approach was developed which yields an estimate of how strong the reradiated field is likely to be, and gives a standard deviation for the estimate. The work was presented at the IEEE 34th Broadcast Symposium in a paper entitled "Initial Assessment of Reradiation from Power Lines"(8), and is presented here in Chapter 3. The "initial assessment" of potential reradiation from a proposed power line near station CBO, Ottawa, at 920 kHz was investigated, resulting in two Interim Reports, "Initial Assessment of Reradiation From the Lennox-Merivale Power Line Into the Pattern of Station CBO, Ottawa"(9), and "Initial Assessment of Reradiation From the Lennox-Merivale Power Line Into the Night Pattern of Station CBO, Ottawa"(10), and are included in this Report as Appendices 1 and 2.

Other work done in this contract period consists of the following. The measurements carried out by Ontario Hydro at the Thornhill site near Toronto were reconsidered, and a paper was published in the IEEE Transactions on Broadcasting entitled "Comparison of Computed RF Current Flow on a Power Line with Full Scale Measurements"(11). The program called "AM Power Line" or "AMPL" described in Ref. (12) was obtained from Mark Tilston. It is written in BASIC on a diskette for a Commodore 64 computer. Initial tests were promising, and so an initial, rough translation of the program into Fortran was done, and its performance was evaluated. Some results of this study are presented in Chapter 2. The program in this form runs on an LSI-11/23 computer and is quite fast, and has been used extensively to generate the results presented in Chapter 3 of this report.

The present Report begins by reviewing the resonant behaviour of power lines, computer modelling of power lines, and other considerations such as ground conductivity in Chapter 2. Then the "initial assessment" of potential reradiation from a proposed power line is discussed in Chapter 3. Once a power line is constructed, "as-built assessment" determines how much reradiation is actually present and which towers on the power line support strong RF current flow, and is presented in Chapter 4. In order to suppress the undesired RF current flow, a systematic procedure is developed which chooses towers of the power line for isolation from the skywire for the "suppression of resonances", so that the resulting power line is essentially non-resonant. The method of "suppression of resonances" is presented in Chapter 5. Thus the present Report attempts to trace the "life cycle" of a reradiation problem from the proposal for the construction of a power line, to its detuning by isolating towers. The concluding Chapter summarizes the work and points out where the present techniques fail, and where further investigations would be required.

1.2 Life Cycle of a Reradiation Problem

The "life cycle" of a reradiation problem begins with a broadcast antenna or directional array operating within its tolerances, and with a proposal to build a power line nearby, which is thought to be close enough to be a potential reradiator. Table 1.1 sets out the "life cycle", leading to the resolution of the reradiation problem by "detuning" the power line and so restoring the pattern back to "within tolerance". The actual radiation pattern of the operating antenna should be measured by the most accurate techniques available(13,14) to serve as a reference against which changes brought about by the construction of the proposed power line can be judged. Such a measurement is intended to show that, even in the presence of existing reradiators, such as other power lines, nearby buildings or towers, or other structures, the actual pattern radiated by the antenna is satisfactory, and will serve as a reference later for patterns measured after the construction of the power line. Ref. (14) recommends that the pattern be measured at different seasons, with snow cover, with wet and with dry ground in summer. Often, there are significant differences due to ground conductivity and other factors, and later, the pattern will need to be measured under similar ground conditions.

Given the construction proposal, which consists of the route chosen for the power line, a "nominal" value for the spacing of the power line towers, or "span length", and a nominal height for the towers, Chapter 3 of this report discusses the use of computer modelling for the "initial assessment" of the power line as a potential reradiator. "Initial assessment" seeks to determine whether the proposed power line is likely to be a damaging reradiator. The level of the reradiated field generally to be expected from such a power line must be determined, although, without knowing the exact position at which each power line tower will be installed, it is not possible to predict with any certainty the details of the radiation pattern to be expected. This is because, as discussed in Chapter 2, resonances of the individual spans of the power line are strongly dependent on the span length, and so are strongly influenced by departures of the span length from its "nominal value". It will be shown in Chapter 3 that the standard deviation of the span length for the power lines near the CHFA array is 46 m, on a mean span length of 363 m, so that substantial departures from the mean are to be expected. If a potentially damaging situation is found, then the broadcastor can intervene to try to have the power line's route altered, or to have resonant lengths for the spans avoided, or to have an understanding with the power utility that detuning measures will have to be taken after construction, in order to suppress reradiation and restore the broadcast antenna's radiation pattern.

The power line is then constructed. The broadcast antenna's pattern must be measured again, under similar ground conditions, to determine the extent of reradiation from the actual power line. Computer modelling can be used for an "as-built" assessment based on the actual, installed location of the power line towers. This serves to provide a computed pattern for the broadcast antenna operating near the "as-built" power line, which can serve as a reference for assessing the effectiveness of detuning measures designed by computation. The "as-built" computer model of the power line is also used to determine which spans are strongly resonant and carry the largest RF currents, and so are likely candidates for "detuning". Chapter 4 discusses "as-built" assessment for the CHFA site.

TABLE 1.1

LIFE CYCLE OF A RERADIATION PROBLEM

EVENT	ACTION
Existing broadcast array.	-Measure the azimuth pattern.
Proposal for construction of a power line near an operating broadcast array.	-"Initial Assessment": Is the proposed power line likely to be a significant reradiator ?
Final construction plans. Actual construction of the power line.	-"As-built assessment" : How much reradiation ? From which spans ?
Broadcast array operating near the power line.	-Measure the "after construction" azimuth pattern, to assess whether there has been a significant change. -Measure the power line tower base currents. -Design of detuning : computer modelling is used to select towers for isolation from the skywire, or to design other detuning measures, and to assess the degree of improvement to be expected.
Installation of detuning measures.	-Measure the power line tower base currents to verify the expected reduction, and to identify any further problems.
Broadcast array operating near detuned power line.	-Measure the azimuth pattern to ensure that it is satisfactory.

If the measurements indicate that the power line is a reradiator, the next stage in the "life cycle" is the design of detuning measures. A variety of schemes for detuning power lines have been proposed(15). Chapter 5 of this report presents a technique for designing "detuning by isolating towers," that is, for systematically choosing which towers should be isolated from the skywire in order to suppress the RF current flow on selected spans. A method for selecting specific towers for isolation, called the technique of "supression of resonances", is presented. Computer modelling can be used to predict the radiation pattern to be expected after selected towers have been isolated from the skywire, and hence to predict the degree to which the pattern can be improved. Tower isolation suppresses loop resonance, and once isolated, a tower acts as a free-standing reradiator. It may reradiate strongly enough to be a problem in itself. Thus tower isolation alone may not be able to restore a broadcast antenna's pattern, and the computer model shows whether further measures may be required. Once a suitable choice of towers for isolation has been arrived at, actual isolation of those towers on the power line can take place. The broadcast antenna's pattern is then measured once again, to assess the degree of improvement. If there are still unacceptable excursions above the station's protection requirements, then certain individual towers on the power line may have to be "treated" with tower stubs, or other means, to suppress RF current flow. In this way, the pattern of the broadcast antenna may be restored. Further pattern measurements may be used to demonstrate whether the pattern is satisfactory after detuning.

In summary, this report traces the "life cycle" of a reradiation problem from the point of view of computer modelling, examines the techniques available for "initial assessment", the objectives and results of "as-built" assessment, and presents the method of "suppression of resonances" for designing detuning by isolating towers from the skywire.

1.3 Overview of the Work

The primary purpose of the present work has been to generalize the results obtained in previous contracts to handle the case of realistic power lines which have non-uniform span lengths and tower heights, and follow routes not as simple as a straight line. Thus the methodology of computer modelling of reradiation from power lines has now been applied to sites of realistic complexity, including the problem of the suppression of reradiation. Real power lines with non-uniform span lengths reradiate differently from a power line which has a uniform tower spacing over its whole length, because on such a uniform power line, all spans have the same resonant frequencies. Consequently all spans are either non-resonant at the operating frequency of the broadcast antenna, or are all resonant at the antenna's frequency. If there is a reradiation problem, then all spans contribute to it. In contrast, if the span length on the power line is non-uniform, then each span has its individual resonant frequencies, and only those spans which are resonant at the broadcast antenna's operating frequency will carry strong RF currents, and so only those spans contribute to reradiation. This basic difference between uniform power lines and realistic power lines with a non-uniform span length has consequences which are explored in this report. The "initial assessment" stage, discussed in Chapter 3, is thus primarily concerned with how many resonant spans there are likely to be on the proposed power line, and how strong the resulting reradiated field from these resonant spans is likely to be. The "as-built assessment" stage deals with identifying the resonant spans given the actual locations of the installed towers, and is discussed in Chapter 4. The problem of "detuning", discussed in Chapter 5, is that of suppressing the resonant response of those spans, without creating further resonances on the power line.

The following Chapter summarizes the computer modelling method, and reviews the behaviour of power lines at MF frequencies for later reference.

CHAPTER TWO

BEHAVIOUR OF POWER LINES AT MF FREQUENCIES

2.1 Introduction

This chapter summarizes the behaviour of power lines at MF frequencies, citing the principal results needed to understand work presented later in the report. Two computer programs are available for the assessment of the reradiation from power lines, namely the "Numerical Electromagnetics Code(NEC)" and the "AM Power Line(AMPL)" program. The principal computer program to be used, NEC, is briefly reviewed. Then the derivation of a "computer model" of the power line for analysis by NEC is reviewed. Then the behaviour of the power line at RF frequencies is reviewed, as found from the NEC program and from scale model measurements. The effect of finite ground conductivity is reviewed. The second computer program, AMPL, is then described, and its usefulness and limitations are discussed. The chapter concludes with a discussion of the limits to present knowledge concerning the RF behaviour of power lines.

Fig. 2.1 shows a typical power line tower, in this case Ontario Hydro's type V1S tower. The three lower crossarms carry the "phase wires" or power-carrying wires, and the top crossarm carries a parallel pair of "skywires" which are electrically connected to the top of each tower and provide a path to ground for lightning strikes. The ground conductivity is typically between 5 and 20 millisiemens/metre, with a relative permittivity of 15, and is sufficiently high that the ground can be usefully modelled as "perfectly conducting." Ground conductivity is discussed further below. At MF frequencies the wavelength is of the order of 300 m, and so the cross-sectional size of the tower and of the skywires is small compared to the wavelength. Thus for analysis the tower can be represented as an "electrically thin" wire. Fig. 2.2 shows a portion of a typical power line model, in which each tower is represented by a vertical wire of "fat" radius, and the pair of skywires has been replaced by a single equivalent wire. In the following, the NEC code for analysing such an interconnection of "thin" wires is discussed, and then the method is given for the choice of the wire radii for the wires to be used to model the power line.

2.2 The Numerical Electromagnetics Code

The Numerical Electromagnetics Code(NEC,16) is a computer program for analysing a general class of radiating structures constructed from straight wires, and is suitable for determining the RF currents flowing on the broadcast antenna and the power line of the model of Fig. 2.2. The NEC program solves Pocklington's Integral Equation by the "moment method(17)", as follows. Pocklington's Equation states that for perfectly conducting wires, the total axial electric field must be equal to zero at any point on any of the wires of the antenna. The total field is broken up into the sum of the excitation field plus the secondary field expressed as an integral of the unknown RF current flow on the wires, and thus Pocklington's Equation equates this integral to the negative of the source field. In the broadcast antenna and power line problem, the primary source field is the excitation at the base of the broadcast tower. The NEC computer program solves Pocklington's Equation by subdividing each wire into "segments" which must be short compared to the wavelength, and expanding the unknown current on each "segment" in terms of a constant plus a sine function plus a cosine function, with three unknown current amplitudes. Continuity considerations for the current and the charge density from one "segment" to the next provide conditions specifying two of these unknown amplitudes. A set of linear equations for finding the remaining unknown current amplitude on each "segment" is derived from Pocklington's Equation, by applying that equation to the center point of each "segment", a procedure called "point matching". Thus NEC requires the user to subdivide the wire antenna into a set of "N" short segments, and must determine one complex-valued current amplitude for each segment, by assembling and solving an NxN complex-valued matrix equation. NEC finds the magnitude and phase of the RF current distribution on the broadcast towers, including all interactions between the towers, and finds the RF current distribution on the power line towers and their interconnecting skywires. The currents are then integrated to find the far-field patterns of the broadcast antenna operating in the presence of the power line.

NEC has been extensively used in the analysis of reradiation from power lines, in Refs. (1,2,3,4,5,6,9,10,11, 15,18) and elsewhere. The results obtained using NEC to model power lines are compared to full-scale measurements in Ref. (11). In theory NEC can analyse reradiation from power lines accurately throughout the entire MF frequency band, provided that each tower is represented in sufficient detail, using "segments" to model the crossarms and other significant features explicitly. In practice, NEC is a large program consuming much CPU time on a mainframe computer, and the number of segments that can be used is limited to 900, depending on the cost the user is willing to tolerate. For this reason, the central problem in using NEC is that of establishing a sufficiently simple model for the power line tower, using as few "segments" as possible, yet able to reproduce measured data throughout the required frequency range. A simple tower model has been established in Ref. (1) and (18) and is discussed in detail in the following. It has been shown to be sufficiently accurate up to about 1100 kHz, and above this frequency the tower model would probably have to include details of the crossarms, as discussed in Ref. (4). The number of power line spans which can be modelled is limited by cost considerations to about 25 using a simple model for each power line tower, unless very large runs of NEC can be funded, in which case as many as 53 towers have been modelled. Twice that might be modelled with a very large computer. NEC can model the conductivity of ground accurately, using the Sommerfeld-Norton representation, but at increased cost, as discussed below. NEC is the most precise modelling tool available at present.

2.3 The "Single Wire Tower" Model of a Power Line

The number of "segments" which would be required for a detailed representation of the complex lattice geometry of a power line tower such as that of Fig. 2.1 is so large that only a few towers could be studied using the NEC code, at great cost. If many power line towers are to be included in the model of a given site, then each power line tower must be represented with as few "segments" as possible. This section described the "single wire tower" model shown in Fig. 2.2, in which each tower is represented by a vertical cylindrical wire of "fat" radius. The "single wire tower" model is discussed in Refs. (1) and (18).

At MF frequencies, the cross-sectional size of the power line tower of the order of 8 metres square is small compared to the wavelength, and so the tower is "electrically thin", and can be replaced by a vertical, cylindrical wire of appropriate radius, hence the term "single wire tower" model. At "low" MF frequencies it has been found that the tower crossarms have little effect and can be ignored. In the simplest model, illustrated in Fig. 2.2, the radius is the same for the whole wire. In a more complex representation, the radius of the tower model is tapered to represent the taper of the actual tower, as was done in computing "loop impedances" in Ref. (4). The wire radius is derived as follows, using Jaggard's "isoperimetric inequalities"(19). The radius is taken to lie between the value which : (i) makes the length of the periphery of the cross-section of the tower equal to the length of the periphery of the circular wire cross-section ; and (ii) the value which makes the area of the tower cross-section equal to the area of the wire cross section. Thus if the tower cross-section is square of side length "s", then the wire radius "r" must lie between $s / \sqrt{\pi} = 0.5642\ s$ and $2s / \pi = 0.6366\ s$. The arithmetic mean value of $(0.5642 + 0.6366)s / 2 = 0.6004s$ has been used. For the tower of Fig. 2.1, the base of the tower is a square 7.62 m on a side, giving a range for the radius of 4.30 to 4.85 m, with a mean of 4.57 m. The top section of the tower is 3.81 m square, for a radius range of 2.15 to 2.43 m, with a mean value of 2.28 m. If one single wire radius is to be used for whole tower, then the mean of the extreme values of 2.15 and 4.85 has been chosen, equal to 3.51 m in this case. Fig. 2.3 compares the tower shape with the equivalent wire of radius 3.51 m. In Refs.(1) and (18), the value of 3.51 m gave reasonable agreement with measured data. In Ref. (18), the "arithmetic mean" is incorrectly reported as the "geometric mean". The results obtained with the computer model are not critically sensitive to the radius of the tower wire.

The parallel pair of skywires joining the tips of the top crossarm on each tower to the top crossarm on the next tower are represented in the computer model by a single "equivalent" skywire which joins the tops of the tower wires. At MF frequencies the actual pair of skywires and their images in ground behave as a two-pairs-of-wires RF transmission line joining the towers. This two-pairs line is represented in the computer model by a single-wire-and-image in ground transmission line with characteristic impedance equal to that of the two-pairs line. This uniquely specifies the wire radius for the single "equivalent" skywire in terms of the original pair as(1,18)

$$d_1 = \frac{2\sqrt{dh}}{\sqrt[4]{1 + \left(\frac{2h}{D}\right)^2}} \qquad \text{... 2.1}$$

where the parameters are defined by Fig. 2.4. To illustrate the calculation, for the tower of Fig. 2.1, the skywires are 50.9 m above the ground, and are separated by 21.3 m. The diameter is 4.7 cm, and the above formula yields a radius of 0.71 m for the "equivalent" single skywire.

The "single wire tower" computer model of Fig. 2.2 is operated in the computer model over a perfectly-conducting ground, and is analysed by the method of images. The NEC computer code analyses the power line model to find the amplitude and phase of the RF current flowing at the center of each "segment" on the power line and on the image of the power line in the ground. This RF current distribution can then be integrated to find the radiation patterns of the broadcast antenna operating near the power line. The behaviour of the model of Fig. 2.2 has been verified against measured data in Refs. (1), (3), (15) and (18). The following section describes the behaviour of the model and reviews the comparisons with measurements.

2.4 Behaviour of a Power Line in the MF Band

The behaviour of a power line at MF frequencies has been investigated in Refs. (1), (3) and (18) using the site shown in Fig. 2.5, in which an omnidirectional broadcast antenna illuminates a straight power line with 13 evenly-spaced towers. Fig. 2.6 shows a typical azimuth pattern which results from operating the "omnidirectional" antenna near the power line. RF currents induced on the towers of the power line "reradiate" strongly and at some azimuth angles the reradiated signal interferes destructively with the signal radiated directly from the omni antenna, and the resulting "net" field strength is low. At other azimuth angles, the "net" field is considerably stronger than that radiated by the antenna alone, due to constructive interference of the "direct" and the "reradiated" signal.

Fig. 2.6 compares the azimuth pattern computed with the NEC computer program using the "single wire tower" model of Fig. 2.2, to a measured pattern using a 1 to 600 scale model of the omni antenna and power line, reported in Ref. (1). Reasonable agreement is seen. Patterns such as Fig. 2.6 have been characterized by computing the "max-to-min ratio", which is the ratio of the largest radiated field to the smallest field, expressed in decibels. By computing or measuring the azimuth pattern over a range of frequencies, and then plotting the max-to-min ratio as a function of the frequency, the resonant behaviour of the power line can be seen, as shown in Fig. 2.7(from Ref. 3). Below about 350 kHz, and between about 550 and 700 kHz the power line has little effect on the omni antenna's pattern. The maximum value and the minimum value of the "distorted" pattern are nearly the same so the pattern remains nearly "omnidirectional". However, in the frequency bands 350 to 550 kHz, and 750 to 1000 kHz and above, the max-to-min ratio is not small, and indeed near 430 kHz takes on values of more than 15 dB. The power line has a resonance in each of these frequency ranges. Fig. 2.7 compares measured and computed data for the max-to-min ratio and shows a resonable coincidence and agreement over the resonant behaviour of the power line.

Fig. 2.7 shows that the power line has a resonance at about 430 kHz and another at about 860 kHz. The "bandwidth" of these resonances has not been defined precisely. If the bandwidth is taken to be the frequency range over which the max-to-min ratio for this power line geometry exceeds 5 dB, then the first resonance band extends from about 390 to about 520 kHz, and that of the second resonance from about 800 to about 940 kHz. Thus a "bandwidth" of 140 kHz is found. A rough but useful estimate takes the "bandwidth" of resonance to be about 100 kHz, centered on the "resonant" frequencies of 430 and 860 kHz. Fig. 2.7 shows that this "bandwidth" is approximate and corresponds for the most part to effects of 5 dB or more due to reradiation. Ref. (3) used the current flowing on a power line tower as a function of frequency to characterise the resonant behariour of the power line, with similar results to those obtained here.

Simple geometrical considerations allow the "prediction" of the resonant frequencies of the power line as described in the following.

2.5 Power Line Resonant Frequencies

In Ref. (2) the RF current flowing on the towers and skywires of the power line of Fig. 2.5 are examined at various resonant and non-resonant frequencies, and it is shown that resonance arises because the "path length" around one "span" of the power line is an integer multiple of the wavelength, and thus can carry a standing wave pattern of RF current distribution containing an integer number of half-wavelength cycles. The resonant length "path" is illustrated in Fig. 2.8, and forms a closed loop, from the base of a tower up to the skywire, along the skywire to the next tower, down that tower, and returning to the starting point on the "images" of the power line in the ground. Fig. 2.9(a) shows the RF current distribution standing wave associated with "one wavelength loop resonance", in which the loop path length is effectively one wavelength at the resonant frequency. In Fig. 2.7 the frequency of "one wavelength loop resonance" is about 430 kHz. At resonance the current distribution on the skywire is a standing-wave, which displays constant phase with position along the skywire, and sharp 180 degree reversals in phase at the nulls in the standing wave pattern. Such sharp phase reversals are characteristic of resonance and are often used to identify resonant current distributions in computations. Fig. 2.9(b) shows the RF current distribution for "two wavelength loop resonance" which has a frequency of about 860 kHz in Fig. 2.7. If the distance between two adjacent towers or "span length" is s, and the tower heights are h_1 and h_2 , then the geometrical loop length is

$$\ell_g = 2h_1 + 2h_2 + 2s \qquad \text{... 2.2}$$

Resonance is expected for loop lengths roughly equal to multiples of the free space wavelength. Thus the geometrical resonance frequencies are, for one-wavelength loop resonance,

$$f_{g1} = \frac{c}{\ell_g} \qquad \text{... 2.3}$$

and for two-wavelength loop resonance,

$$f_{g2} = 2 \frac{c}{\ell_g} \qquad \ldots 2.4$$

where c is the speed of light in free space. Because of capacitive coupling between the vertical tower wire and the horizontal skywire, the current tends to "cut off the corner" to some extent, which makes the electrical path length shorter than the geometrical path length, and hence the electrical resonance frequencies higher than f_{g1} and f_{g2} . The frequency difference can be estimated from the study of the site of Fig. 2.5, for which the geometrical resonance frequencies are calculated as f_{g1} = 400 and f_{g2} = 800 kHz. The max-to-min ratio graph of Fig. 2.7, shows that the electrical resonance frequencies found by computation using the Numerical Electromagnetics Code, or by scale mode measurement, are 430 and 860 kHz, respectively. Thus the estimates of Eqns. 2.3 and 2.4 must be corrected to agree with the behaviour shown in Fig. 2.7.

Two "correction methods" will be presented. The first will be referred to as the "simple estimate". The geometrical path length of Eqn. 2.2 is shortened by a factor k to become the electrical path length given by

$$\ell_e = k\,\ell_g \qquad \ldots 2.5$$

and the resonant frequencies are estimated as

$$f_{en} = n \frac{c}{\ell_g} \qquad \ldots 2.6$$

where n = 1 for "one wavelength loop resonance" and n = 2 for "two wavelength loop resonance." To "align" the estimate with the observed response of Fig. 2.7, "k" is chosen such that the "one wavelength loop resonance" frequency is 430 kHz, for the power line of Fig. 2.5. This gives the value k = 0.926 . Thus the "simple estimate" of power line resonant frequencies is given by

$$f_{en} = 1.08\, n \frac{c}{\ell_g} \qquad \ldots 2.7$$

where 1.08 = 1/0.926, and ℓ_g is the geometrical path length of Eqn. 2.2 .

Eqn. 2.5 states that $\ell_g - \ell_e$ is proportional to the path length,

$$\ell_g - \ell_e = \ell_g - k\ell_g = (1-k)\,\ell_g$$

However, it is expected that the electrical path length ℓ_e is shorter than the geometrical path length ℓ_g because the current "cuts the corner" from the skywrie to the tower. Hence $\ell_g - \ell_e$ should be independent of the spacing of the towers. The "simple estimate" can thus be improved upon, as follows.

An alternate "correction method" for the geometrical estimates of Eqns. 2.3 and 2.4 argues that the shorter electrical path length arises because the RF current "cuts the corner" at the junction of the top of the tower and the skywire, and so the effective path length is shorter, as illustrated in Fig. 2.8. The effective path length is

$$\ell_e = 2(s-2d) + 2(h_1-d) + 2(h_2-d) + 4(\sqrt{2}\,d)$$
$$= 2s + 2h_1 + 2h_2 - (8-4\sqrt{2})\,d$$

or

$$\ell_e = \ell_g - 4c \qquad \text{... 2.8}$$

where "c" is the "corner factor". The corner factor is expected to be a function of the tower geometry and thus could be determined by measurement for each type of power line tower. For the type V1S tower, the value of "c"is chosen so that the one-wavelength loop resonance frequency given by

$$f_{e1} = \frac{3\times10^8}{\ell_e}$$

falls at 430 kHz, giving a value of c = 13.7 m, or 4c = 54.8 m. Thus the "cut corner" estimate of resonant frequencies is given by

$$f_{en} = n\,\frac{3\times10^8}{\ell_g - 54.8} \qquad \text{... 2.9}$$

and the frequencies of one- and two-wavelength loop resonance agree with Fig. 2.7 .

The resonant frequency estimates of Eqns. 2.7 and 2.9 differ significantly for multi-span resonance modes of the power line, as discussed in the following.

2.6 Multi-Span Resonances

The spectrum of Fig. 2.7 shows resonance peaks at 470 and 510 kHz, and shows an extended response above the two-wavelength loop resonance frequency of 860 kHz. These effects are associated with multi-span resonance modes, in which a path including two or more adjacent spans is of resonant length. Fig. 2.11 shows the RF current distributions associated with three-, four-, and five-wavelength double-span resonance. The electrical length of the path including two adjacent skywires exactly "fits" n times the wavelength at the resonant frequency. The path length for double-span resonance is

$$\ell_g = 2h_1 + 2h_3 + 2s_1 + 2s_2 \qquad \ldots 2.10$$

where h_1 and h_3 are the heights of the towers, and s_1 and s_2 are the span lengths. For the power line of Fig. 2.5, the two-wavelength double-span resonant frequency can be estimated using the "simple" formula as 498 kHz, and the "cut corner" formula as 482 kHz, which puts the "cut corner" estimate closer to the resonance peak seen in Fig. 2.7 at 470 kHz. The four-wavelength double-span resonance frequency is estimated by the "cut corner" method to be 963 kHz, but no pronounced peak is seen in the response spectrum. It is possible that the phasing of the tower excitation for the power line configuration of Fig. 2.5 is such that this resonance mode is not strongly excited. Table 2.1 compares the resonant frequencies of Fig. 2.7 with those predicted by the "simple" formula and by the "cut corner" formula.

The reader can readily verify that the "cut corner" formula predicts one- and three-wavelength double-span resonance at 241 and 722 kHz, respectively. However, no such resonant peaks are seen in the spectrum of Fig. 2.7 . The RF current distribution associated with such resonance modes would have a current minimum at the position of the centre tower of the double-span, as illustrated in Fig. 2.11(b) for three-wavelength double-span resonance. A current minimum is accompanied by a voltage maximum at the same position, but the presence of the centre tower effectively "shorts out" the strong electric field across the skywire-and-image transmission line associated with the voltage maximum, and so resonance modes with a current minimum at the centre tower are suppressed or "detuned" by that tower.

TABLE 2.1 Power Line Resonant Frequencies

Resonance Mode	Observed Frequency Fig. 2.7	Simple Formula Eqn. 2.7	Cut-Corner Formula Eqn. 2.9
One-wavelength loop resonance	430 kHz	430 kHz	430 kHz
Two-wavelength double-span resonance	470	498	482
Three-wavelength triple-span resonance	510	525	501
Two-wavelength loop resonance	860	860	860
Four-wavelength double-span resonance	- - -	996	963
Five-wavelength triple-span resonance	extended response - -	876	836
Six-wavelength triple-span resonance	1000 ?	1051	1003

"Triple-span" resonance modes can also exist. Fig. 2.12 illustrates the RF current distribution for four-, five-, and six-wavelength triple-span resonance. The associated path length over three adjacent spans is

$$\ell_g = 2h_1 + 2h_4 + 2s_1 + 2s_2 + 2s_3 \qquad \ldots\ 2.11$$

and is 1850 m for the power line of Fig. 2.5 . The "simple" formula predicts "three-wavelength triple-span" resonance at 525 kHz, and the "cut corner" formula predicts the same mode at 501 kHz, both being somewhat in disagreement with the value of 510 kHz seen in Fig. 2.7 . The "cut corner" formula predicts "six-wavelength triple-span" resonance at 1003 kHz, and the frequency spectrum of Fig. 2.7 rises sharply as 1000 kHz is approached, but Ref. (3) did not extend the data for Fig. 2.7 beyond 1000 kHz. The reader can sketch the RF current distributions expected of triple-span resonance, and it will be seen that the position of the current maxima do not coincide with the location of the two intervening power line towers enclosed by the triple-span. This means that to some extent, the towers "short out" the resonance mode, and may also shift the resonant frequency. Thus strong resonant response peaks associated with triple-span resonance are not seen in frequency spectra such as Fig. 2.7 . It can happen, on an actual power line site with unevenly spaced towers, that on a specific triple-span, the location of the two enclosed towers coincides, by chance, with the position of the current maxima for a triple-span mode. In such a case, a strong triple-span resonant response can be found.

Thus the resonant frequencies of a power line can be estimated for single-span loop resonance modes, and for double- and triple-span modes, using either the "simple" formula of Eqn. 2.7 or the "cut corner" formula of Eqn. 2.9 . In previous work the "simple" formula has generally been used. The "cut corner" formula is presented here for the first time, and will be preferred in future work.

2.7 Higher Frequency Resonances

The investigations of power line reradiation given in Refs. (1) to (4) have emphasized one- and two-wavelength loop resonance, and generally have not extended beyond 1000 kHz into the three- and four-wavelength resonance regions of the power line. For a given physical height for the towers of the power line, the electrical height of the tower becomes a larger fraction of the wavelength as the frequency is raised. Thus a 51 m tower is 0.073 of the wavelength tall at 430 kHz, 0.146 of the wavelength tall at 860 kHz, and 0.219 of the wavelength tall at the three-wavelength loop resonance frequency of 1290 kHz. As the height of the tower increases towards one-quarter of the wavelength, the radiation resistance of the tower also increases, and the increasing resistance "damps" the higher-order resonant responses more and more strongly. Thus in Fig. 2.7, the two-wavelength resonant response is much smaller in magnitude than that seen for one-wavelength loop resonance, because the damping contributed by the radiation resistance of each power line tower is larger at 860 kHz than at 430 kHz. Indeed, at 1290 kHz, the response would be even more strongly damped. Also, as the frequency increases, the skywire-and-image transmission line conductors become separated by a substantial fraction of the wavelength, and so the skywire radiates energy in an E-phi component. This contributes additional damping. Thus reradiation is not expected to give rise to as dramatic a distortion of the pattern at higher frequencies.

The existence, frequencies, and bandwidth of three- and four-wavelength loop resonance have not been systematically investigated by computation and measurement and this report recommends that such an investigation be undertaken. It is expected that the power line of Fig. 2.5 would exhibit three-wavelength loop resonance at 1290 kHz, accompanied by "double-span" resonance at 1446 kHz, and "triple-span" resonance at 1169, 1336, and 1503 kHz, although those modes would be suppressed to some extent by the "enclosed" towers. Thus a broad resonance region extending from below 1290 to above 1500 kHz, but heavily damped, is expected. Four-wavelength loop resonance is expected at 1720 kHz, providing another broad but heavily damped resonance region.

It has been shown in Ref. (4) that the presence of the crossarms of the power line tower have a significant effect on the resonant frequencies of the power line above 1000 kHz. Indeed with 51 m tall towers having a top crossarm extending 10.9 m on either side, the 61.9 m tower-plus-crossarm path is one-quarter wavelength at 1212 kHz, and the power line is expected to show "self-resonant" response for the towers near that frequency. Thus the resonant frequency estimates given in the above paragraph may be in error in the three- and four-wavelength loop resonance frequency ranges, due to the top-loading effect of the crossarms.

2.8 Excitation of Resonances

In order for a span of a power line to be a strong reradiator, it must carry a large RF current, and, in turn, in order for the RF current to be large, the operating frequency of the antenna must be near a resonance of the power line, and the towers of the span must be suitably excited. Thus the relative phase of the broadcast antenna's field at one tower of the span relative to the next must be suitable to excite the resonance mode of the power line. This section discusses the factors which lead to a strong RF current on a given span.

If a span is resonant at frequency f_s and the broadcast antenna operates at f_o , then f_s must be within the bandwidth of the resonance mode centred on f_o in order that a significant RF current be induced on the span. The bandwidth of resonance has been estimated from Fig. 2.7 as roughly 100 kHz, extending from roughly 50 kHz below to 50 kHz above the resonant frequency. The 100 kHz figure provides a very rough guide to the frequency range over which significant reradiation effects may be present for a given resonance mode. As illustrated in Table 2.1, several resonance modes are often close together over a given frequency range. Thus the "one-wavelength resonance range" encompasses a single-span mode at 430 kHz, a double-span mode at 482 kHz(estimated) and a triple-span mode at 510 kHz, and the "bandwidth" estimate suggests that "significant" reradiation effects could be expected from 430-50 = 380 kHz to 510+50 = 560 kHz. In comparison with Fig. 2.7, this is a reasonable estimate of the extent of the "one-wavelength resonance region" for this power line.

The strength of the broadcast antenna's field, or "excitation field", decreases inversely with distance in the far field, and faster in the antenna's near field. All else being equal, a span which is further away is more weakly excited and so responds more weakly. The "all else" includes the span length and tower heights, and hence proximity to a resonant frequency. Also, it includes the orientation of the span, which is shown in the following to be a significant factor. For a directional antenna, the strength of the antenna's field is a function of the azimuth angle at which the span is located in the radiation pattern. Thus distance from the antenna is only one factor among many. On a given power line, it does not necessarily follow that a span which is further from the antenna reradiates more weakly than another span which is closer to the antenna. But ultimately, as distance to the antenna increases, reradiation effects decrease to insignificance.

It has been noted in Ref. (4) that resonance modes require either "common mode" or "difference mode" excitation. "Common-mode" refers to in-phase excitation of adjacent towers, while "difference mode" refers to a 180 degree phase difference in the excitation from one tower to the next. In general, the excitation field can be split into a common-mode component and a difference-mode component, as discussed in the following paragraph. The current distribution associated with one-wavelength loop resonance makes the RF current on two adjacent towers exactly in-phase. Thus, if the current is directed upwards with zero phase on one tower, it is also upward with zero phase on the adjacent tower. Such a resonance mode can only be excited by an excitation field which is also in-phase at the two towers, that is, by the "common-mode" component of the excitation field. Conversely, the current distribution associated with two-wavelength loop resonance has the RF current directed upward on one tower and downward on the next, and so two-wavelength loop resonance can only be excited by the difference-mode component of the excitation field. Thus even if a span is resonant at the operating frequency, it may not be excited to resonance if the excitation field does not contain a strong component of the appropriate common- or difference-mode.

The influence of the orientation of the span on the response of the span can be seen by factoring the excitation field into a common-mode component C which is in-phase at the two towers, and a difference-mode component D which is 180 degrees out of phase. In Fig. 2.13, let the field at the two towers be given by

$$E_1 = E_0 \, e^{-jkr_1} \qquad \text{... 2.12}$$

and

$$E_2 = E_0 \, e^{-jkr_2} \qquad \text{... 2.13}$$

where r_1 and r_2 are the distances of the two towers from the broadcast antenna, and k is the wave number. These fields are factored into common and difference mode components satisfying at tower # 1

$$C + D = E_1 \qquad \text{... 2.14}$$

and at tower # 2

$$C - D = E_2 \qquad \text{... 2.15}$$

which can be solved to obtain

$$C = \frac{E_1 + E_2}{2} \qquad \text{... 2.16}$$

and

$$D = \frac{E_1 - E_2}{2} \qquad \text{... 2.17}$$

The distances r_1 and r_2 can be compared to the distance r from the antenna to the center of the span, by assuming that both r_1 and r_2 are large compared to the length of the span, s. From Fig. 2.14,

$$r_1 = r - \frac{s}{2} \cos \theta \qquad \text{... 2.18}$$

and

$$r_2 = r + \frac{s}{2} \cos \theta \qquad \text{... 2.19}$$

where θ is the orientation angle of the span relative to the radial from the antenna, and s is the span length. By substitution, C and D can be written as

$$C = E_o e^{-jkr} \cos\left(\frac{ks}{2}\cos\theta\right) \quad \text{... 2.20}$$

and

$$D = E_o e^{-jkr} \sin\left(\frac{ks}{2}\cos\theta\right) \quad \text{... 2.21}$$

For a span with 51 m tall towers with a span length of 274.3 m, one-wavelength loop resonance falls at 430 kHz, and the span must be oriented perpendicular to the radial from the antenna in order for the excitation field to be in-phase at the two towers. If the span is skewed at 60 degrees to the radial the common-mode component is 2.1 dB below the level of the excitation field, and so the RF current induced on the span is 2.1 dB less than it would be if the excitation were entirely common-mode. If the span is skewed at 30 degrees, the common-mode component is 6.1 dB down. Thus to excite one-wavelength loop resonance effectively, the span must be roughly perpendicular to the radial from the antenna. Two-wavelength loop resonance requires difference-mode excitation. If the 274.3 m span is excited at 860 kHz, then it is two-wavelength loop resonant, but if the span is oriented perpendicular to the radial from the antenna, then the excitation is pure common-mode and so two-wavelength loop resonance is not excited, and little RF current flows on the resonant span. If the span is oriented at 50 degrees to the radial, the excitation is pure difference-mode, and the largest possible RF current is induced on the span. If the span is oriented at 70 degrees, then the difference-mode component is 2.5 dB down from the magnitude of the excitation field, and if the span is oriented at 20 degrees to the radial, almost parallel, then the difference-mode component is 2.7 dB down. Thus to excite the strongest possible RF current flow on a resonant span, the span must be "favorably oriented" relative to the radial from the antenna.

In summary, the strength of the RF current induced on a span depends upon : (i) the distance from the antenna ; (ii) the location of the span in the antenna's azimuth pattern ; (iii) the angular orientation of the span relative to a radial from the antenna ; and (iv) the nearness of the frequency of operation to a resonant frequency of the span. A non-resonant span generally carries small RF currents, with the exception of such a span located adjacent to a strongly resonant span. A resonant span may carry strong RF currents but does not necessarily do so, depending on the orientation of the span and on its location in the pattern and distance from the antenna.

2.9 Effect of Ground Conductivity on Power Line Resonance

The foregoing discussion of power line resonant behaviour has been based on computations and measurements made over a highly-conductive ground. The ground conductivity is typically 5 to 15 millisiemens/metre, with a relative permittivity of 15. If the loss tangent

$$\tan \phi = \frac{\sigma}{\omega \epsilon} \qquad \text{... 2.22}$$

is much greater than unity, then the material is generally considered to be a "good conductor"(20). At 430 kHz, with a conductivity of 5 millisiemens/metre, the ratio is about 14, and the assumption that ground is a good conductor is justified. At 860 kHz, the ratio is about 7, and at 1290 kHz the ratio is 4.6. Evidently as the frequency increases the use of the perfectly conducting ground in the computer models is less justified, although with realistic ground parameters, the ratio still remains greater than unity.

In order to assess the effect that the actual conductivity of the ground has on the resonant behaviour of a power line, Ref. (3) explored the behaviour of the power line configuration of Fig. 2.5 using a version of the Numerical Electromagnetics Code which accounts for the interaction of the power line with ground of a given conductivity and permittivity(21,22,23). The solution of Maxwell's Equations for thin wires above a lossy half-space, i.e. : a ground of given conductivity and permittivity, gives rise to Sommerfeld Integrals for the fields due to the interaction of the wires with the ground. Norton(24) obtained asymptotic expressions for the evaluation of the Sommerfeld Integrals when the distance from the wire to the observation point is large. Banos(25) derived approximations for very close distances. Miller et al.(22,23) have used numerical integration and interpolation to construct an efficient method for approximating the interaction terms for any distance from the radiating wire to the observation point. It should be noted that the Sommerfeld Integral expressions give the exact interaction of each wire of the antenna with the ground. The only approximations introduced into the Numerical Electromagnetics Code are those associated with evaluating the integrals, and the treatment of the junction between a wire and the ground. These approximations are not expected to introduce significant error for the ground parameters discussed above, which result in a "good" ground in all cases.

Ref. (3) computed the azimuth pattern for the power line of Fig. 2.7 with five towers, over the range of frequencies encompassing the one-wavelength loop resonance region, and the two-wavelength loop resonance region, and obtained the graphs reproduced in Figs. 2.15 and 2.16. The figures compare the max-to-min ratio of the azimuth pattern of the omnidirectional antenna scalloped by reradiation from the five tower power line, for the case of ground of high conductivity ("perfect ground") with the case of realistic ground conductivity, using the values 5, 10, and 20 millisiemens/metre, and relative permittivity 15. The principal result contained in the figures is that realistic ground conductivity primarily introduces damping into the resonant behaviour, and so reduces the value of RF current flowing on the power line, and so reduces the reradiated field and the amount of scalloping of the radiation pattern. Thus for example, the worst-case scalloping of the pattern occurs at about 430 kHz and is about 22 dB over highly-conductive ground, but is only about 11 dB with a conductivity of 20 millisiemens/metre, and only about 7 dB at 5 millisiemens/metre ground conductivity. Thus reduction of the RF current induced on the power line by a factor of 3.5 to 5.5 is expected due to the conductivity of the ground.

A second important conclusion can be drawn from Figs. 2.15 and 2.16. The resonant frequencies of the power line are not strongly dependent upon the conductivity of the ground. Thus as the ground conductivity is decreased from "high" to realistic values in the range of 5 to 20 millisiemens/metre, the resonant frequencies drop by about 10 kHz. Thus the estimates of the resonant frequencies of Eqns. 2.7 and 2.9 remain reasonable even for the case of finite ground conductivity.

Silva, Balmain and Ford(26) have proposed the modelling of the conductivity of the ground as a lumped "footing impedance" to be included in series with the base of each power line tower, in the model of the power line operated over highly-conducting ground. The footing impedance is calculated based on Monteath's formula(27) obtained using the Compensation Theorem. In Monteath's method, each power line tower is modelled as having a "footing" which is a perfectly conducting cylinder of a given radius, extending into the conducting half-space to a great(infinite) depth, and a formula is obtained for the difference between the impedance of the tower over ground of realistic conductivity with the cylindrical footing, and the impedance of the same tower over highly conductive ground. This difference is the "footing impedance" and is inserted in series with the base of each power line tower in a computer model which is then analysed over highly-conductive ground. The usefulness of the replacement can be investigated by re-computing the data for Figs. 2.15 and 2.16 using the footing impedance approximation. Fig. 2.17 shows the result obtained in the two-wavelength loop resonance range, for ground conductivity 10 millisiemens/metre. The curve obtained with the Sommerfled-Norton ground model shows a smaller max-to-min ratio at resonance, and a lower resonant frequency than the curve obtained with "perfect" ground. When the "footing impedance" is included as a lumped load at the base of each power line tower, over "perfect ground", the curve obtained is closer to the values computed with the Sommerfeld-Norton ground model than to those obtained with "perfect" ground. The footing impedance lowers the max-to-min ratio, although not as much as is seen in the Sommerfeld-Norton curve. The footing impedance also shifts the resonant frequency down to agree with that using the Sommerfeld-Norton ground model . Thus the inclusion of "footing impedance" can reasonably account for the damping of resonance by ground conductivity and for the small shift in resonant frequency due to ground conductivity, at a much smaller cost to the user than is incurred by using the Sommerfeld-Norton ground model. However, the value of the footing impedance is highly dependent upon the radius of the cylindrical footing in the Monteath model, and this radius bears little physical relationship to the actual reinforced concrete base used as a footing for each leg of a real power line tower.

In summary, it has been found that the conductivity of ground "damps" the resonances of the power line by a factor of 3.5 to 5.5 as the conductivity is decreased from 20 to 5 millisiemens/metre, and that ground conductivity has a small effect, about 10 kHz, on the resonant frequencies of the power line. The footing impedance has been found to be a useful, economical method for including the effects of ground conductivity in a computer model analysed over highly-conductive ground.

2.10 Transmission Line Modelling and the AMPL Program

The AM Power Line program(AMPL,12) models the skywire and its image in ground as a lossy "ideal two-wire transmission line", where the losses are due to the conductivity of the wires and to the conductivity of the ground. Thus the skywire-and-image forms a transmission line which connects each tower to the next, and the tower is represented by its impedance as seen across the two-wire line, which differs in concept from its impedance at the tower base. Each tower is excited directly by the broadcast antenna. The excitation of each tower is represented as a voltage generator in series with the tower impedance, the series combination being connected across the skywire-image transmission line at the location of the tower. The value of the voltage generator is obtained by computing the magnitude and phase of the broadcast antenna's field at the position of the tower, which accounts for the broadcast antenna's directional pattern, for the attenuation of the antenna's field with distance, and for the phase difference in the excitation field from one power line tower to the next, which, as discussed above, is an important factor in the excitation of the various resonance modes. The tower impedance seen across the skywire-image transmission line is found using a tower model which is similar to that discussed above for use with the NEC program, and hence has the same frequency limitation, being valid to about

1100 kHz. The tower model lumps the conductivity of ground into a "footing impedance" at the tower base. AMPL finds the RF currents flowing on the towers of the power line from the tower excitations by solving a system of equations based on transmission line theory, for the travelling-wave amplitudes of the current on each skywire of the power line. KCL is enforced at the junction of the top of a tower and the two skywires leading to the adjacent towers. Once the tower currents are known, the reradiated field is readily evaluated. The ability of the AMPL program to compute reradiated field patterns for the power line geometry of Fig. 2.5 has been extensively checked, and reasonable agreement has been found up to about 1100 kHz.

To illustrate the degree of similarity of the results obtained using the NEC program and the AMPL program, the pattern of a directional broadcast antenna near a power line will be presented. The CHFA array is used extensively as an example in the following chapters, and is a three-tower directional array operating at 680 kHz, with the azimuth pattern shown in Fig. 3.1. The frequency is well within the limitation of the AMPL code. The "north" power line is shown in Fig. 4.4 later in this report, which gives the span lengths in metres, and Table 4.1 gives the "as built" locations of the towers relative to the CHFA array. The effect of the power line is to introduce radiation into the minimum in CHFA's pattern, as shown in Fig. 2.18, which may be compared with Fig. 3.1. Fig. 2.19 shows that reradiation by the power line into CHFA's minimum causes its protection limit to be considerably exceeded. These figures compare the preformance of the NEC code with that of AMPL for this problem. The pattern obtained using the AMPL program is very similar to that obtained with NEC, and indeed AMPL traces out most of the detail predicted by the NEC program in the minimum of CHFA's pattern. Thus AMPL could be used with confidence to analyse this reradiation problem. This problem is a "major" run of the NEC code, requiring a Cyber 174 computer and using about 1100 seconds seconds of CPU time. The AMPL result is obtained on an LSI-11/23 computer in a couple of minutes, at minimal cost, and indeed could be run on an IBM-PC on an engineer's desktop. The original "run" of AMPL to assess its usefulness was done for this problem on a Commodore-64 computer, requiring over one hour of computation.

Another comparison between the NEC result and the AMPL result for this problem can be made, based on the magnitude and phase of the RF current flowing at the base of each power line tower, shown in Fig. 2.20. Part (a) compares the tower current magnitudes, using the tower numbering system of Fig. 4.4. It is seen that on most towers the NEC and AMPL currents are similar in value on most towers. The towers carrying large currents are those which are part of resonant-length spans, as discussed further in Chapter 4 of this report. On those towers, it is seen that the AMPL program predicts somewhat less current than does the NEC program. This is to be expected, as the AMPL model includes losses in the skywires, and includes tower footing impedance to model the conductivity of the ground, whereas, for this comparison, the NEC model used "perfectly" conducting ground, and did not include footing impedances. Fig. 2.20(b) compares the phase of the currents using AMPL and NEC. Good agreement is seen on most towers.

The AMPL program allows a microcomputer to be used to calculate the reradiation from lengths of 40 or more spans of power line. As many as 53 spans can presently be analysed with the NEC code using the Cyber computer, and the "run" uses about 2000 CPU seconds, and is prohibitively expensive. Even with 40 spans, AMPL runs in a few minutes on the LSI-11/23 and this makes AMPL an inexpensive tool for reradiation analysis. AMPL could be dimensioned to handle many more than 40 spans. AMPL is valid and generates results comparable to those of the NEC program throughout the frequency range where the tower model used in AMPL is a valid representation of the electrical behaviour of a power line tower, which extends up to roughly 1100 kHz. Thus AMPL provides a quick, accurate, inexpensive tool for the analysis of power lines. Indeed, AMPL makes practical a statistical approach to the "initial assessment" of reradiation from a proposed power line, to be described in the next Chapter.

2.11 Conclusion

This chapter has described the mechanism of loop resonance which gives rise to strong reradiated fields from power lines in certain frequency ranges. Simple formulae have been given for estimating the frequencies of resonance. Computer models have been described which allow the radiation patterns of a broadcast array to be computed when it operates in the presence of a given power line. The remainder of this report describes procedures for using these tools to deal effectively with reradiation problems. The next chapter discusses the assessment of potential reradiation from a proposed power line, where the location of the towers is not precisely known, and so the number and location of resonant spans cannot be judged. Once a power line has been constructed and identified as a reradiator, it must be "treated" or "detuned" to suppress RF current flow and hence the reradiated field. The following chapter deals with the selection of a set of power line towers for isolation from the skywire in order to suppress the reradiated field effectively.

CHAPTER THREE

INITIAL ASSESSMENT OF RERADIATION FROM POWER LINES

3.1 Introduction

Many broadcast arrays are required to maintain radiation below a specified level over a certain "protected arc" of azimuth angles, in order to avoid interference in a distant city with another station on the same frequency. When a high-voltage power line is built near a directional broadcast array, the signal is "scattered" or "reradiated" from the power line, and reradiation into this "protected arc" can result in a field strength in excess of the protection requirement. At an early planning stage, when a proposed power line is under discussion and public debate, a route for the line is set out, and a nominal value is given for the tower height and span length. The operator of a broadcast array which is located near the route of the proposed power line should be concerned that reradiation may change his antenna pattern. The objective of this chapter is to set out a method for obtaining an estimate at this early planning stage of the level of reradiation to be expected from the power line, and to assess the likelihood that the resulting antenna will have field strengths larger than the protection limit in the "protected arc". This "initial assessment" can provide the basis for discussion of alterations to the design of the power line, or its rerouting, in order to suppress the anticipated reradiation.

The construction proposal for a power line specifies a "corridor" or route which the line will follow, and provides a nominal value for the height of the towers and for the spacing of the towers or "span length". The exact positions of the towers of the power line will not be known until detailed planning is done, and are determined by local terrain features such as highways, railroad tracks, and gullies. Indeed, sometimes tower positions are slightly adjusted upon installation. Thus the actual span lengths on a power line are not all uniform and equal to the nominal value, but instead vary above and below the nominal value by, very roughly, 10 percent. The problem of "initial assessment" is that of estimating the strength of the reradiated field without knowing the exact position of the towers on the power line. The plus-or-minus roughly 10 percent variations in the span length determine which spans are resonant and so are a key factor in determining the strength of the reradiated field. The problem of "initial assessment" is that of determining whether the "net" radiation pattern of the antenna near the power line is likely to exceed the protection requirement, without knowing the exact position of each power line tower.

The mechanism of reradiation from a power line is that of "loop resonance", and has been described in Chapter 2. On a power line with a variable span length, the reradiated field is primarily due to those spans whose length makes them resonant at the broadcast array's operating frequency. Thus the question of "how much reradiation" implies asking "how many of the spans are of resonant length", which in turn depends both on the nominal value for the span length and on the degree of variability expected of the span length. At our early planning stage, the expected variability of the span length can be estimated by examining other similar power lines and calculating a standard deviation for the span length. Thus the value of the reradiated field must be estimated without knowing the exact tower positions, but instead based on a knowledge of the mean tower spacing and its standard deviation. Given this statistical description of the power line, the best approach will be to estimate how strong the reradiated field is likely to be, or in other words, determine a mean value and a standard deviation for the strength of the reradiated field.

Computer programs for determining the field reradiated from a power line require knowledge of the precise position of each one of the power line towers relative to the broadcast array. But at the "early planning stage", the exact location of each of the power line towers is not known, and so such power line analysis programs cannot be used directly to find the reradiated field.

The "initial assessment" procedure to be described in this chapter has three stages. The first stage uses simple formulae to estimate the resonant frequencies of the power line, and to estimate how many resonant spans there are likely to be on a power line which has the given "nominal" span length and standard deviation for the span length. A "high" probability of resonant spans indicates a potential reradiation problem. The term "high" becomes more meaningful in the light of results presented in this report. At the second stage, the assessment accounts for the route of the power line, the distance from the broadcast antenna to the power line, and the broadcast antenna's directional pattern. Thus, a hypothetical power line is constructed, on which the towers are perfectly evenly-spaced, following the prescribed route. This obtains a set of precise tower locations, and so a computer program can be used to find the radiation pattern of the broadcast antenna near the hypothetical "evenly-spaced" power line. If this is done using the nominal tower spacing and also using nearby resonant values for the span length, then the results provide a rough guide or "ballpark figure" for the strength of the reradiated field possible from the proposed power line. However, such tests using "evenly-spaced" power lines can be misleading, because all the spans on an "evenly-spaced" power line are either non-resonant and thus poor reradiators, or all the spans are resonant and thus all strong reradiators, which is generally the "worst case". This is quite different from a real power line with a variable span length, where those few spans of resonant length are the primary source of reradiation. It would not be expected that the radiation pattern of the broadcast array near an evenly-spaced power line with the nominal tower spacing would be similar to that to be expected of the real broadcast array near the real power line. If the levels of reradiation from such "evenly-spaced" test lines are significant, then further investigation should be pursued.

The third stage of "initial assessment" recognises that the levels of reradiation from a power line with perfectly uniformly-spaced towers can be misleading, especially if the nominal span length is non-resonant but close to a resonant value. The third stage consists of constructing a set of "test power lines" having randomly-distributed span lengths with the given mean value and standard deviation, and following the prescribed route, and analysing each with a computer program. The low cost of "running" the AMPL program makes such an approach practical. The resulting set of radiation patterns characterise the behaviour of the antenna near a power line with the given span statistics and route, and can be used to compile statistics on the amount of reradiation to be expected. Thus, if the "excess field" is the amount by which the field strength of the broadcast antenna operating near a "test power line" exceeds protection, then the mean value and standard deviation of the excess field can be found from the radiation patterns for many "test lines". The mean and standard deviation of the excess field characterize the amount by which protection is likely to be exceeded by a power line with the given span statistics and route.

To illustrate this initial assessment procedure, it is applied to a directional antenna located about 2500 m from a power line. Six sets of span statistics are studied, including non-resonant and resonant mean span lengths, and small and large variability of the span length. It is shown that if the span variability is large, then significant levels of reradiation can be expected even if the mean value of the span length is non-resonant.

3.2 CHFA Broadcast Array

Station CHFA, using a three tower broadcast array with the azimuth pattern shown in Fig. 3.1(a), will be used as an illustrative example throughout this chapter. The field strength in the pattern minimum is about 38 dB down from the pattern's maximum value. The protection requirement specifies a maximum field strength in the arc from 168 to 236 degrees azimuth, and the level is about 35 dB down from the pattern maximum. Fig. 3.1(b) shows the field strength plotted on a linear scale over the angular region of the protection requirement, and is a far-field radiation pattern "normalized" or scaled to a distance of 1 mile from the broadcast array. The maximum field strength is 960 mV/m at about 10 degrees azimuth, and the R.M.S. field strength is 590 mV/m. The broadcast array's pattern is close to the protection limit near 236 degrees, and so even a few millivolts of reradiation in this azimuth direction could cause a problem. This illustrates the notion that the strength of the reradiated field which can be tolerated is dependent on the specific antenna pattern and protection requirement. In a "tight" situation such as this one, even a small amount of reradiation from an essentially non-resonant power line can cause small excursions above protection. But it will be shown that with many resonant spans, protection can be exceeded by more than 80 mV/m.

3.3 Power Line Construction Proposal

The power line shown in Fig. 3.2 is "proposed" for construction near station CHFA. It is about 2000 m away at closest approach. The leg of the power line southeast of the antenna lies for the most part in the minimum of the broadcast array's pattern, so is not strongly excited and will not be a significant reradiator, and thus only about 1500 m of this portion will be included in the computer model. The north leg is strongly excited by the broadcast array, and a length of 3117 m will be modelled. The route continues beyond the end of the north leg, going due east for some distance. A rather arbitrary decision has been made concerning how much of the power line to include in the computer model, and this decision could be "second guessed" later if it were thought that a longer line would cause stronger reradiation. The nominal height of the power line towers is 32.6 m, and the nominal span length is 363 m. An estimate of the variability of the span length is necessary for the study to proceed and can be obtained by examining similar power lines in the area and computing the standard deviation of their span lengths. Fig. 3.3 shows the actual distribution of the span lengths for the power line eventually built near station CHFA, plotted in 10 m intervals of span length, as percentage of the total number of spans. Thus, for example, about 10.8 percent of the spans have a length between 320 and 330 m. The mean span length is readily calculated as 358.4 m, close to the "nominal" value of 363 m quoted in the construction proposal. The standard deviation of the span length, calculated using a length of about 100 spans of the power line, is 45.9 m, which is about 13 percent of the nominal span length. In computing the standard deviation, the exceptionally long spans, of length greater than 540 m, have been omitted. These long spans arise because of natural obstacles such as gullies. A "Gaussian" or "normal" distribution is a convenient approximation to the actual distribution of span lengths, and is given by(28)

$$p(s) = e^{-\frac{(s-\bar{s})^2}{\sigma_s^2}} \times 100 \text{ percent} \qquad \ldots 3.1$$

where p is the probability density in percent of spans per metre of span length, s is the span length, $\bar{s}$ is the mean span length, and σ_s is the standard deviation of the span length. The percentage of the total number of spans which will have a length between s_1 and s_2 is equal to the area under the "normal" probability density curve, and is readily evaluated using the polynomial approximation which is given in Ref. (29). To compare the normal distribution with the actual span length distribution in Fig. 3.3, the mean span length and the standard deviation have been chosen to be 358.4 m and 45.9 m, respectively, and the probability that the span length lies between s-5 and s+5 m, equal to the area under the density curve of Eqn. 3.1 from s-5 to s+5, has been plotted as a dashed curve for s = 225, 235, 245, ..., 675 m. A reasonable correlation is seen. A somewhat smaller standard deviation might even be chosen.

Thus the length of the spans on the power line proposed for construction near station CHFA will be approximated by a normal probability density, with mean equal to the nominal span length of 363 m, and standard deviation 46 m. The normal distribution implies that 68 percent of the spans have lengths within one standard deviation of the mean, in the range 317 to 409 m, and that 95 percent of the spans have lengths within two standard deviations of the mean, from 271 to 455 m. In the following, the resonant frequencies of the power line are related to the span length, and it is seen that this wide range encompasses a resonance mode of the power line, and spans of resonant length are expected to be strong reradiators.

3.4 Power Line Resonant Frequencies

The first stage of "initial assessment" is a pencil-and-paper evaluation of the resonant frequencies of the power line with the nominal span length, and of the ranges of values for the span length which make the spans of the power line resonant at the operating frequency of 680 kHz. The resonant behaviour of power lines at MF frequencies has been discussed in Chapter 2. For the present purpose the estimate of the resonant frequencies given by Eqn. 2.7 has been used. Whether or not a power line is a strong reradiator is determined primarily by whether the spans on the power line are of resonant length at the operating frequency. Eqn. 2.7 indicates that with towers 32.6 m tall, a span of length 411 m will be resonant at the operating frequency of 680 kHz, and so the nominal span length of 363 m is not greatly different from a resonant span length. The following explores the amount of reradiation that can be expected from one resonant span, and then a method is proposed for assessing how much reradiation will likely result from the construction of the power line near station CHFA.

3.5 Resonant Ranges of Span Length

With the "nominal" tower height of H = 32.6 m, Eqn. 2.7 can be used to estimate the range of span lengths which give strongly resonant spans. Thus if a span has a resonant frequency within 50 kHz of the operating frequency of 680 kHz, then it is considered "resonant". If the span is in "one-wavelength loop resonance", then with N = 1 the span length must satisfy

$$\frac{1.08\,c}{(4 \times 32.6 + 2s)} = 680 \pm 50 \text{ kHz} \qquad \ldots 3.2$$

which can be solved to find that spans of length from 156 to 192 m are expected to be strongly resonant. Similarly, in order for the two-wavelength resonant frequency of a span to lie within 50 kHz of 680 kHz, the span length must lie in the range 378 to 449 m. A span whose length is close to these ranges will show some resonant response. Thus the "nominal" span length of 363 m is "marginally resonant" because it is only 15 m different from the lower limit of the "two-wavelength loop resonance" range of span lengths. It is thus expected that the power line will have some resonant spans. The following sections investigate how much reradiation could be expected from one span, and then ask how much reradiation is expected from the power line as a whole when all the spans have the same length.

3.6 Reradiated Field from One Span

Engineers frequently enquire about the strength of the reradiated field from one span of the power line, at a distance from the broadcast antenna representative of the whole power line. Implied in the question is the idea that N times the "typical" one-span figure will give a representative figure for the whole power line. This section shows that the figure so obtained considerably overestimates the strength of the reradiated field. In the following, a single isolated span is used to illustrate the directional pattern of the reradiation from one span. Reradiation from a power line can be thought of as the phasor sum of the radiation pattern of each of the individual spans, and so the net reradiated field depends both on the directional patterns of the individual spans and on their relative phasing. These factors are well accounted for the in available power line analysis computer programs, and this Chapter sets out means to use such programs to estimate the level of the reradiated field to be expected, even though the precise positions of the towers are not known at the time of "initial assessment".

Fig. 3.4 shows an omnidirectional broadcast antenna illuminating an isolated span consisting of two power line towers and the interconnecting skywire. The span is separated from the antenna by 2300 m, which is a representative distance for the power line of Fig. 3.2, and has length 363 m, equal to the nominal span length for the power line near CHFA. The span is not oriented perpendicular to the radial line from the antenna, but instead is "skewed" at an angle of 40 degrees. The reradiation pattern of the span is shown in Fig. 3.5. The span reradiates with a "butterfly" pattern, which is tilted at the skew angle of the span. The level of reradiation from this span varies with direction, and has a maximum value of 4.64 mV/m compared to the R.M.S. level of the broadcast antenna's pattern of 590.7 mV/m. Clearly such a span would be most damaging as a reradiator if one of the four lobes of the pattern were directed into the protected arc of a directional broadcast array's pattern. The level of the reradiation from a 363 m span 2300 m distant from the antenna cannot be characterized as 4.64 mV/m, however, because the strength of the reradiated field is also dependent on the skew angle of the span. Fig. 3.6 shows the variation of the maximum value of the reradiated field pattern as a function of the skew angle, plotted as the solid curve for a 363 m span. The reradiated field is nearly zero when the span is perpendicular to the radial, with a "skew angle" of zero degrees. The reradiated "butterfly" pattern has its largest amplitude when the span is skewed at about 40 degrees, as shown in Fig. 3.4. For larger skew angles the largest value of the reradiated field drops somewhat. Fig. 3.6 also shows the variation of the maximum value of the reradiated field pattern for a 411 m span, which is resonant at the operating frequency. This resonant span reradiates much more strongly than the marginally resonant span of length 363 m. The largest reradiated field is found when the span is skewed at about 30 degrees, which makes the amplitude of the butterfly pattern about 33 mV/m compared to the R.M.S. field level of 590.7 mV/m. Clearly the level of the reradiated field is strongly dependent on the angular orientation of the span, as well as on the distance from the broadcast antenna and on the span length. This is because the resonance mode, two wavelength loop resonance, is excited only by the difference-mode component of the broadcast antenna's field. Thus when the span is perpendicular to the radial, the broadcast antenna's field has the same phase at the two power line towers, and so the difference-mode excitation is zero, and the resonance mode is not excited. But when the 411 m span is skewed at about 30 degrees, the difference in distance from the broadcast antenna to each of the two power line towers is about half a wavelength, and so the broadcast antenna's field is phased 180 degrees different at one tower compared to the other. The excitation is purely difference-mode, and so a maximum two-wavelength loop resonant response is found.

It is tempting to estimate an upper bound for the strength of the reradiated field simply by multiplying the number of spans times the maximum value of the radiation pattern from one span. Thus, considering a length of about 4.6 km of power line, with 363 m spans there will be 4,600/363 = 13 spans, times 4.64 mV/m of reradiated field from each span, for a total of about 60 mV/m of reradiated field strength relative to the antenna's isotropic level of 590.7 mV/m. This estimate is readily shown to be too large, especially for resonant spans. If an evenly-spaced line with 363 m spans is analysed with the AMPL program, as described below, it is found that the pattern of the CHFA antenna operating near the power line exceeds protection by only 15.8 mV/m. It is shown in the following that with a standard deviation of the span length of 46 m, then on the average protection is exceeded by about 30 mV/m. Thus the 60 mV/m figure is high. Similarly, for a power line with resonant 411 m spans, the largest value of the reradiated field from one span is 33 mV/m, and the simple estimate would have an 11 span power line reradiating 363 mV/m of field, whereas an evenly-spaced power line with 411 m spans causes protection to be exceeded by 74 mV/m, much less than 363 mV/m. Thus "maximum field per span times number of spans" fails as a useful estimate. This is because it assumes that the maximum value of the "butterfly" reradiation pattern will be the same for each span, whereas many spans will not be favourably skewed and will reradiate much less. Also, adding the maximum value of the reradiation pattern for each span assumes that the direction in which the maximum value occurs will coincide for each span, and this is not so. Also, the relative phase of the individual span patterns will be different, and so the patterns cannot be added without considering phase. Another objection is that all the spans will not be of the same length, because the span length is not a constant on a real power line. Also, not all the spans are illuminated at the R.M.S. field level, and so the estimate should account for CHFA's actual radiation pattern.

Two useful conclusions can be drawn from the reradiation pattern for a single span. Considering the resonant span length nearest to the given nominal span length, the largest value of the reradiated field that could possibly arise equals the maximum value of the reradiated field for the most favorable orientation of one span, times the number of spans. If this estimate of the reradiated field is so small that it represents an insignificant level of reradiation, then the power line will not be a significant reradiator. Conversely, if the largest reradiated field from one span of length equal to the nominal span length is so large that by itself it could cause the protection requirement to be exceeded, then the power line is likely to be a problem and its effect will have to be investigated further. In the case of CHFA and the southeast power line, a reradiated field as strong as 33 mV/m from only one resonant span could be enough to cause protection to be exceeded, so further investigation of the problem is called for.

3.7 Computer Model of the Power Line

Fig. 3.7(a) shows the type Z7S power line tower which is specified in the design proposal for the power lines near CHFA. This tower type has not been modelled systematically in the way that was done to develop the "single wire tower" model of the type V1S tower of Fig. 2.1. For that tower type, the resonant behaviour of the computer model was verified against the resonant behaviour of a 1 to 600 scale model of the power line, as described above in Sect. 2.3 and 2.4. The type Z7S is quite different from the type V1S and so any proposed computer model should be verified against measured behaviour. The resources for such a study were not available.

A "single wire tower" representation of the Z7S was derived in a similar fashion to the model of the V1S. The actual tower geometry of Fig. 3.7(a) is replaced by the simple tower model of Fig. 3.7(b). In this model the height of the tower is equal to the height above ground of the skywires on the actual tower, which was taken as 32.6 m. The radius of the skywire and the radius of the tower wire must be chosen.

The wire radius for the tower is chosen according to Jaggard's isoperimetric inequalities, as discussed in Sect. 2.3. Table 3.1 lists the cross-sectional size of the type Z7S tower at three heights above the ground, and gives the equivalent-area and equivalent-periphery radii for a cylindrical wire. A reasonable choice among the arithmetic mean values is a radius of 4 m for the tower wire.

The skywire radius is chosen according to Eqn. 2.1. The type Z7S tower carries two skywires at a height of 32.6 m above the ground, separated by 11.34 m. The wire radius of the skywire was estimated to be one inch, and by Eqn. 2.1, the equivalent single skywire will have a radius of 0.38 m.

Thus the wire radii for the tower model of Fig. 3.7(b) are chosen as 4 m for the tower wire and 0.38 m for the skywire. Before the power line can be analysed by AMPL or NEC to determine the azimuth pattern of the CHFA array operating in the presence of the power line, the precise location of each power line tower relative to the CHFA array must be specified. When the tower positions are known, then AMPL or NEC can be used to compute the RF current flow on the towers and skywires of the power line, and hence the azimuth pattern including reradiation from the power line.

TABLE 3.1
Type Z7S power line tower dimensions.

TOWER SECTION	DIMENSIONS m	AREA m**2	PERIPHERY m	WIRE RADII Equal Area m	Equal Periphery m	Arithmetic Mean m
base	7.45 x 7.45	55.5	29.8	4.20	4.74	4.47
mid	3.49 x 3.49	12.2	14.0	1.97	2.22	2.09
upper	3.49 x 10.94	38.2	28.9	3.49	4.59	4.00

3.8 Tests with a Uniformly-Spaced Power Line

The second stage of "initial assessment" looks at the specific case of a power line with uniformly spaced towers. The AMPL program must have, as input data, the set of coordinates giving the precise location of each power line tower relative to the broadcast antenna, and hence cannot be used to analyse the power line outlined by the construction proposal, which gives only the route and mean span length. Definite tower positions are required before AMPL can be used. A set of tower positions can be conveniently defined for a power line with uniformly-spaced towers, which is then analysed with AMPL to obtain a "ballpark figure" for the amount of reradiation.

A hypothetical power line with uniformly-spaced towers which follows the given route is readily constructed by starting at the corner of the power line southeast of the antenna in Fig. 3.2, and adding towers separated by the desired span length going north until a length of 3117 m or slightly more has been set up, and similarly by adding towers going southwest until 1500 m of power line has been built. The result is a power line along the given route, with a perfectly uniform span length, such as that shown in Fig. 3.8 for a span length of 363 m. Analysing this uniformly-spaced power line with AMPL yields the pattern shown in Fig. 3.9(a), and it is seen that there is reradiation in excess of the protection requirement near azimuth 230 degrees. Fig. 3.9(b) shows the field strength throughout the protected arc. The nominal span length of 363 m is near the resonance range of span lengths from 378 to 449 m, and reradiation into the protected arc causes protection to be exceeded by 15.8 mV/m at about 230 degrees azimuth. Even with no resonant spans on the power line, there is significant reradiation, and so there may be a problem from the proposed power line. In fact, 363 m spans are close to the resonance band of span lengths and so are not strictly "non-resonant". Since the power line will have a variable span length, it is expected that some spans will fall in the resonant range of span lengths from 378 to 449 m, and more reradiation than that shown in Fig. 3.9 is expected. By constructing an evenly-spaced power line with a resonant span length of 411 m, a "worst case" assessment can be obtained. Fig. 3.10(a) shows the azimuth pattern, and Fig. 3.10(b) gives the field strength in the pattern minimum. Large excursions above protection are seen and the protection limit is exceeded by 74.0 mV/m. The least possible reradiation is expected if the spans are all of length very different from the resonant length of 411 m. For example it was found that the field strength in the pattern minimum for a uniformly-spaced power line with 292 m tower spacing did not exceed protection, although it came within 0.1 dB of the protection limit.

Appendices 1 and 2 describe an "initial assessment" problem which was investigated using evenly-spaced power lines. Station CBO operates near Ottawa at 920 kHz, and Ontario Hydro plans to build a power line about 15 km from the antenna, which will run across the main lobe in both the "day" pattern and the "night" pattern. The proposed power line tower height of about 40 m and span length of 300 m, with a variability of 30 m in either direction, make the power line with 270 m spans resonant at 926 kHz, and so there is a potential reradiation problem. The question here is whether a long segment of the power line, illuminated by the broad main lobe, but 15 km distant from the antenna, will reradiate strongly enough to cause a violation of CBO's protection requirement. Appendix 1 discusses reradiation into the "day" pattern, which has a minimum field strength of about 16 mV/m at one mile on a broadly directional pattern with a maximum field strength in the main lobe of 2050 mV/m. Fourty spans of the power line were modelled, following the route proposed by Ontario Hydro. The power line was modelled with evenly-spaced towers, and was analysed with spans of length 270 m, 300 m and 330 m. It was found that the power line adds a ripple to the CBO pattern, and that the amplitude of the ripple is about 21 mV/m for the resonant span length of 270 m. Reradiation into the "night pattern" is investigated in Appendix 2. The main lobe of the "night" pattern, of field strength 2900 mV/m, illuminates the power line. The "night" pattern is more directional than the "day" pattern, with a broad minimum extending from azimuth 82 degrees to azimuth 246 degrees, in which the field strength is 120 mV/m, on a pattern with R.M.S.

field strength 1250 mV/m. Reradiation from the power line with 40 spans of resonant length 270 m adds a ripple to the "night" pattern of amplitude 22 mV/m. The station's protection requirements were not specified, and so it was not possible to judge whether these levels would result in violation. Thus the thrust of the "initial assessment" for the case of CBO was to obtain an estimate of the level of reradiation to be expected from the power line, and a "test" power line with a uniform span length provided a convenient model. If more detailed information about the expected level of reradiation were required, either the power line would have to be modelled with a non-uniform span length, or more detailed design information specifying the precise locations planned for the power line towers would be required.

Thus a "hypothetical" power line with evenly-spaced towers provides a useful model to obtain an estimate of the level of reradiation to be expected from a power line along a given route with a given nominal tower height and span length. The hypothetical power line should always be analysed with both the nominal span length, and with the nearby resonant value of span length. The principal objection to assessment using a power line with a uniform span length is that an evenly-spaced power line has either all spans resonant, or all spans non-resonant, and reradiates quite differently from a real power line, which has a variable span length, and so will have some spans of resonant length, and others of non-resonant length. It is primarily the resonant spans which are the reradiators. If the level of reradiation from the "hypothetical" power line is sufficiently feeble that there is not likely to be a problem, then the "initial assessment" is complete, and nothing further need be done. For the case of the CHFA antenna, the tests using an evenly-spaced power line indicate that there is a potential reradiation problem. In order to obtain an estimate of the amount of reradiation to be expected from a power line with a variable span length having the given nominal span length of 363 m, and the given span length standard deviation of 46 m, "test power lines" with a variable span length can be constructed, and a statistical approach can be used to assess the amount of reradiation to be expected. In the following, the "normal" distribution is used to estimate the likelihood of having resonant spans on the power line.

3.9 Probability of Resonant Spans

Given that the distribution of the span lengths on the power line is "normal" with mean 363 m and standard deviation 46 m, and that spans from 378 to 449 m long are resonant, then the probability that any individual span is resonant is readily calculated as the area under the "normal" density curve from 378 to 449 m. This yields a probability of 34.1 percent. Thus "on the average" 34 percent of the spans on the power line will be resonant. The segment of power line in Fig. 3.2 is about 4600 m in length, and with a mean span of 363 m, there will be, on the average, 4600/363 = 13 spans. If the probability that each individual span is resonant is about 34 percent, then "on the average", about 34 percent of 13 spans, that is, about 4 of the 13 spans will be resonant. A more precise statement than this can be made, based on the binomial expansion(28). If the probability that any individual span is resonant is p, then the probability that at least k spans out of a total of n spans are resonant is given by

$$b = \sum_{i=k}^{n} \frac{n!}{i!\,(n-i)!}\, p^{i}(1-p)^{n-i} \qquad \text{... 3.3}$$

Each term in the sum gives the probability that exactly i spans are resonant. The probability that at least k spans are resonant is thus the probability that exactly k are resonant, plus the probability that exactly (k+1) are resonant, plus ... up to the probability that exactly n are resonant. Table 3.2 shows the results obtained with this formula. If the mean span length is 363 m and the standard deviation is 46 m, then the probability that any individual span is resonant is 34 percent, or p = 0.34. Then there is better than 95 percent chance that there will be at least two resonant spans on a power line of 13 spans. Thus if 20 sample power lines of 13 spans are constructed, then 19 would be expected to have two or more resonant spans. There is a chance of about 70 percent that four spans out of the 13 are resonant, but only a 4 percent chance that 8 or more spans are resonant. Thus on any given power line, it is expected that there will be 2 or 3 or perhaps 4 resonant spans, but there is not likely to be 8 or more. Another case considered below is that of a tightly controlled span length, with a standard deviation of only 10 m on a mean value of 363 m. Then the probability that any one of the 13 spans is resonant is 7 percent. There is about a 60 percent chance of that there will be at least one resonant span on a 13 tower segment of such a power line, but it is not likely that there will be more than 3 resonant spans.

TABLE 3.2

The probability that at least k spans out of a total of 13 spans are resonant, given that the probability that any individual span is resonant is 34 percent, and 7 percent.

Minimum Number of Resonant Spans k	Probability That at Least k Spans are Resonant	
	p=0.34	p=0.07
1	99.6 %	61.1 %
2	96.6	23.0
3	87.4	5.8
4	69.8	1.0
5	47.2	0.1
6	26.1	0.01
7	11.5	0.001
8	4.0	-
9	1.0	-
10	0.2	-
11	0.02	-
12	0.002	-
13	-	-

How many resonant spans are enough to cause protection to be exceeded ? The reradiated field from one resonant span in Fig. 3.6 can be as large as 33 mV/m. Thus with a protection limit of about 20 mV/m, one resonant span with a lobe of its radiation pattern directed into the protected arc may be enough to cause protection to be exceeded. With a standard deviation of the span length of 46 m, it is very probable that there will be more than 2 resonant spans, so there is likely to be significant reradiation. A more precise answer would specify how strong this reradiation is likely to be in the protected arc, and provide an indication of how variable this is likely to be with the given span length statistics. The computer programs available for power line analysis account for all factors in the reradiation of the power line, including the excitation of each span, its response and resonant behaviour, and the relative phasing of the radiation from the various spans in the far field, and so, for a specific power line, can predict the net field strength in the protected arc, and hence determine by how much protection will be exceeded. But such programs require a knowledge of the exact locations of the towers on the power line. In the following, a random number generator is used to generate specific "test power lines" with known tower positions conforming to the given mean span length, span length standard deviation, and the "normal" distribution. In order to provide a systematic assessment of how strong the reradiated field is likely to be, many such "test lines" will be examined.

3.10 Determining the Statistics of the Reradiated Field

The given information describing the power line does not specify the exact tower locations, but instead gives a nominal value for the tower separation, and a measure of the variability of the separation of the towers. It has been demonstrated above that the span lengths on a real power line follow a "normal" distribution reasonably closely. Many different sets of base coordinates for the power line towers are possible, conforming to a "normal" distribution with the given mean and standard deviation, and without further information on the tower locations for the proposed power line, there is no way to distinguish among these many possible tower configurations. Each configuration of towers on the power line will result in a different reradiated field, depending primarily on how many resonant spans there are, and on where those resonant spans are located relative to the broadcast antenna. In this paper, a "large number" of power lines along the given route, and having span lengths conforming to the given statistics will be examined, taking advantage of the capability of the AMPL program for analysing power lines quickly and cheaply. Accordingly, a random number generator is used to generate a set of span lengths conforming to the desired mean and standard deviation, and having a "normal" distribution, and these span lengths are used to construct a sample power line or "test line" along the desired route. AMPL is then used to find the radiation pattern. If many such "test lines" are examined, then the statistics of the reradiated field can be found. It will be shown that for most "test lines", the reradiated field is strong enough to cause protection to be significantly exceeded, and so it can be concluded that the proposed power line is very likely to cause a reradiation problem.

To construct a "test line", a random number generator is used to obtain sets of span lengths with mean value 363 m and standard deviation 46 m, having a "normal" distribution. The route of the power line plus the randomly-found span lengths are used to derive the coordinates of each power line tower. In this way, "test lines" such as those shown in part (a) of Figs. 3.11, 3.12, and 3.13 are obtained. AMPL is then used to calculate the radiation pattern of the CHFA antenna operating near each "test line", and the net field strength of the CHFA antenna operating near the "test line" is plotted throughout the protected arc, as shown in part (b) of the three figures. For the power line of Fig. 3.11(a), there are 14 spans, of which 4 are of lengths in the resonance range of 378 to 449 m. Fig. 3.11(b) shows that the reradiated field from this specific "test line" is modest and protection is exceed by only 1.7 mV/m at about 203 degrees azimuth. The "test line" of Fig. 3.12(a) has 5 resonant spans out of 14 spans, and Fig. 3.12(b) shows that there is reradiation in excess of protection of about 47 mV/m at about 225 degrees azimuth. Clearly this specific "test line" reradiates unacceptably strongly. The "test line" of Fig. 3.13(a) has five resonant spans, and three spans near resonance, of lengths 367, 368 and 374 m, and is a strong reradiator. The field strength near 232 degrees azimuth is in excess of protection by 83 mV/m. These three cases show that for power lines with the given span statistics, it is possible that protection will be barely exceeded, or that it will be exceeded by a large amount. Is it likely that protection will be met or barely exceeded for most power lines of the given span statistics ? Or, conversely, would most cases give rise to fields greatly in excess of protection ? Clearly the assessment of whether protection is likely to be met for any power line of the given mean span length and span standard deviation cannot be based on the analysis of only a few "test line" configurations, because, by chance, the random number generator may have produced a power lines with few resonant spans, or with resonant spans not strongly excited, or not oriented to reradiate into the pattern minimum. The assessment must be based on many "test line" configurations. In order to assess whether, in general, a "test line" with the given statistics will cause protection to be exceeded, many such test lines must be formulated and examined. In the following, a set of 40 "test lines" has been studied.

The computer program which generated the "test lines" of Figs. 3.11, 3.12 and 3.13 will readily generate thousands of such configurations, all different. As a check, the sequences of "random" span lengths obtained from the computer random number generator were verified to have a "normal" distribution with the desired mean and standard deviation, when a large number of spans, such as 1000 or more, is examined. But any set of about 13 spans required to construct a "test line" will not, in general, have exactly the desired mean or standard deviation, even though, averaged over many spans, the desired statistics will be obtained. To ensure that results obtained from analysing "test lines" do indeed represent power lines with the desired mean span length and the desired standard deviation, even though only 40 test lines will be analysed with AMPL, the computer was instructed to calculate the mean and standard deviation of the span length for each "test line", and to throw away any test line with a mean more than 2 m different from the desired value, or a standard deviation more than 1 m different from that desired. The computer then searches through many possible test lines, sometimes hundreds of them, in order to find suitable candidates for analysis. This would not be necessary if some hundreds of "test lines" could be studied. By selecting only certain "test lines" conforming to the given span statistics, it was ensured that the lines analysed would conform to the desired statistics.

Thus tower base coordinates for 40 "test lines", all different, and all with the desired span statistics, are readily generated. Examining the collection of 40 radiation patterns obtained with AMPL would show that in the great majority of cases, protection is substantially exceeded, but in a very few cases, the protection limit is only marginally exceeded. The conclusion would be that there is likely to be a problem resulting from the construction of a power line with the given span statistics. A convenient parameter is required which can characterise each pattern in a single number. The largest excursion of the field strength above the protection limit is the important quantity in "initial assessment", and will be called the "excess field". A positive value indicates that protection is violated, whereas a negative value means that protection is met. For the "test lines" of Figs. 3.11, 3.12 and 3.13, the "excess fields" are 1.7, 47 and 83 mV/m, respectively. A few mV/m above a protection limit might not be cause for concern, whereas more than 10 mV/m of "excess field" is a serious violation of protection requirements. Table 3.3 gives the value of the "excess field" for all 40 of the test cases examined. One possible summary of all 40 patterns for the 40 "test lines" would be the largest "excess field" encountered in any of the 40 radiation patterns. Such a parameter tends to give a pessimistic evaluation of the magnitude of the problem. A better evaluation of the strength of the "excess field" is had by making a bar graph such as Fig. 3.14, classifying the "excess field" into 5 mV/m intervals. Thus, for example, 20 percent of the cases examined had an "excess field" of between 20 and 25 mV/m. The bar graph is quite spread out, with some "test lines" giving little reradiation, and some being strong reradiators. It is readily verified that 82.5 percent of the 40 "test lines" led to an excess field of more than 5 mV/m, and so it is very likely that the radiation pattern will exceed protection by at least that amount when the power line is constructed. The results of the study can be summarized by computing the mean value for the excess field, which is 29.8 mV/m, and the standard deviation of the excess field, which is 22.5 mV/m, for the 40 cases studied. Thus in Fig. 3.14, 75 percent of the cases studied lie within one standard deviation of the mean. Given that the mean excess field is as high as 29.8 mV/m, then it is likely that construction of the power line, with the given span statistics, will change CHFA's pattern such that the protection requirement will be substantially exceeded. The station management would do well to intervene.

TABLE 3.3

The value of the excess field for the 40 "test lines" analysed, for the case of mean span length 363 m, and span standard deviation 46 m. The mean excess field is 29.8 mV/m, and the standard deviation is 22.5 mV/m.

Test Line Number	Excess Field	Test Line Number	Excess Field
1	1.7 mV/m	21	47.3 mV/m
2	47.3	22	37.4
3	83.1	23	2.7
4	52.5	24	50.2
5	24.9	25	52.1
6	17.6	26	31.0
7	71.7	27	52.4
8	17.5	28	3.2
9	5.0	29	20.1
10	6.5	30	32.2
11	8.9	31	24.7
12	28.4	32	82.5
13	20.3	33	20.1
14	50.0	34	4.9
15	11.5	35	5.1
16	4.4	36	31.4
17	26.5	37	26.0
18	51.7	38	1.6
19	65.1	39	25.4
20	22.1	40	24.8

3.11 Span Statistics - Tightly Controlled Span Length

It is of interest to enquire about the mean value and the standard deviation of the "excess field" for other mean span lengths, and for other standard deviations. Does a non-resonant choice for the mean span length lead to inconsequential levels of reradiation ? How much variation in the span length can be tolerated, such that reradiation is kept to a sufficiently low level ? In the following, three nominal span lengths will be examined, namely, non-resonant, marginally resonant and strongly resonant, and for each mean span, the span length will be either tightly controlled with a small standard deviation, or allowed to vary widely with a large standard deviation. It will be shown that even if the nominal span length is non-resonant, reradiation can still be significant if the span length is not maintained close to the nominal value.

If the span length is tightly controlled, then the standard deviation of the span length will be small. To study this case, a standard deviation of 10 m was chosen, and "test" power lines were constructed with a non-resonant mean span length of 292 m, a marginally-resonant mean span length of 363 m, and a resonant mean span length of 411 m. In each case, 20 test lines were formulated and analysed with the AMPL computer program. Tables 3.4, 3.5, and 3.6 show the value of the excess field in each case. The results shown in the Tables are summarized in the bar graphs of Figs. 3.15, 3.16 and 3.17.

TABLE 3.4

The value of the excess field for the 20 "test lines" analysed, for the case of mean span length 292 m, and span standard deviation 10 m. The mean excess field is 0.04 mV/m, and the standard deviation is 0.5 mV/m.

Test Line Number	Excess Field	Test Line Number	Excess Field
1	-0.52 mV/m	21	-0.14 mV/m
2	0.60	22	-0.20
3	0.12	23	0.16
4	0.26	24	-0.84
5	-0.10	25	0.86
6	0.26	26	0.68
7	-0.50	27	-0.08
8	0.88	28	-0.40
9	-0.28	29	0.70
10	-0.24	30	-0.34

Table 3.4 shows the values of the excess field obtained with a non-resonant mean span length of 292 m, and a small standard deviation of 10 m, making most span lengths fall near 292 m. All values in Table 3.4 fall within 1 mV/m of zero excess field, and so the power line causes at most excursions of less than 1 mV/m above the protection requirement. It is not likely that such small deviations can be measured with confidence. The corresponding bar graph, Fig. 3.15, shows all 20 cases clustered about zero value for the excess field, and so if the mean span length is non-resonant and the span length is tightly controlled, there is little reradiation and the power line does not pose a significant reradiation problem.

TABLE 3.5

The value of the excess field for the 20 "test lines" analysed, for the case of mean span length 363 m, and span standard deviation 10 m. The mean excess field is 20.9 mV/m, and the standard deviation is 6.4 mV/m.

Test Line Number	Excess Field	Test Line Number	Excess Field
1	22.1 mV/m	11	14.2 mV/m
2	21.1	12	26.1
3	28.1	13	20.6
4	29.5	14	13.3
5	16.5	15	17.2
6	32.3	16	17.5
7	26.6	17	22.5
8	31.4	18	19.4
9	13.1	19	11.9
10	13.6	20	20.1

Table 3.5 shows the values of the excess field from 20 azimuth patterns for 20 different power lines, with a "marginally resonant" mean span length of 363 m, and a tightly controlled span length. Thus, 68 percent of the span lengths lie from 353 to 373 m, and 95 percent from 343 to 383 m, and so some spans in the resonance range from 378 to 449 m are possible. This is reflected in the data of Table 3.5, showing much higher excess field values than for the non-resonant mean span of 292 m. Fig. 3.16 shows that all these "test" power lines gave rise to reradiation in excess of protection, and that 75 percent of the cases studied exceeded protection by more than 5 mV/m. Thus, a non-resonant value of the mean span length, 363 m, is not sufficient to ensure insignificant levels of reradiation, even if the span length is tightly controlled, because a few resonant spans are still possible.

Table 3.6 shows the excess field values obtained when the mean span length is a resonant value, 411 m, and the span length is tightly controlled to ensure that 95 percent of span lengths lie in the range 381 to 431 m, so that nearly all the spans are of resonant length. This is a "worst case". Protection is exeeded in all cases by at least 30 mV/m, and by as much as 81.2 mV/m in one individual case. Fig. 3.17 shows that the distribution of excess field values is spread fairly uniformly from 30 to 75 mV/m. Thus if most spans are of resonant length, the power line will reradiate significantly.

TABLE 3.6

The value of the excess field for the 20 "test lines" analysed, for the case of mean span length 411 m, and span standard deviation 10 m. The mean excess field is 51.9 mV/m, and the standard deviation is 15.4 mV/m.

Test Line Number	Excess Field	Test Line Number	Excess Field
1	60.6 mV/m	10	47.7 mV/m
2	55.2	12	31.4
3	49.9	13	74.1
4	65.9	14	43.2
5	45.6	15	39.0
6	46.5	16	43.8
7	51.1	17	81.2
8	32.3	18	69.9
9	74.3	19	34.0
10	60.4	20	30.5

TABLE 3.7

The value of the excess field for the 40 "test lines" analysed, for the case of mean span length 292 m, and span standard deviation 46 m. The mean excess field is 8.3 mV/m, and the standard deviation is 10.1 mV/m.

Test Line Number	Excess Field	Test Line Number	Excess Field
1	2.9 mV/m	21	27.2 mV/m
2	-1.7	22	3.1
3	-0.1	23	4.4
4	14.6	24	-0.6
5	3.6	25	2.1
6	5.8	26	4.7
7	2.2	27	2.3
8	23.6	28	4.9
9	9.2	29	30.1
10	14.7	30	3.6
11	-0.4	31	10.9
12	7.4	32	-0.2
13	0.0	33	20.3
14	13.5	34	3.3
15	11.6	35	41.1
16	0.3	36	31.6
17	5.7	37	4.0
18	7.1	38	0.3
19	1.8	39	9.6
20	5.0	40	2.1

TABLE 3.8

The value of the excess field for the 40 "test lines" analysed, for the case of mean span length 411 m, and span standard deviation 46 m. The mean excess field is 31.2 mV/m, and the standard deviation is 13.7 mV/m.

Test Line Number	Excess Field	Test Line Number	Excess Field
1	33.5 mV/m	21	45.2 mV/m
2	18.6	22	63.2
3	22.4	23	69.5
4	21.6	24	17.2
5	36.0	25	17.0
6	16.6	26	21.4
7	9.7	27	16.8
8	12.4	28	19.5
9	46.1	29	45.7
10	34.6	30	43.9
11	35.9	31	16.8
12	17.4	32	22.3
13	34.1	33	58.5
14	57.9	34	38.5
15	23.8	35	23.3
16	34.7	36	32.4
17	33.3	37	24.9
18	18.2	38	20.3
19	43.9	39	43.2
20	21.6	40	33.6

3.12 Span Statistics - Realistic Span Length Variability

The foregoing has shown that the actual power lines built near the CHFA antenna have a highly variable span length, with a standard deviation of 46 m, and so do not constitute a "tightly controlled" situation. Table 3.3 studied the case of a mean span length of 363 m, with a standard deviation of 46 m, and concluded that in this case there is a high probability of resonant spans and so a significant reradiated field is in excess of protection by, on the average, 29.8 mV/m. If the mean span length is chosen to be far from resonance, say 292 m, will reradiation be a problem if the span length is relatively uncontrolled, with a standard deviation of 46 m ? Table 3.6 shows the value of the excess field in each case for CHFA operated near 40 different "test power lines". It is seen that most values are between -5 and 15 mV/m, with a few higher values, the largest being 41.1 mV/m. Fig. 3.18 shows the corresponding bar graph. If excursions of more than 5 mV/m above the protection limit are considered a serious cause for concern, then 18 out of 40 of the "test power lines", or 45 percent, are significant reradiators.

Thus even if the mean span length is far from resonance, at 292 m, the power line is not guaranteed to be "safe" from reradiation, because, if the span length is poorly controlled with a large standard deviation, then there will be spans of resonant length and those spans will cause significant reradiation.

It might be considered, since the mean span length for the power line proposed for construction near CHFA, namely 363 m, is outside the resonance range of 378 to 449 m, that the proposed line is less likely to be a significant reradiator than a line with a resonant mean span length such as 411 m. This is readily demonstrated to be false, for the case of a realistic standard deviation for the span length of 46 m. Thus the excess field seen in 40 azimuth patterns for CHFA operated near each of 40 "test power lines", of mean span 411 m and standard deviation 46 m, is given in Table 3.8, and can be compared with the data of Table 3.3. Fig. 3.19 shows the corresponding bar graph, and it is seen that the excess field values are more tightly grouped around the mean in Fig. 3.19 compared to Fig. 3.14, but that the average value of the excess field is almost the same, being 31.2 mV/m with a mean span of 411 m, and 29.8 for the mean span equal to 363 m. Thus when the span length is permitted to be highly variable, it makes little difference whether the mean span lies inside the resonance range of span lengths or merely "close" to the resonance range, namely within 1 standard deviation.

TABLE 3.9

The mean value of the excess field and its standard deviation are given for six combinations of nominal span length and span length standard deviation.

Case	Span Length metres Mean	Span Length metres Std. Dev.	Probability that any span is resonant	Excess Field mV/m Mean	Excess Field mV/m Std. Dev.
Non-Resonant	292	10	0.1 %	0.04	0.5
		46	3.0	8.3	10.1
Marginally Resonant	363	10	6.7	20.9	6.4
		46	34.1	29.8	22.5
Resonant	411	10	99.9	51.9	15.4
		46	55.9	31.2	14.7

3.13 Relation of Span Statistics to the Excess Field

The foregoing has presented the behaviour of the reradiated field for six cases, and the data is summarized in Table 3.9. The mean span length and span length variability are directly related to the probability that there will be resonant spans on the power line, which is then related to the level expected for the reradiated field.

Fig. 3.20 shows the result of constructing the power line with a tightly controlled span length, such that the standard deviation of the span length is only 10 m. Assuming the "normal" probability distribution for the span lengths, 68 percent of the span lengths lie within 10 m of the mean span length, and 95 percent of all span lengths are within 20 m of the nominal value. The lower part of Fig. 3.20 shows the probability density curve for the span length for three cases, with mean span lengths of 292, 363 and 411 m. For the small standard deviation of 10 m, the "normal" distribution is tall and narrow. The probability of having a resonant span is equal to the area under the probability density curve from 378 to 449 m. If the mean span length has the non-resonant value of 292 m, the small standard deviation makes the value of the "normal" density curve negligible throughout the resonance range of span lengths, and so the probability of resonant spans is less than 0.1 percent, and the effect of the power line on CHFA's pattern is very small. Averaged over 20 "test lines", the excess field in this case has a mean value of only 0.04 mV/m, with a standard deviation of 0.5 mV/m. Protection is exceeded, but by negligible amounts. If the mean value of the span length of the power line is near resonance, such as 363 m, then the standard deviation of 10 m is such that the "normal" density curve overlaps the resonance region, and the probability that any span is resonant is about 7 percent, and there will be, on the average, at least one resonant span on the 13 span "test line", as shown in Table 3.2. Whether that resonant span is a damaging reradiator depends on where it falls in the power line, which determines whether it is strongly or weakly illuminated by CHFA's pattern, and also determines the phase relationship of the excitation field at the two towers of the span. Averaged over 20 "test lines", the excess field is found to have a mean value of about 21 mV/m, with a standard deviation of 6.4 mV/m. Protection is thus likely to be exceeded, and there is cause for concern, even though the mean span length is non-resonant and the span length is tightly controlled. Thus the length of 363 m can be termed "marginally resonant" because the normal probability curve substantially overlaps the resonance range of span lengths, giving a 7 percent probability of resonant spans. If the mean span length is itself resonant, such as 411 m, then the probability that any span is resonant is about 50 percent, and, averaged over 20 "test lines", the mean excess is found to be 52 mV/m with a standard deviation of 15 mV/m. This is a "worst case". Clearly a resonant value for the "nominal" span length for the power line should be avoided. Evidently, to avoid significant reradiation, the mean span length should be chosen so that the "normal" distribution does not significantly overlap the resonant range of span lengths.

Fig. 3.21 shows the results obtained with various mean span lengths using the actual standard deviation of 46 m for the power line eventually built near the CHFA antenna. In this case, 68 percent of the span lengths lie within 46 m of the mean, and 95 percent of the span lengths are within 92 m of the mean. Thus the span lengths are spread out over a considerable range of values. The "normal" distribution is very broad, and covers a range of span lengths hundreds of metres wide. Evidently, it is not possible to choose the mean span length such that no part of the "normal" distribution overlaps the resonance range of span lengths. If the mean span length is far from resonance, such as 292 m, then the large standard deviation causes the "tail" of the normal distribution to overlap the range of resonant span lengths, and there is a 3 percent chance that any span on the power line is resonant. The excess field, averaged over 40 such "test lines", has a value of 8.3 mV/m with a standard deviation of 10 mV/m. In some cases the power line causes no problem with CHFA's pattern, but in well over half the cases studied, protection is violated by more than 5 mV/m, and there is cause for concern. Thus a "nominal" span length far from a resonant value does not necessarily assure low reradiation, if the variability of the span length is large. If the mean span length is 363 m, it is "marginally resonant" because the "normal" probability density curve substantially overlaps the range of resonant span lengths and there is a 34 percent chance that any span on the power line is resonant. The excess field has mean value 29.8 mV/m with a standard deviation of 22.5 mV/m. Thus a mean span length chosen just outside the resonance range of 378 m to 449 m does not assure low reradiation. If the mean span length is chosen to be resonant, at 411 m, then the situation is not much worse. The probability that any individual span is resonant is about 56 percent, and the excess field is found to have mean value 31.1 mV/m and standard deviation 14.7 mV/m. Clearly, in order to avoid resonant spans, the mean span length and especially the standard deviation of the span length must be chosen such that the "normal" distribution has a negligible value throughout the resonance range of span lengths.

3.14 Conclusions

This Chapter has examined the problem of assessing whether the construction of a proposed power line near a broadcast antenna is likely to cause the antenna to radiate in excess of its protection limits. The power line proposal specifies a route, and a nominal value for the span length and tower height, and an estimate of the variability of the span length can be obtained from similar power lines. The "initial assessment" procedure set out in this paper has three stages. The resonant frequencies of the power line are estimated using simple formulae, and the probability that there will be resonant spans on the power line is evaluated by modelling the variablility of the span length using a "normal distribution". Table 3.9 shows that a probability that any span is of resonant length of as low as three percent can lead to significant levels of reradiation, if the protection requirement is severe. The second stage of "initial assessment" uses a computer model of the power line with perfectly evenly-spaced towers, using the nominal span length, and also using nearby resonant values for the span length. If the levels of reradiation from such "evenly-spaced" test lines are insignificant even for resonant span lengths, then the power line is not likely to be a significant reradiator. This is possible if the power line is quite far away from the antenna, such as 20 kilometers or more, or if the power line lies in a broad minimum of the directional pattern. The third stage of "initial assessment" recognises that the levels of reradiation from a power line with perfectly uniformly-spaced towers can be misleading, especially if the nominal span length is non-resonant but close to a resonant value. The third stage consists of constructing a set of "test power lines" having randomly-distributed span lengths with the given mean value and standard deviation, and a "normal" distribution, and analysing each with the AMPL program. The resulting set of radiation patterns characterise the behaviour of the antenna near a power line with the given span statistics and route, and can be used to compile statistics on the amount of reradiation to be expected. Thus for the case of CHFA, if the field strength in excess of the protection requirement is significantly large for most of the "test lines" analysed with AMPL, then the actual power line is also likely to be a significant reradiator.

In some cases it may be possible to obtain from the power utility, prior to construction, a detailed initial design of the power line, including a precise position and height for each tower, usually presented in the form of terrain profiles designed to verify that the power-carrying wires remain sufficiently high above any structures, roads or buildings. Some tower positions may be adjusted upon installation, and it is important to be aware of how variable each tower position could be. Such detailed information makes the problem of "initial assessment" in this case much more deterministic than that discussed above, because the detailed design makes the tower positions known to within 5 or 10 m in every case. The given design can be analysed for resonant span lengths and for spans which would become resonant if the towers were shifted in position by a small amount. AMPL can be used to determine the pattern of the broadcast antenna near the power line with the given specific tower positions, and also with derived tower positions obtained by shifting towers to obtain resonant spans, as a "worst case". Clearly a more definite answer to whether the power line will cause objectionable reradiation can be obtained when a definite design for the power line is made available.

The results of this Chapter suggest that reradiation from the power line could be limited by controlling the span length on the power line such that no resonant spans will be present. Table 3.9 shows that a non-resonant value for the mean span length in a power line construction proposal is no assurance that reradiation will be negligible. It is just as important that the standard deviation of the span length is such that no significant part of the "normal" distribution overlaps the resonance range. Even a very small probability of resonant spans can lead to significant reradiation if the protection limit is far below the effective field strength of the antenna, such as 30 dB down for CHFA. Thus in CHFA's case, Table 3.9 shows that with a non-resonant mean span of 292 m, but with a large standard deviation of 46 m, the probability that any span is resonant is only 3 percent, yet the protection limit is likely to be significantly exceeded, by 8.3 mV/m, and the power line is potentially a problem. Evidently, the span length will have to be more tightly controlled, or else the designers of the power line will need to be instructed to avoid span lengths in certain ranges. If this increases the number of towers on the power line, it may be more expensive than installing detuning measures later.

A second conclusion concerns the assessment of a potential reradiation problem based on an evenly-spaced power line. If a "test line" is constructed using evenly-spaced towers, then a span length of 363 m leads to an excess field of 15.8 mV/m, and a resonant span length of 411 m leads to an excess field of 74.0 mV/m. In comparison with Table 3.9, both of these figures are misleading. With the span length of 363 m, and a realistic standard deviation of 46 m, the excess field has a mean value of 29.8 mV/m, much worse than the 15.8 mV/m figure obtained using a uniform span length of 363 m for the "test line". The reason for this is that some resonant spans will almost always be present on the power line when the span length is variable with the given statistics, and resonant spans reradiate strongly. Yet the evenly-spaced power line has no resonant spans. Conversely, with uniformly spaced towers 411 m apart, the "test line" reradiates such that the excess field is 74.0 mV/m, which is larger that that obtained in most cases with a variable span length of standard deviation 46 mV/m. The evenly-spaced line makes the situation seem worse than it actually is likely to be, because it has more resonant spans than the power line with a variable span length. Thus an evenly-spaced power line may provide a quick indication of the order of magnitude of a reradiation problem, if it is analysed for several span lengths, including the mean span length and nearby resonant lengths. But if a significant level of reradiation is found, then further investigations should be carried out using a realistic power line with a non-uniform span length, by the statistical technique described above.

In the study presented in this Chapter, two "arbitrary" decisions were made. The first concerned the length of the section of power line which was modelled, illustrated in Fig. 3.2

and taken to be about 4600 m or 13 times the mean span length. In general as much power line as possible should be modelled. The section of power line closest to the antenna is likely to reradiate most strongly. The strength of the reradiated field declines in proportion to 1/distance from the broadcast antenna, so more distant spans generally reradiate less. An exceptional case could arise where the closest section of the line lies in the pattern minimum, and more distant sections are much more strongly illuminated by the directional pattern. Another possibility is that the power line is quite far from the broadcast antenna, and several tens of kilometers of power line are uniformly illuminated. It is possible to represent upwards of 40 spans with the AMPL computer program, and the present study could be extended to model the power line east of the broadcast antenna, if there were doubt about whether a problem is likely to exist.

The second "arbitrary decision" concerns the number of "test power lines" to examine in compiling statistics about the reradiated field. A well-known theorem of elementary statistics(28) states that if a sample of N "test lines" is used to determine an estimate $\overline{x}$ of the true mean value of the excess field $\overline{e}$, then the standard deviation of the estimate $\overline{x}$ is $\sigma_e / \sqrt{N}$, where σ_e is the true value of the standard deviation of the excess field. Thus as the number N of "test lines" examined is increased, the estimate $\overline{x}$ becomes closer and closer to the true value $\overline{e}$, and the standard deviation $\sigma_e / \sqrt{N}$ of the estimate tends to zero. Thus for a case where the standard deviation of the excess field is expected to be "small", say 5 mV/m, then a sample of N = 20 test lines determines the mean value of the excess field with a standard deviation of about 1 mV/m, and a lot of confidence can be placed in the estimate $\overline{x}$ of the true mean value $\overline{e}$. For a "large" standard deviation, such as 20 mV/m, a larger sample of 40 "test lines" determines an estimate $\overline{x}$ of the mean $\overline{e}$, with a standard deviation of about 3 mV/m. To achieve a standard deviation of x as low as 1 mV/m, 400 test line would have to be examined. Fortunately it is not necessary to know the mean $\overline{e}$ of the excess field to great accuracy, for if the mean value of the excess field is several tens of mV/m above protection then a few mV/m in either direction makes little difference.

If the "initial assessment" procedure determines that the proposed power line is likely to be a significant reradiator, the broadcastor will want to measure the azimuth pattern of the broadcast array as accurately as possible so that it can be used as a reference to demonstrate that the pattern is significantly changed by the construction of the power line. Once the line is constructed, the broadcastor can follow up the problem by measuring the pattern of the broadcast antenna near the "as-built" power line, and by obtaining the precise "as-built" locations of the power line towers, for analysis by computation to determine which spans reradiate significantly, as described in the following Chapter.

CHAPTER FOUR

AS-BUILT ASSESSMENT

4.1 Introduction

Once a power line has been constructed, the actual "as-built" locations of the towers can be obtained from the hydro utility, and are generally known to high precision. "As-built" assessment consists of determining the radiation pattern of the broadcast antenna near the "as-built" power line, and identifying those spans of the power line which are resonant and carry strong RF current flow. The actual radiation pattern of the broadcast antenna operating in the presence of the power line should be measured as precisely as possible, as discussed in Refs. (13) and (14). The RF current flowing on each tower of the power line can also be measured, and will clearly indicate which towers are strong reradiators. The "as-built" tower locations can be used in a pencil-and-paper analysis of the resonant frequencies of the "as-built" power line. Those spans which are of resonant length at the broadcast antenna's operating frequency are potentially the strongest reradiators. The "as-built" tower positions and heights can be incorporated into a computer model of the power line, which is then used to determine the azimuth pattern of the broadcast antenna operating near the power line, and to determine the RF current flow on the towers and skywires. The RF current is a good indicator of which spans on the power line are the primary reradiators, and it will be seen that some of the resonant spans on the power line carry substantial RF current flow. Those spans are candidates for "detuning". This Chapter illustrates "as-built assessment" for the case of the CHFA broadcast array, and the "north" and "southeast" power lines.

The material in this Chapter and the next are extracted from reports prepared for the Canadian Broadcasting Corporation, Refs. (5) and (6), which dealt with the "as-built" assessment of the reradiation from the two power lines near CHFA, and with the selection of towers for isolation from the skywire to detune the two power lines. These two reports followed up work done for the CBC in 1980, Refs. (30) and (31), which assessed the reradiation from the "proposed" power lines, using evenly-spaced towers on the two power lines.

4.2 "As-Built" Power Lines

Station CHFA, operating at 680 kHz near Edmonton, must maintain a radiation pattern which is severely restricted from azimuth angles 165 to 236 degrees, and as shown in Fig. 3.1. Fig. 4.1(a) is a plan of the "as-built" north and "southeast" power lines, showing the location of the CHFA array in relation to the routes of the two power lines, and showing the numbering system used by TransAlta, the power utility, to identify the power line towers. The figure shows a complex site with a total of 49 towers shown on the 1202 "north line", and 56 towers on the 1209 "southeast" line. This Chapter deals with the prediction by computation of the radiation pattern of station CHFA, radiating in the presence of the "north" and the "southeast" line. Fig. 4.1(b) is a computer-generated view of the site. Tables 4.1 and 4.2 give the heights of the power line towers, and give their positions relative to the centre tower of the CHFA array. The data was derived from maps supplied by Trans-Alta(32).

It is of interest to compare the "as-built" locations of the power line towers with those generated for the purpose of assessing potential reradiation from the power line, in Refs. (30) and (31). In those reports, evenly-spaced towers were used, with a 363 m span length, following simple straight-line paths. Figs. 4.2 and 4.3 compare the "as-built" tower positions with those used for "initial assessment". It is seen that the "as-built" route is, in each case, similar to the "proposed" route, with minor variations introduced to accomodate local terrain features. The significant difference between the "proposed" and the "as-built" power lines is that the span lengths are far from uniform on the "as-built" power lines. Thus Figs. 4.4 and 4.5 show the span lengths, which vary from 236 to 555 m. The distribution of span lengths has already been examined in Fig. 3.3, and found to approximately follow a "normal" probability distribution. The mean span length was computed as 358.4 m, quite close to the "proposed" nominal value of 363 m, but the span length is highly variable, with a standard deviation of 45.9 m. The most significant consequence of a non-uniform span length is that each span on the power line has its own individual resonant frequency, and that some of those resonant frequencies will be close to CHFA's frequency. The consequences of a variable span length have been explored in Chapter 3 above, and are discussed in detail for this specific situation in this Chapter and in the following Chapter.

TABLE 4.1

Tower base coordinates, heights and distances from the CHFA array's centre tower for the towers of the "north" power line.

Tower Number	North m	West m	Height m	Distance m
194	3047	-9922	38.6	10380
193	3046	-9676	36.0	10144
192	3044	-9282	35.7	9769
191	3043	-8876	32.6	9383
190	3041	-8489	35.8	9018
189	3040	-8110	35.8	8661
188	3038	-7782	35.6	8354
187	3037	-7436	32.4	8033
186	3267	-7166	36.0	7875
185	3463	-6935	32.4	7751
184	3427	-6381	38.6	7243
183	3400	-5981	38.6	6880
182	3374	-5579	38.6	6519
181	3352	-5235	39.0	6216
180	3321	-4776	35.6	5818
179	3200	-4472	39.0	5499
178	3062	-4128	33.0	5140
177	2911	-3749	32.2	4747
176	2861	-3466	36.0	4494
175	2784	-3035	35.4	4119
174	2709	-2612	35.8	3763
173	2814	-2323	35.8	3650
172	2931	-2006	35.8	3552
171	3043	-1701	29.8	3486
170	3236	-1459	32.6	3550
169	3466	-1253	32.6	3686
168	3767	-1100	34.8	3924
167	4135	-913	38.6	4234
166	4351	-818	35.5	4427
165	4675	-677	35.8	4723
164	5026	-523	31.1	5054
163	5334	-389	32.7	5349
162	5623	-263	32.6	5629
161	5643	97	34.4	5645
160	6166	504	33.4	6186

TABLE 4.1 continued

Tower Number	North m	West m	Height m	Distance m
159	6171	768	33.0	6219
158	6180	1177	39.0	6291
157	6186	1487	32.8	6363
156	6194	1834	31.0	6460
155	6201	2189	32.8	6576
154	6209	2545	33.0	6710
153	6217	2910	32.8	6864
152	6225	3282	35.8	7037
151	6232	3609	35.7	7202
150	6242	4028	35.9	7429
149	6250	4362	32.0	7622
148	6259	4716	33.0	7836
147	6267	5057	31.4	8053
146	6273	5368	32.6	8257

On a "real" power line with non-uniformly spaced towers, such as those near CHFA, each span on the power line has a different length, and so each span has its own resonant frequency. Those spans whose resonant frequency is close enough to 680 kHz that the bandwidth of the resonance mode includes 680 kHz can be excited to resonance by the CHFA array, and may carry strong RF currents. Thus the resonant frequencies of the individual spans are of considerable interest, and are listed in Tables 4.3 and 4.4. The frequencies have been estimated using Eqn. 2.7. The bandwidth of resonance has been discussed in Sect. 2.4 above, and a "rule of thumb" estimate of 100 kHz has been proposed. For the present purpose it is desired to identify all those spans of the power line which could carry even small resonant current distributions, so the bandwidth estimate will be extended to include a frequency band extending 60 kHz on either side of the resonant frequency of the span. In Tables 4.3 and 4.4, those spans with resonant frequencies that are within 60 kHz of 680 kHz have been marked with a "*". Thus on the "north" line, spans 193-192-191-190-189, 184-183-182, 179-178-177, 176-175-174, 168-166, 165-164, 159-158, 153-152, and 151-150 are two-wavelength loop resonant near enough to 680 kHz that they may possibly be excited by the broadcast antenna, and so may carry strong RF currents. In addition, span 161-160 has its three-wavelength loop resonance at 666 kHz and is a potential reradiator. On the "southeast" power line, spans 198-197-196-195-194, 184-183-182, 181-180-179-178, 176-175, 167-166, 165-164, 161-160, 158-157, 156-155, 153-152, 150-149, 148-147-146, and 144-144 are potential reradiators.

TABLE 4.2

Tower base coordinates, heights and distances from the CHFA array's centre tower for the towers of the "southeast" power line.

Tower Number	North m	West m	Height m	Distance m
199	2949	-9922	38.6	10351
198	2948	-9676	35.8	10115
197	2947	-9282	36.0	9738
196	2945	-8876	32.8	9351
195	2943	-8489	36.0	8984
194	2942	-8110	35.4	8627
193	2941	-7782	35.8	8319
192	2939	-7424	32.8	2984
191	3177	-7144	36.0	7818
190	3365	-6923	32.6	7697
189	3329	-6381	35.4	7197
188	3307	-6038	38.8	6884
187	3276	-5579	38.8	6470
186	3254	-5236	38.8	6164
185	3224	-4780	35.8	5766
184	3105	-4483	36.0	5454
183	2968	-4140	32.8	5094
182	2815	-3757	34.8	4695
181	2764	-3470	39.0	4436
180	2688	-3039	39.0	4057
179	2623	-2677	39.0	3748
178	2452	-2276	31.0	3345
177	2140	-2276	37.6	3124
176	1839	-2278	35.6	2927
175	1408	-2279	35.8	2679
174	1045	-2281	32.2	2509
173	687	-2282	32.8	2383
172	329	-2283	35.9	2307
171	-28	-2283	34.8	2283
170	-391	-2283	32.4	2316
169	-620	-2056	32.2	2148
168	-849	-1829	32.8	2016
167	-1078	-1601	34.6	1930
166	-1289	-1280	33.0	1817
165	-1549	-1030	36.0	1860
164	-1816	-774	33.0	1974
163	-2056	-543	35.2	2127
162	-2297	-312	33.0	2318
161	-2536	-83	32.2	2537
160	-2826	179	37.0	2832

TABLE 4.2 continued

Tower Number	North m	West m	Height m	Distance m
159	-3068	397	36.7	3094
158	-3311	615	35.8	3367
157	-3609	883	33.5	3715
156	-3850	1101	32.6	4004
155	-4139	1361	32.6	4357
154	-4408	1603	32.6	4691
153	-4681	1849	32.6	5033
152	-4964	2103	32.6	5391
151	-5237	2349	32.6	5740
150	-5503	2588	32.6	6081
149	-5781	2839	32.6	6441
148	-6036	3068	32.6	6771
147	-6374	3332	32.6	7193
146	-6685	3611	32.6	7598
145	-6955	3853	32.6	7951
144	-6976	4257	32.8	8173

Other resonance modes exist on the power line and could be excited if the resonant frequency is close enough to 680 kHz. The most likely candidate is "four-wavelength double span resonance", with the current distribution illustrated in Fig. 2.11. This resonance mode has a current maximum at the location of the centre tower of the double-span, hence a voltage minimum at that point, and so the tower does not "short out" the electric field, which is small at the voltage minimum. Table 4.5 gives the double-span resonant frequencies of the "north" power line, estimated using Eqn. 2.7. Only "four-wavelength loop resonance" is likely to be present on the double-spans of the power line when all the power line towers are connected to the skywire, because the centre tower of the double-span "shorts out" the voltage-maximum in the standing wave pattern associated with either three- or five-wavelength double-span loop resonance. In Table 4.5, those double spans resonant in the frequency range 620 to 740 kHz have been marked with an asterisk, and are potentially reradiators. Those which are resonant within 20 kHz of 680 kHz have been marked with two asterisks. Thus double-spans 186-184, 176-174 and 161-159 could carry strong RF currents associated with "four-wavelength double-span loop resonance". Table 4.6 gives the double-span resonant frequencies for the "southeast" power line, and shows that double-span 190-188 is resonant closest to 680 kHz and could be a strong reradiator in the four-wavelength double-span loop resonance mode.

TABLE 4.3

Span lengths, and resonant frequency estimates for the "north" power line. Starred spans are resonant within 60 kHz of CHFA's frequency of 680 kHz.

SPAN Tower to Tower		Span Length m	RESONANT One-wavelength loop resonance kHz	FREQUENCIES Two-wavelength loop resonance kHz
194	193	246	505	1010
193	192	394	348	* 695
192	191	406	341	* 683
191	190	387	355	* 711
190	189	379	359	* 719
189	188	328	405	811
188	187	346	391	782
187	186	355	382	765
186	185	303	436	872
185	184	555	259	517
184	183	401	339	* 677
183	182	403	337	* 674
182	181	344	384	768
181	180	460	303	606
180	179	328	402	804
179	178	370	366	* 733
178	177	408	342	* 684
177	176	288	454	909
176	175	437	318	* 637
175	174	430	323	* 646
174	173	308	426	853
173	172	338	395	790
172	171	324	416	831
171	170	310	435	869
170	169	309	433	865
169	168	337	400	801
168	167	413	333	* 666
167	166	236	522	1044
166	165	353	382	763
165	164	384	359	* 718
164	163	336	405	810
163	162	315	426	851
162	161	360	379	758
161	160	662	222	* 444 (666)
160	159	264	490	980

TABLE 4.3 continued

SPAN Tower to Tower		Span Length m	RESONANT One-wavelength loop resonance kHz	FREQUENCIES Two-wavelength loop resonance kHz
159	158	409	337	* 673
158	157	310	424	848
157	156	347	394	788
156	155	355	387	773
155	154	356	384	768
154	153	365	376	752
153	152	372	367	* 735
152	151	328	405	810
151	150	419	330	* 660
150	149	334	403	806
149	148	354	386	773
148	147	341	399	799
147	146	311	432	863

Triple-span loop resonance modes are shown in Fig. 2.12. It is seen that "six-wavelength triple-span loop resonance" tends to put the two centre towers of the triple-span at current maxima in the standing wave pattern, hence at voltage minima, and so the resonance mode can exist on the power line with all towers connected to the skywire. Other triple-span modes tend to be "shorted out" by the centre towers. Table 4.7 gives the triple-span loop resonance frequencies of the "north" power line. Most "six-wavelength" resonant frequencies are too high to be excited at CHFA's frequency of 680 kHz. However, triple-spans 185-182, 163-160 and 161-158 are "six-wavelength" resonant close enough to CHFA's frequency to be excited. Table 4.8 gives the triple-span loop resonant frequencies for the "southeast" line. Triple-span 190-187 is resonant close enough to 680 kHz to be a potential reradiator in this resonance mode.

4.3 Model of the Power Line

The CHFA broadcast array was modelled with the NEC program in Ref. (30) and the azimuth pattern, shown in Fig. 3.1 was verified to be close to that specified by the CBC. The computer model of the power line was discussed in Sect. 3.7 above. The computer model uses 2 "segments" on each power line tower and about 10 "segments" on each skywire, for a total of about 12

TABLE 4.4

Span lengths, and resonant frequency estimates for the "southeast" power line. Starred spans are resonant within 60 kHz of CHFA's frequency of 680 kHz.

SPAN Tower	to Tower	Span Length m	RESONANT One-wavelength loop resonance kHz	FREQUENCIES Two-wavelength loop resonance kHz
199	198	246	505	1011
198	197	394	348	* 695
197	196	406	341	* 682
196	195	387	355	* 710
195	194	379	359	* 719
194	193	328	406	811
193	192	358	379	759
192	191	367	371	743
191	190	290	451	903
190	189	543	265	530
189	188	344	387	774
188	187	460	301	602
187	186	344	384	768
186	185	456	305	610
185	184	320	413	826
184	183	370	369	* 738
183	182	412	338	* 675
182	181	292	443	885
181	180	437	314	* 629
180	179	368	363	* 726
179	178	437	319	* 639
178	177	312	425	851
177	176	301	433	865
176	175	431	322	* 644
175	174	363	376	751
174	173	358	383	765
173	172	358	379	759
172	171	357	379	757
171	170	363	376	753
170	169	322	418	837
169	168	323	417	835
168	167	323	415	829
167	166	384	358	* 716
166	165	360	377	755
165	164	370	369	* 738
164	163	334	403	805
163	162	333	404	807
162	161	332	408	815
161	160	390	353	* 705

TABLE 4.4 continued

SPAN Tower to Tower		Span Length m	RESONANT One-wavelength loop resonance kHz	FREQUENCIES Two-wavelength loop resonance kHz
160	159	326	405	810
159	158	326	406	813
158	157	401	344	* 688
157	156	325	414	828
156	155	389	356	* 713
155	154	362	379	758
154	153	367	375	749
153	152	380	364	* 727
152	151	368	374	747
151	150	357	383	767
150	149	375	368	* 736
149	148	343	397	794
148	147	429	328	* 655
147	146	418	335	* 670
146	145	362	379	758
145	144	405	344	* 688

segments per span. Thus, with a very large run of the NEC program using 600 segments, as many as 50 spans could be modelled. The total number of spans on the power lines of Tables 4.1 and 4.2 is 101, and so a reduced length of power line must be represented in the NEC model. At 680 kHz, the AMPL program could also be used with good accuracy. The version of AMPL available at Concordia has been used with as many as 40 power line towers, but could be dimensioned for more without incurring unmanageable running time. At the time the work of this Chapter was carried out, AMPL was not available. In order to keep computer costs down, the "north" and "southeast" power lines were analysed separately, and so the azimuth pattern of CHFA operating near the "north" line only was found, and then the pattern of CHFA near the "southeast" line only, was also found. These results are presented in the following sections. In order to judge whether the power lines interact significantly, a computer model representing a reduced length of both power lines was then analysed, and the result compared with the "runs" of CHFA near each of the two individual power lines.

TABLE 4.5

Double span resonant frequencies for the "north" power line.

SPAN Tower to Tower		DOUBLE SPAN RESONANT FREQUENCIES Three wavelength loop kHz	Four wavelength loop kHz	Five wavelength loop kHz
194	192	680	907	1133
193	191	559	746	932
192	190	562	749	936
191	189	582	776	970
190	188	624	832	1040
189	187	654	873	1091
188	186	629	838	1048
187	185	672	896	1120
186	184	521	** 694	868
185	183	473	* 631	788
184	182	551	* 735	919
183	181	589	785	982
182	180	553	* 737	922
181	179	561	748	935
180	178	634	845	1056
179	177	572	763	953
178	176	635	846	1058
177	175	613	817	1021
176	174	517	** 690	862
175	173	600	800	1000
174	172	677	902	1128
173	171	668	890	1113
172	170	691	922	1152
171	169	713	950	1188
170	168	681	908	1135
169	167	591	789	986
168	166	675	900	1125
167	165	732	976	1220
166	164	604	806	1007
165	163	616	821	1027
164	162	680	906	1133
163	161	654	873	1091
162	160	446	595	744
161	159	489	** 692	815
160	158	652	869	1086
159	157	619	825	1031
158	156	668	891	1113
157	155	633	844	1055
156	154	627	836	1044

TABLE 4.5 continued

SPAN Tower to Tower		DOUBLE SPAN Three wavelength loop kHz	RESONANT Four wavelength loop kHz	FREQUENCIES Five wavelength loop kHz
155	153	617	823	1029
154	152	603	804	1005
153	151	632	843	1053
152	150	593	791	989
151	149	592	789	986
150	148	642	856	1069
149	147	640	854	1067
148	146	677	902	1128

4.4 CHFA near the North Line

This section investigates the azimuth pattern of the CHFA antenna operating near a section of the "north" power line including towers 149 to 185, for a total of 35 spans, as illustrated in Fig. 4.4. The NEC program uses about 1200 seconds of CPU time on a Cyber 174 to analyse such a configuration. Fig. 4.6 shows the radiation pattern of the CHFA array operated near this section of the "north" line. The field strength in the protected arc, shown in Fig. 4.6(b), varies rapidly with angle, and there is strong reradiation between 185 and 230 degrees. The protection requirement is exceeded by a large amount. The figure also shows a measured pattern for the actual CHFA array operating in the presence of both the "north" and the "southeast" power line(33). The measured pattern shows strong reradiation from about 185 to about 220 degrees, and a strong peak near 230 degrees. Thus there is a reasonable correlation of the angular extent of reradiation between the NEC computation and the actual pattern. The NEC model does not include any losses due to the conductivity of the ground, and so indicates larger reradiated fields than are actually found, by a factor of as much as 4, as discussed above in Sect. 2.9. Thus the pattern of CHFA operating near the "north" line violates the protection requirement substantially.

The RF currents flowing on the towers and skywires of the "north" line are shown in Fig. 4.7. The figure gives the magnitude of the current relative to an excitation of 1 amp on the centre tower of the CHFA array, and the phase of the current relative to that at the base of CHFA's centre tower. There are large RF currents flowing on towers number 176, 174, 169, 168, 167, 166, 165, 164, 151 and 150. The relative phase of the

TABLE 4.6

Double span resonant frequencies for the "southeast" power line.

SPAN Tower	to Tower	DOUBLE SPAN RESONANT FREQUENCIES Three wavelength loop kHz	Four wavelength loop kHz	Five wavelength loop kHz
199	197	680	906	1133
198	196	559	746	932
197	195	561	749	936
196	194	582	776	970
195	193	624	831	1039
194	192	644	859	1073
193	191	610	813	1016
192	190	672	896	1121
191	189	537	* 716	895
190	188	507	** 676	845
189	187	553	* 737	922
188	186	551	* 735	918
187	185	555	* 740	926
186	184	571	761	951
185	183	640	854	1067
184	182	570	759	949
183	181	626	835	1043
182	180	605	807	1008
181	179	550	* 733	917
180	178	555	* 740	925
179	177	588	784	980
178	176	715	953	1191
177	175	603	804	1005
176	174	564	751	939
175	173	615	820	1025
174	172	619	826	1032
173	171	621	827	1034
172	170	616	821	1027
171	169	646	861	1076
170	168	684	911	1139
169	167	681	908	1136
168	166	628	837	1047
167	165	596	794	993
166	164	610	814	1017
165	163	627	835	1044
164	162	663	883	1104
163	161	663	884	1105
162	160	613	818	1022
161	159	619	825	1031
160	158	670	893	1117

TABLE 4.6 continued

SPAN Tower to Tower		DOUBLE SPAN Three wavelength loop kHz	RESONANT Four wavelength loop kHz	FREQUENCIES Five wavelength loop kHz
159	157	609	812	1015
158	156	611	815	1019
157	155	623	830	1038
156	154	595	793	922
155	153	612	815	1019
154	152	598	797	997
153	151	597	796	995
152	150	615	820	1024
151	149	609	812	1015
150	148	620	827	1034
149	147	580	774	967
148	146	532	710	887
147	145	575	766	958
146	144	583	778	972

currents on towers 175-174-173, 169-168-167-166, 165-164 and 151-150 is 180 degrees different from tower to tower, and suggests that those spans are in two-wavelength loop resonance. The current distribution on the skywires, given in Fig. 4.7(b), shows the magnitude curve expected of two-wavelength loop resonance on the spans from tower 176 to 175, 175 to 174, 168 to 167, 159 to 158, and 151 to 150, which, as illustrated in Fig. 2.9(b) has a maximum at the center of the span and a null adjacent to each tower. The phase distribution on these spans is that of two-wavelength loop resonance, being constant with distance, except for sharp 180 degree phase changes coincident with the nulls in the magnitude of the current. The estimated resonant frequencies for these spans are given in Table 4.3, and are 637, 646, 666, 673, and 660 kHz, respectively, and are all close to CHFA's 680 kHz. The double-span from tower 176 to 174 is resonant at 690 kHz, and carries an RF current distribution similar to that expected for "four-wavelength double-span resonance" in Fig. 2.11(b).

It is notable in Fig. 4.7 that some spans not expected to be resonant carry significant RF currents. Thus the spans from tower 169 to 168 and from tower 167 to 166 are resonant at 801 and 522 kHz, quite different from 680 kHz, yet both spans carry large currents. These spans are excited by direct coupling to the strongly resonant span from tower 168 to 167. If the resonace of this adjacent span is detuned, then the currents on the spans 169

TABLE 4.7

Triple-span resonant frequencies for the "north" power line.

SPAN Tower to Tower		TRIPLE SPAN RESONANT FREQUENCIES Four wavelength loop kHz	Five wavelength loop kHz	Six wavelength loop kHz
194	191	580	725	869
193	190	514	643	772
192	189	521	651	781
191	188	557	696	836
190	187	578	722	866
189	186	588	735	882
188	185	604	755	906
187	184	504	630	757
186	183	486	607	* 728
185	182	453	566	** 679
184	181	528	660	793
183	180	505	632	758
182	179	535	669	803
181	178	526	658	790
180	177	552	690	828
179	176	568	709	851
178	175	539	674	809
177	174	529	662	794
176	173	519	649	779
175	172	564	706	847
174	171	625	782	938
173	170	622	778	934
172	169	640	800	960
171	168	634	793	952
170	167	573	716	859
169	166	614	768	922
168	165	604	755	906
167	164	621	776	932
166	163	567	709	851
165	162	587	734	880
164	161	602	752	902
163	160	462	577	** 692
162	159	479	599	* 719
161	158	460	575	** 690
160	157	617	772	926

TABLE 4.7 continued

SPAN Tower to Tower		TRIPLE SPAN RESONANT FREQUENCIES Four wavelength loop kHz	Five wavelength loop kHz	Six wavelength loop kHz
159	156	573	716	860
158	155	597	747	896
157	154	576	720	864
156	153	568	710	852
155	152	557	697	836
154	151	571	714	857
153	150	545	682	818
152	149	564	705	846
151	148	551	688	826
150	147	591	738	886
149	146	605	756	907

to 168 and 167 to 166 disappear. In general, the RF current flowing on a strongly resonant span can induce an RF current on an adjacent span, but the influence is local and little current is induced on spans further away. It might be of interest to explore this effect further by measurement on a scale model of a power line.

Thus the "as-built" "north" power line is found to be a significant reradiator, with strong RF current flow particularly on towers 168, 167 and 166, and also on towers 176, 174 and 151 and 150.

4.5 CHFA near the Southeast Line

The "southeast" power line was represented in the computer model by the section from tower 156 to tower 190, and shown in Fig. 4.5. Fig. 4.8(a) is the azimuth pattern of the CHFA array operating near this section of 33 spans of the "southeast" power line. The NEC program uses about 1100 sec of CPU time to analyse this configuration. The field strength in the restricted arc in Fig. 4.8(b) shows that the protection requirement is violated by a small amount between 186 and 190 degrees and between 221 and 225 degrees. Comparing Figs. 4.6(b) and 4.8(b), it is clear that the "north" line is the damaging reradiator for this site.

TABLE 4.8

Triple-span resonant frequencies for the "southeast" power line.

SPAN Tower to Tower		TRIPLE SPAN RESONANT FREQUENCIES Four wavelength loop kHz	Five wavelength loop kHz	Six wavelength loop kHz
199	196	580	724	869
198	195	514	643	772
197	194	521	651	781
196	193	557	696	836
195	192	571	714	857
194	191	576	720	864
193	190	598	747	897
192	189	511	638	766
191	188	517	647	776
190	187	457	571	** 685
189	186	530	662	795
188	185	485	607	* 728
187	184	542	677	813
186	183	532	665	798
185	182	552	690	828
184	181	564	704	845
183	180	534	667	801
182	179	553	691	830
181	178	494	617	* 740
180	177	543	678	814
179	176	576	720	864
178	175	583	729	874
177	174	556	695	834
176	173	531	663	796
175	172	563	703	844
174	171	568	710	852
173	170	566	708	850
172	169	583	729	875
171	168	602	752	903
170	167	625	782	938
169	166	591	739	887
168	165	570	712	855
167	164	548	685	822
166	163	572	715	858
165	162	586	732	878
164	161	609	761	913
163	160	574	718	862
162	159	579	724	869
161	158	583	729	875
160	157	576	720	865

TABLE 4.8 continued

SPAN Tower to Tower		TRIPLE SPAN RESONANT FREQUENCIES Four wavelength loop kHz	Five wavelength loop kHz	Six wavelength loop kHz
159	156	578	722	866
158	155	547	684	821
157	154	567	709	850
156	153	547	684	821
155	152	551	689	827
154	151	549	686	823
153	150	553	692	830
152	149	556	695	834
151	148	568	710	852
150	147	534	668	802
149	146	516	645	774
148	145	508	635	762
147	144	518	647	777

The RF currents induced on the towers, shown in Fig. 4.9(a), are less than half of those on the north line, even though the southeast line is closer to the CHFA array. There are large currents on the power line on towers 183, 182, 181, 179, 176, 175, 174, and 173, with towers 180, 178, 172, 171 and 170 also carrying larger currents than the remainder. The plan of the power line, Fig. 4.1, shows that towers numbered 170 and lower lie south of east of the antenna, where the field strength decreases rapidly with azimuth angle. Thus due east the field strength is about 5 dB down from the maximum, and 30 degrees south of east, roughly at tower # 167, the field strength is 15 dB down. This is reflected in the induced RF current, which decreases progressively from tower 174 towards tower 156. For this reason, the power line model was not extended southwest beyond tower 156. Only the span from tower 176 to 175 carries a very substantial RF current. The skywire currents are plotted in Fig. 4.9(b). Spans 183-182, 181-180, 180-179, 179-178 and 176-175 show two-wavelength resonant current distributions, and in Table 4.4 are resonant at 675, 629, 726, 639 and 644 kHz, respectively. The phase distribution does not show strong resonance, except for span 176 to 175. It is clear that this span is the primary reradiator.

Thus the "as-built" "southeast" line is not found to be a significant reradiator.

4.6 Response of Resonant Spans

The strength of the RF current induced on a span depends on the strength of the excitation field, on the relative phase of the excitation field at the two towers terminating the span, and on whether the frequency of operation of the broadcast antenna lies within the bandwidth of a resonance mode of the span, and how close the resonant frequency is to the operating frequency. These factors were examined in Sect. 2.8 above. This section presents an examination of these factors for two strongly resonant spans on the power lines near CHFA.

The impact of orientation on the excitation of two-wavelength loop resonance is contained in Eqn. 2.20 and 2.21. To excite two-wavelength loop resonance, the difference-mode excitation, D, must be large. For a typical span with 32.6 m tall towers, the span length must be about 411 m for two-wavelength loop resonance at 680 kHz, and such a span is most favorably oriented roughly at θ = 60 degrees to the radial in Fig. 2.14, where D is largest and C is smallest. In general, when a span makes an angle near θ = 60 degrees to the radial from the broadcast antenna, it is "favorably" oriented, but when it is roughly parallel to the radial with θ = 0 degrees, or roughly perpendicular to it with θ = 90 degrees, it is "unfavorably" oriented and most of the excitation field is in the common mode component, and two-wavelength loop resonance will not be strongly excited. For a 411 m span, the difference-mode field D is 6 dB or more down from its largest value if the span is oriented at less than 25 degrees or more than 80 degrees to the radial. Referring to Fig. 4.1, most of the spans lie within the 25 to 80 degree range, and so most see less than 6 dB of excitation loss due to orientation. Spans oriented between 35 and 75 degrees to the radial see less than a 3 dB loss in the excitation due to orientation.

Two strongly resonant spans can be compared to assess the impact of the various factors. The span from tower 168 to tower 167 on the north line is about 4080 m from the broadcast antenna, is located at 14 degrees azimuth in the radiation pattern and so is just about exactly in the maximum of CHFA's pattern, makes an angle of 41 degrees to the radial for D equal to about 80 percent of its largest value, and is resonant at 666 kHz. Span 176 to 175 on the southeast line is about 2800 m from the antenna at 54 degrees azimuth in the pattern, where the field is down about 0.7 dB from its largest value, makes an angle of about 54 degrees to the radial for D about 98 percent of its largest value, and is resonant at 645 kHz. To compare loss of excitation due to distance, inverse distance variation is assumed, and so span 168 to 167 on the north line sees 4.7 dB less excitation than span 176 to 175. Span 168 to 167 sees 0.7 dB more than span 176 to 175, due to azimuth position, for a net difference of 4.0 dB. Due to orientation, span 176 to 175 is more favorably oriented, and the difference is 20 log(.98/.80) = 1.8 dB, for a net difference of 5.8 dB more difference-mode excitation for span 176 to 175 on the southeast line compared to span 168 to 167 on the north. This would suggest that the span on the southeast line should respond more strongly, but recall that the resonant frequency of the span on the north line, 666 kHz, is much closer to 680 kHz than that on the southeast line, 645 kHz. In fact, the current distributions results shown in Figs. 4.7 and 4.9 indicate that span 176 to 175 carries a much larger RF current, of about 85 mA compared to 36 mA for span 168 to 167, a difference of 7.5 dB. Thus analysis of excitation could be misleading. The "transfer function" between the excitation of a single span embedded in a power line, and the resulting RF current on the span is not at present available in a simple form. Thus even if a span is much further away and less favorably oriented than some other span, it can carry the stronger current if it is closer to resonance.

In summary, the strength of the RF current induced on a span depends upon : (i) the distance from the antenna ; (ii) the location of the span in the antenna's azimuth pattern ; (iii) the angular orientation of the span relative to a radial from the antenna ; and (iv) the nearness of the frequency of operation to a resonant frequency of the span. A non-resonant span generally carries small RF currents, with the exception of such a span located adjacent to a strongly resonant span. A resonant span may carry strong RF currents but does not necessarily do so, depending on the orientation of the span and on its location in the pattern and distance from the antenna.

4.7 CHFA and Both Power Lines Together

The foregoing has found the pattern of CHFA operating near each power line individually. Thus CHFA's pattern was found when towers 149 to 185 of the "north" power line are included in the computer model, and then CHFA's pattern with towers 156 to 190 of the "southeast" line was found. The results show that the "as-built" north line is the primary reradiator, and on that line it is towers 176, 174, and 168, 167, 166 and 165 which carry the large RF currents. About 35 spans were modelled in each case. It is of interest to ask whether the results obtained for the power lines individually can be used to judge the amount of reradiation from the two power lines acting together. If the power lines do not interact significantly then the computer models of the individual lines can be used to design "detuning" measures for the individual power lines, which will then be expected to be effective for the two power lines together. The plan of Fig. 4.1(a) shows that the power lines are widely separated west of tower 173 on the "north" line and of tower 178 on the "southeast" line. However, east of these towers the power lines are closely parallel and may interact significantly. Thus it might be expected that the "southeast" line would screen the "north" line from the antenna.

To account for interactions between the power lines and for "screening" effects, both power lines must be included in the computer model at the same. To keep the number of "segments" in the computer model as low as possible, fewer towers were included on each power line. Thus towers 157 to 190 on the "north" line, or 33 spans, and towers 165 to 185 on the "southeast" line, or 20 spans, were included in the computer model, for a total of 53 spans in the computer model, shown in Fig. 4.10. The Cyber 174 used about 2000 CPU seconds in running the NEC program to analyse this configuration, considerably more than the roughly 1100 sec used to analyse longer segments of the "north" line by itself or the "southeast" line by itself. Fig. 4.10 shows the computer model of the site including "both lines". In Fig. 4.7(a), towers 149 to 156 of the "north" line carry small currents, except towers 150 and 151, and so in omitting towers 149-156 two significant tower currents are ignored. These two towers are distant from the southeast line and so will not contribute to interactions between the two lines. The "north" line model has been extended in the "both lines" computer model to tower 190 to include as long a section of the parallel power lines as possible. In Fig. 4.9(a), towers 156 to to 164 on the "southeast" line carry very little RF current and can be omitted from the "both lines" model. These towers lie in the minimum of CHFA's pattern. The "southeast" line in the "both lines" model extends to tower 185, so that on the parallel segment, the two power lines terminate at corresponding towers.

Fig. 4.11(a) shows the azimuth pattern obtained by using the NEC program to determine the RF current flow on the power lines illuminated by the CHFA array and then to find the reradiated field from the power lines. The azimuth pattern is quite similar to that of CHFA radiating in the presence of the "north" line only, shown in Fig. 4.6(a). This is to be expected since the "north" line is the primary reradiator, and that result is not changed by modelling the two lines together. Fig. 4.11(b) shows the field strength in the restricted arc, and is similar to Fig. 4.6(b). There is substantial field strength in excess of the protection requirement, which is thus seriously violated.

4.8 Comparison of Tower Base Currents

The RF current distribution computed with the power lines individually can be compared with that found for both lines together, to show if there are significant interactions. Fig. 4.12(a) compares the RF current found when only the "north" line is included in the computer model with that found when both power lines are included. The currents are nearly identical on all the towers of the power line along the section where the "north" and "southeast" lines are widely separated, west of tower number 174. However, on the parallel section of the power lines, tower number 177 carries much less current when both lines are included together in the computer model. In Table 4.3, span 177 to 178 is resonant at 684 kHz. Possibly the excitation of the resonance is "screened" by the presence of the "southeast" power line.

Fig. 4.12(b) compares the current distribution on the towers of the "southeast" line when only that line is included in the computer model, with the current distribution found with both power lines included in the model. Once again, on the widely separated sections of the power lines, the current distribution is identical for the two cases. But on the parallel sections, significantly different currents are found, particularly on towers 182 and 183. The span from tower 182 to 183 is resonant at 675 kHz in Table 4.4. In this case the resonance is more strongly excited in the presence of the other parallel power line. The conclusion to be drawn from the comparison of the tower current distributions is that if two power lines are closely parallel, then they interact significantly and must both be included in the computer model at the same time. But if two power lines are widely separated, then they can be studied individually, which is simpler and results in a saving in computer cost.

4.9 Comparison with Measured Tower Base Current

After the construction of the power lines near CHFA, the CBC contracted Til-Tek to measure the base currents on each of the towers of the "north" and the "southeast" power lines(34), and this set of measured tower currents can be compared with those predicted by the NEC code, using the "both lines" model described above. Fig. 4.13 shows the result. The measured currents have been re-scaled to correspond to the 1 amp excitation used on the centre tower of the CHFA array in the computer model. The distribution of the measured currents on the "north" line, Fig. 4.13(a), is similar on towers 152 to 173, including the large RF currents on towers 165 to 169. The computed currents are larger by a factor of about 2.5. This is well accounted for by the conductivity of ground, which was not represented in the computer model. Thus as discussed in Sect. 2.5, the computed current when no losses are accounted for in the computer model is as much as 5.5 larger than when the conductivity of the ground is included in the computer model. Thus the difference in the magnitude of the current flow of a factor of 2.5 is readily explained as being due to damping of resonances introduced by the lossy ground. In Fig. 4.13(a), it is seen that the measured and computed RF current flow differ by a factor of about 3.5 on towers 174 and 176 on the parallel section of the power lines, although the general variation of current from tower to tower corresponds well between the computation oand the measurement.

Towers 178 and 179 show different behaviour between the computation and the measurement although this may be due to the proximity of the end of the power line in the computer model, where the actual power line continues beyond tower number 180.

Fig. 4.13(b) compares the measured and computed currents on the "southeast" power line. Once again, the distribution of currents is very similar on towers 165 through 178, where the "north" and "southeast" power lines are widely separated. However, on the section of the "southeast" line which parallels the "north" line, the measured currents do not agree well with the computed currents. Thus the computation shows a strongly resonant span from tower 183 to tower 184, but this is not seen in the measured tower base currents.

4.10 Conclusion

This Chapter has illustrated "as-built" assessment for the power lines near station CHFA, Edmonton. "As-built assessment" seeks to determine whether the "as-built" power lines are significant reradiators, and if so, to identify those towers on each power line which carry the strongest RF current flow. For the example of the CHFA site, this Chapter has demonstrated that the "north" line causes the protection requirement to be substantially exceeded, whereas the "southeast" line causes only small excursions above the protection requirement. On the "north" line, towers 168, 167 and 166 carry particularly strong RF current flow, and towers 176, 174 and 151 and 150 also carry significant RF currents. At the "as-built assessment" stage in the life cycle of a reradiation problem, the broadcastor may wish to measure the azimuth pattern of the broadcast antenna, and the strength of the RF current flow at the base of each power line tower. This Chapter has shown that the field strength in the restricted arc as measured by the CBC for the CHFA antenna operating in the presence of the "as-built" lines is similar in angular distribution to that predicted by the computer model. Also, the distribution of tower base currents is similar in the computer model and in the full-scale measurement, except for the some towers where the "north" and "southeast" power lines are closely parallel. Knowledge of the RF current flow on the towers is necessary for the design of detuning measures for the power lines, as discussed in Chapter 5.

The question of how many towers need to be included in the computer model in order to assess whether protection is met is a difficult one. If a computer model representing the 10 or 15 spans closest to the antenna indicates a large excursion above protection, as is the case for the north line, then it can be stated with confidence that protection will be exceeded with a longer power line model. However, if a model representing the 10 or 15 closest towers shows that protection is met, or is marginal as in the case of the southeast line, then it is difficult to guarantee the same result as towers are added to the line. The case of the southeast line suggests that the same result would hold for longer power line models provided that there are not a great many strongly resonant spans. This Chapter has used the NEC computer code with as many as 53 spans, but at 680 kHz the AMPL code could be used with good accuracy, possibly with enough spans to represent the whole site of Fig. 4.1. The accuracy of the AMPL approximation has not been tested for parallel power lines, which evidently interact significantly.

Ideally, a single computer "run" should be used to find the azimuth pattern of the CHFA antenna operating near both power lines of Fig. 4.1 together, and the resulting current distribution on the towers of the power lines would include any interactions between the power lines. In practice, the number of spans which can be represented in a single "run" of the NEC code is limited by the available computer resources and by cost. It has been found useful to analyse reradiation from each power line individually. It has been shown in this Chapter that, on sections of the power lines which are widely spaced, the RF current flow on the power line towers is practically the same when each power line is analysed individually and when both power lines are analysed simultaneously. But on the parallel section, there is significant interaction and the RF current distribution on each power line is affected by the presence of the other. Also, poor correlation with the full scale measured tower base currents was found on the parallel sections. Thus modelling long runs of parallel power lines may be a problem for the present analysis techniques.

The current distributions calculated on the two power line models indicate the usefulness of the resonant frequency estimate of Chapter 2. Thus where a span is estimated to be resonant within half of the 120 kHz bandwidth of resonance of CHFA's frequency, a strong response is often seen. If a span is not estimated to be resonant, then a weak response is generally found, with the exception of non-resonant spans directly adjacent to strongly resonant spans, where there is a direct coupling. The factors involved in exciting a resonant span have been discussed, with the conclusion that even if a span is resonant it will not necessarily be strongly excited, because of distance from the antenna, location in the azimuth pattern, and orientation, and so a strong RF current will not necessarily be found.

The good correlation between the estimated resonant frequency for each span and the response of the spans of the north and southeast power line suggests that such frequency estimates may be a good basis in themselves for assessing the influence of a power line. In particular, a power line which has no spans resonant near the frequency of operation of the broadcast antenna would be expected to reradiate a low field. Any real power line is likely to have some spans resonant at the frequency of a nearby broadcast antenna. Thus it may be necessary to identify the problem spans, which could be few or could be many, and take some measures to "detune" each resonant span so that its resonance is shifted away from the frequency of operation of the broadcast antenna. The power utilities are attracted to detuning by isolating towers from the skywire, as a simple and inexpensive technique.

CHAPTER FIVE

DETUNING POWER LINES BY ISOLATING TOWERS

5.1 Introduction

Once a power line has been constructed near a broadcast antenna, and once it has been established by computation or by direct measurement that the power line is a significant reradiator, it is necessary to design measures for "detuning" the power line. "Detuning" involves modifying the power line or attaching devices to the power line which suppress the RF current flow on the power line at the frequency of operation of the broadcast antenna. Ref. (15) discusses detuning devices and their principles of operation. Ref. (35) discusses the use of "straight" stubs and "elbow" stubs on the power line towers to suppress RF current flow. Such modifications can cost as much as $ 40,000 per power line tower. A much simpler and less expensive technique is that of isolating selected towers from the skywire, which requires inexpensive insulators. Ref. (6) was prepared as an interim report in this project, and developed a systematic technique for selecting which towers should be isolated from the skywire in order to suppress existing resonance modes without creating resonant double-spans or triple-spans which would themselves reradiate. This Chapter summarizes this method of "suppression of resonances" for selecting towers for isolation from the skywire.

In Chapter 4, the "north" line was modelled from tower 149 to 185, and the "southeast" line from tower 156 to 190, and it was shown that CHFA operating near the "north" power line radiates in excess of its protection requirement. It was found that certain individual spans are strongly resonant and that reradiation from these spans into the minimum of CHFA's azimuth pattern exceeded the maximum field strength specified by the "protection requirement" which CHFA must meet. It was found that there are substantial RF currents on some of the towers of the "north" line, and that detuning will be required.

This Chapter considers detuning by the method of "suppression of resonances" for both the "north" and the "southeast" power lines. The criterion used to select towers for isolation from the skywire is examined, and a rational choice is made based on the estimated resonant frequencies of the power lines. A "resonance chart" is drawn, summarizing the resonant behaviour expected of a power line, including resonance modes involving two and three spans. The thrust of this Chapter is to provide a systematic procedure for choosing towers for isolation. A poor procedure is examined, called "bulk isolation", in which a large number of towers are isolated in a regular fashion, such as isolating every second tower, or two out of each three towers. Such an "arbitrary" procedure inevitably leads to the creation of resonant paths involving two spans or three spans, and these are shown to respond strongly to the excitation of the broadcast antenna. A "selective isolation" technique is presented, in which the "resonance chart" is used to choose towers for isolation such that all resonant single-span loops are broken, without creating any resonant double- or triple-span loops. This method of "suppression of resonances" is used to select a set of towers for isolation from the skywire for the "north" and the "southeast" power lines, and yields a greatly improved radiation pattern for CHFA operating in the presence of each of the two power lines.The tower base currents computed with all towers connected to the skywire are used to classify the set of towers chosen for isolation according to the anticipated effect on the radiation pattern. Thus "Group 1" towers carry the strongest currents, "Group 2" towers carry significant currents and "Group 3" towers carry little RF current. Disconnecting only the Group 1 towers from the skywire substantially improves the radiation pattern, whereas disconnecting Group 2 and Group 3 towers results in minor improvements.

5.2 Computer Model for a Tower Isolated from the Skywire

The skywire on a real power line is normally connected to all the towers, and so lightning striking the skywire is directed to ground via the nearest tower. Some of the towers can be electrically insulated or "isolated" from the skywire without a serious degradation in the lightning protection, and isolating towers has in the past resulted in reduced reradiation at RF frequencies on some sites. The skywire is isolated by inserting an insulator between the skywire and the crossarm. The insulator provides a high series resistance, and will be assumed here that the dielectric material of the insulator contributes an additional series capacitance between the tower and the crossarm, of 27 pF, which is that of a typical series insulator. Note that the NEC program implicitly accounts for the capacitance between the tower wire and the overhead skywire. It will be assumed here that at least every third tower must be connected to the skywire to provide lightning protection, so that no more than two adjacent towers can be isolated from the skywire.

The isolated tower was modelled as shown in Fig. 5.1. A short "segment" of length 2 m was inserted into the top of the tower, of mean radius between the tower and skywire radii. This segment was then loaded with a high series resistance in parallel with the 27 pF insulator capacitance.

5.3 Consequences of Isolating a Tower

The question of which towers to isolate to obtain the largest reduction in the radiation into the protected arc is a difficult one. When one tower is isolated from the skywire, a double-span is created, which could be resonant. and a free-standing tower is created, which could carry a strong RF current flow.

When one tower in a power line is isolated, it "open-circuits" two adjacent spans. If either span were resonant, open-circuiting the span effectively suppresses or "detunes" the resonace mode. Thus isolating one tower can greatly reduce the RF current on the two adjacent towers, if the spans were resonant. However, isolating a tower also creates a double-span loop out of the two spans adjacent to the isolated tower, and if the double-span loop is resonant at the operating frequency, it could carry a substantial RF current flow. Then the RF current on the two towers adjacent to the isolated tower could be greatly increased by isolating the tower. Clearly, the creation of resonant double-spans by isolating towers must be avoided.

An isolated tower does not carry zero RF current. It behaves as a free-standing tower, top-loaded by its crossarms, and coupled capacitively to the nearby skywire passing overhead, and so it can carry a substantial RF current. The isolated tower is excited both by the broadcast antenna's field, and by the field across the skywire-and-image transmission line. If the isolated tower stands in a voltage-maximum in the standing wave pattern on the overhead skywire, it can be strongly excited as a free-standing tower, and so the isolated tower can carry a large RF current. If a substantial RF current is found to flow on an isolated tower, then a tower-stub will be necessary to suppress that current flow(35).

Evidently, isolating a tower from the skywire changes its RF current and that on nearby towers in a complex fashion, depending on the resonant frequencies of the two adjacent spans and on the resonant frequencies of the double-span created by isolating the tower. The choice of which towers to isolate from the skywire is thus determined by the resonant frequencies of the spans of the power line, and also by the resonant frequencies of the double-spans which could be created by isolating one tower, and the resonant frequencies of the triple-spans which could be obtained by isolating two adjacent towers. The next section draws a "resonance chart" depicting the resonant frequencies of the power line.

5.4 Resonance Chart

This section reviews the resonance modes of a power line, and their associated resonant frequencies and current distributions. A "resonance chart" is drawn, depicting graphically the resonant frequencies, and will be used later to select towers for isolation from the skywire.

A "single span" consists of two towers interconnected by a skywire, and creates a loop of geometrical length equal to the distance from the base of one tower, up the tower, along the skywire to the next tower, and back down to ground, plus the corresponding return path on the images of the towers and skywires in ground. The loop is resonant at those frequencies which make its electrical length equal to integer multiples of the wavelength. At a resonant frequency, the skywire carries a characteristic standing-wave current distribution associated with the "mode" of resonance. Fig. 2.9 shows the current standing-wave for three resonance modes. "One-wavelength loop resonance" gives rise to a current maximum at the base of each tower, and a minimum at the skywire center. The phase of the current changes abruptly by 180 degrees in crossing the minimum in the current. "Two-wavelength loop resonance" is characterized by a maximum in the RF current at the center of the span and a sharp null with its associated 180 degree phase reversal near each of the towers. The arrows in the figure show the actual direction of current flow, and show that the phase of the current differs by 180 degrees at the towers for two-wavelength loop resonance. Eqn. 2.7 has been used to estimate the resonant frequencies associated with "single span" loop resonance, and these frequencies have been given for "one wavelength loop resonance" and for "two-wavelength loop resonance" in Table 4.3 for the "north" power line and in Table 4.4 for the "southeast" power line.

A "double-span" is created by isolating one tower from the skywire, and consists of the two towers adjacent, plus the skywire from one of these towers to the isolated tower, and from there to the other adjacent tower. This path length is filled up with half-wavelength long cycles of the current distribution and is resonant when an integer number of these half-waves "fit" perfectly. Fig. 2.11 shows the RF currrent standing-wave on the skywire associated with three modes of "double-span" resonance. Tables 4.5 and 4.6 give the "double-span" loop resonance frequencies associated with the "north" and the "southeast" power line, respectively. The "bulk isolation" tests described in the next section demonstrate the existance of such resonances.

Fig. 2.12 shows the current modes expected for triple-span loop resonance. In this case, two adjacent towers are isolated, creating a three-span loop, which, with the tower spacings encountered on the power lines near CHFA, can be four-, five- or six-wavelength resonant. Tables 4.7 and 4.8 give the "triple-span" loop resonance frequencies for the power lines near CHFA.

Because the power lines have a variable span length, the mode of resonance which is closest in frequency to 680 kHz varies. Thus in Table 4.5, the double-span obtained by isolating tower # 186 is three-wavelength resonant near 680 kHz, whereas that obtained by isolating tower # 175 is four-wavelength resonant near 680 kHz. None of the double-spans are long enough to be five-wavelenth loop resonant at that low a frequency. In Table 4.7, isolating towers 183 and 182 would create a five-wavelength resonant loop at about 660 kHz, and isolating towers 184 and 183 would give rise to a six-wavelength resonant loop at 679 kHz. All these loops might possibly be troublesome because 680 kHz lies within the bandwidth of the resonance mode.

In selecting towers for isolation, the objective is to "open-circuit" any span which has a "single-span" resonant frequency within about 50 or 60 kHz of the operating frequency, by isolating one, or the other, or both of the towers terminating the span. Table 4.3 (or 4.4) is consulted to identify the resonant spans. In isolating one tower, the resonant frequency of the resulting double-span must not lie within about 50 kHz of the operating frequency, and this can be verified by checking Table 4.5 (or 4.6). If it is decided to isolate two adjacent towers, then a resonant triple-span must be avoided, by consulting Table 4.7 (or 4.8).

A set of tables, such as Tables 4.3, 4.5, and 4.7 for the north power line, giving the frequency of resonance for various modes of single-, double-, and triple-span resonace, are cumbersome to use for selecting towers for isolation from the skywire. The tables give the resonant frequencies of several modes of resonance, most of which are not near to CHFA's frequency. It is useful to pick out from the tables those resonant frequencies which have CHFA's frequency within their bandwidth, or are at least closest to CHFA's frequency, regardless of mode. Thus a "resonance chart" can be prepared, depicting the resonant frequency estimates in a schematic form, as shown in Fig. 5.2 for the "north" power line and Fig. 5.3 for the "southeast" line. The charts show the power line pictorially with the tower spacing proportional to the actual span length. Above the center of each span the chart shows the single-span resonant frequency estimate. A double-span is created by isolating a single tower, and so above each tower is shown the resonant frequency of the double-span obtained by isolating that tower and leaving the adjacent two connected to the skywire. For example, on the north line, isolating tower # 163 creates a double-span from tower # 164 to tower # 162, which is estimated to be resonant at 680 kHz. The mode of resonance, if it is of interest, can be found from the tables. A triple-span is created by isolating two towers in a row, and the chart shows the resonant frequency for the triple-span above the center of the span between the two isolated towers. Thus isolating towers # 162 and 161 creates a triple-span from tower # 163 to # 160, which is resonant at 693 kHz. The chart shows at a glance which towers or pairs should not be isolated, lest the power line be made more strongly resonant at CHFA's frequency, and the reradiation problem thus be worsened.

The "resonance chart" will be used below to select towers for isolation for both the "north" and "southeast" power lines. The following section demonstrates the existence of multi-span resonances by making a poor choice of towers for isolation and thus creating resonant double- and triple-spans on the power lines.

5.5 Bulk Isolation and Multi-Span Resonances

It is tempting to specify that a power line be "treated" by isolating towers from the skywire according to some regular "rule". Thus if every second tower is isolated to obtain a configuration of "isolated, connected, isolated, connected, ...", then the possibly resonant path associated with every individual span is broken open, and it might be supposed that the power line is effectively detuned. Alternately, a scheme of two isolated, one connected could be used, to obtain a "connected, isolated, isolated, connected, isolated, isolated, ..." configuration. This breaks up all single-span and all double-span loops. Such schemes will be termed "bulk isolation". This section shows that "bulk isolation" fails because multi-span resonant paths are created which respond strongly. Thus the choice of the towers to be isolated from the skywire must be made on an individual basis to avoid the creation of resonant multi-span loops.

Isolating every second tower constitutes a "bulk isolation" scheme. To demonstrate this technique, a model of the "north" line including towers 164 to 176 will be used, with towers # 165, 167, 169, 171, 173, and 175 isolated from the skywire. This creates double-spans 164-166, 166-168, 168-170, 170-172, 172-174 and 174-176. Fig. 5.4(a) is a "resonance analysis" of the power line with the specified towers disconnected, and is readily constructed by selecting the appropriate frequencies from the resonance chart of Fig. 5.2. Thus in Fig. 5.2, double-span 176-174 is resonant at 690 kHz, and this is indicated on the "resonance analysis" diagram. Fig. 5.4(a) shows that 5 out of the six double-spans created by this "bulk-isolation" scheme are resonant near 680 kHz. It is not suprising, then, that the field strength in the restricted arc, shown in Fig. 5.4(b), exceeds the protection requirement by a large amount. The RF currents flowing on the towers of the power line are shown in Fig. 5.4(c) plotted relative to a current of 1 amp on the centre tower of the CHFA antenna. The RF currents are uniformly large and about equal to 40 milliamps on the center part of the power line section. The RF current distribution on the skywires, Fig. 5.4(d), shows constant-phase with abrupt 180 degree reversals, and is characteristic of resonance, and the magnitude shows large amplitude standing waves. The "double-span" from tower 176 to tower 174 is expected to be in resonance at 690 kHz, and Table 4.5 shows that the mode is four-wavelength, double-span resonance. A comparison of the skywire current from tower 176 to tower 174 in Fig. 5.4(d) with the idealization of Fig. 2.11 shows a strong resemblance, with three distinct half-wavelength cycles of standing wave on the skywire proper and a fourth distributed between the two towers. Similarly, the double-span from tower 174 to tower 172 is resonant at 677 kHz, but Table 4.5 indicates that in this case the shorter span length gives three-wavelength double-span resonance. Indeed, two half-wavelength cycles of standing wave can be counted on the skywire from tower 174 to tower 172, with the third distributed between the two towers. Thus isolating individual towers can create resonant "double-spans", which respond strongly to excitation by the broadcast antenna.

It is striking in Fig. 5.4(c) that some of the "isolated" towers, namely numbers 171 and 173, carry RF currents which are as large as those on the "connected" towers, while other isolated towers, such as number 175, carry little current. This is readily explained in terms of the distribution of the voltage standing-wave for the resonance mode on each double-span loop. An isolated tower is a free-standing reradiator, and is excited both by the broadcast antenna and by the field across the skywire-plus-image transmission line. This latter field is largest at the maxima in the voltage standing-wave pattern, corresponding to the location of the current minima. Thus on the doublespan from tower 176 to tower 174, the mode of resonance is four-wavelength loop resonance, and it is seen in Fig. 5.4(d) that a current maximum coincides with the position of tower 175. Thus tower 175 is at a voltage minimum of the skywire-plus-image transmission line, so is not excited and little current is seen. Conversely, double-spans 174 to 172 and 172 to 170 are in three-wavelength loop resonance, with a current minimum and hence a voltage maximum at the position of the isolated tower. Thus the isolated tower is strongly excited by the the skywire-image transmission line's field, and Fig. 5.4(c) shows large currents on towers 173 and 171. One conclusion is that if a strong current is seen on an isolated tower, the overhead skywire is probably part of a strongly-resonant loop. It is tempting to conclude that free-standing towers should be treated with tower-stub detuners to suppress the current. A better solution is the suppression of the strong resonance of the double-spans, so that no large voltage maxima are present on the skywires.

Isolating two out of every three towers to obtain a configuration of "connected, isolated, isolated, connected, ..." is another possible bulk isolation scheme. Thus for the section of the north line from tower 164 to number 176, towers number 167 and 168, 170 and 171, and 173 and 174 can be isolated to test the potential of this scheme. The "resonance chart" of Fig. 5.2 can be used to prepare the "resonance analysis diagram" of

Fig. 5.5(a) for this set of isolated towers, and shows that the triple-span from tower 166 to 169 is resonant at too low a frequency to be a problem. The triple-span from tower 169 to 172 is resonant at 641 kHz, just close enough to 680 that there may be some resonant response. The triple-span from tower 172 to 175 is resonant at 706 kHz, very close to CHFA's 680 kHz. The resulting field strength in CHFA's minimum is shown in Fig. 5.5(b), and it can be seen that a considerable improvement is obtained over the all-connected case. The protection requirement is still exceeded by more than 10 millivolts per metre at some angles. The RF currents on the towers in Fig. 5.5(c) show that triple-span 166-169 carries little RF current. Triple-span 169-172, resonant at 641 kHz, shows some resonant response in the clear standing wave pattern of the current magnitude and in the sharp reversals of the phase, but the current magnitude is too small to be significant. However, triple-span 172-175, resonant at 706 kHz, shows a large resonant response. The current distribution shows that the section of power line from towers 164 through 171 has been detuned, including the strong RF currents on towers 165 through 168 in Fig. 4.7(a). But tower 172 now carries a much stronger current than it did previously. Triple-span 172-175 carries a five-wavelength, triple-span resonance mode. The skywire currents of Fig. 5.5(d) show resonant phase behaviour on the triple-span from tower 172 to tower 175. The phase is roughly constant, except for 180 degree reversals at the nulls in the current distribution. The current distribution corresponds to five-wavelength triple-span resonance in Fig. 2.12. Tower 173 is near a current minimum and so is excited by the voltage across the skywire-plus-image transmission line, and responds with a strong RF current. Tower 174 is near a current maximum and hence is weakly excited and shows a low value of RF current. Thus an injudicious choice of towers for isolation from the skywire can result in a triple-span which is strongly resonant and carries large RF currents.

The attraction of "bulk isolation" as a detuning technique is that the application of a simple, regular "rule" for the choice of towers for isolation requires no previous knowledge of the RF currents flowing on the towers with all towers connected. The fatal defect of "bulk isolation" is the creation of strongly resonant multi-span loops. In the tests presented above, the spans expected to be double-span resonant or triple-span resonant respond strongly, and carry large RF currents which reradiate significantly. Thus "bulk isolation" fails as a detuning technique. An attractive alternate approach is the use of the "resonance chart" to select towers for isolation such that no multi-span resonant loops are created, while at the same time opening all resonant single-span loops. The next section investigates the efficacy of such an approach.

5.6 Tower Isolation for the Suppression of Resonances

This section proposes to base the choice of towers for isolation upon the resonance chart. "Selective isolation" seeks to identify those towers which must be isolated to suppress specific resonances. The resulting power line is essentially non-resonant and carries relatively small RF currents, and so the radiation pattern has been systematically improved.

Any span of the power line which has a resonant frequency near the frequency of operation of CHFA at 680 kHz could be excited to resonance and so carry a significant RF current flow. The objective of "tower isolation for the suppression of resonances" is to "open circuit" all such resonant spans, without creating any double- or triple-spans which are themselves resonant near CHFA's frequency. Thus a procedure for the selection of towers for isolation for the suppression of resonances consists of :

(i) the definition of "resonant near 680 kHz" as resonance within a specific range of frequencies ;

(ii) the identification and listing of resonant spans ;

and (iii) the selection of specific towers for isolation.

This selection can be further refined given a computation (or measurement in the field) of the RF current flowing on each power line tower with all towers connected to the skywire, by the following steps :

(iv) correlation of the resonant frequency estimates with actual current flow ;

and (v) selection of further towers for isolation to suppress non-resonant currents.

The implementation of steps (i) to (iii) results in considerable pattern improvement, based solely on the resonance chart, which is derived from the power line geometry by simple arithmetic without the aid of a computer. Steps (iv) and (v) deal with the excitation of the resonant spans, and with non-resonant currents flowing on the power line, and require a "run" of a computer model, or a measurement. Such small currents are significant only in the case that the station is required to maintain a deep minimum, such as that in CHFA's pattern.

Step (i) of this procedure asks whether a span resonant at f_s will respond to CHFA's signal at f_0=680 kHz. In Sect. 2.4 it was noted that the bandwidth of resonance is about 120 kHz, and so the span will respond to CHFA's signal if CHFA's frequency f_0 lies in the range

$$(f_s - 60) < f_o < (f_s + 60) \text{ kHz}$$

Since f_o is constant at 680 kHz, but the span resonant frequency f_s varies from one span to the next, this relationship can be solved for the range of span resonant frequencies. Thus if the resonant frequency of the span lies in the range

$$(f_o - 60) < f_s < (f_o + 60) \text{ kHz}$$

then the span could be excited to resonance by CHFA's signal at f_o. If the resonant frequency lies outside this range then the span will not be excited to resonance. With f_o = 680 kHz, the range is

$$620 < f_s < 740 \text{ kHz}$$

As previously noted, resonance tapers and does not cut off abruptly. Thus spans resonant near the limits of this frequency range are "borderline" resonances and their response is not likely to be strong. Spans resonant from 660 to 700 kHz are likely to respond strongly.

In the following sections, the application of steps (ii) to (v) to the specific cases of the north and southeast power lines is described in detail.

5.7 Selection of Towers for Detuning the North Line

Table 5.1 summarizes the selection of towers for isolation for the suppression of resonance for the north line. The resonance chart of Fig. 5.2 is consulted to construct columns 2 and 3 of the Table, which list potentially resonant single- and double-spans. All resonant single spans must be "treated" by selecting one or more towers for isolation. In column 2 the resonant frequency of each single-span resonant in the range 620 to 740 kHz is listed, in between the tower numbers of the two towers making up the span. In column 3, the resonant frequency of each double-span which is resonant in the range 620 to 740 kHz is listed opposite the tower number of the middle tower of the double-span. As previously pointed out, a double-span can show a resonant response even with the center tower connected, but the primary purpose of listing double span resonant frequencies is to aid in the selection of towers for isolation. Thus Table 5.1 indicates that spans 184-183-182, 179-178-177, 176-175-174, 168-167, 165-164, 161-160, 159-158, 153-152 and 151-150 are resonant close enough to 680 kHz to require "treatment" by tower isolation. The fourth column of the Table shows the towers selected for isolation, which are derived as follows. To detune the pair of spans 184-183-182, either tower 183 alone could be isolated, or towers

184 and 182 could be selected for isolation. Isolating tower 183 creates a double-span resonant at 735 kHz, whereas isolating tower 184 creates a double-span resonant at 631 kHz. Both of these are "borderline" resonances, and an arbitrary choice was made to isolate towers 184 and 182. To detune spans 179-178-177, tower 178 is selected for isolation, which breaks up both resonant single-spans and creates a double-span which is not resonant. If either tower 179 or 177 were selected for isolation, the resulting double-spans are "borderline" resonant at 634 and 635 kHz. To detune span 168-167, tower 168 is selected for isolation. Note that isolating tower 167 is not an alternative choice since the resulting double-span would be resonant at 676 kHz, very close to CHFA's 680 kHz. But both towers 167 and 168 could be chosen for isolation, since the resulting triple-span is shown in Fig. 5.2 to be resonant at 615 kHz, which is "safe". To detune span 165-164, tower 165 can be isolated. To detune span 161-160, tower 161 can be isolated, creating a double-span resonant at 744 kHz in preference to isolating tower 160 for a double-span resonant at 652 kHz. To detune span 159-158, tower 158 is isolated. To detune span 153-152, near the borderline of resonance at 735 kHz, tower 153 can be isolated. To detune span 151-150, either tower 151 or tower 150 can be isolated, and # 151 was arbitrarily chosen. Note that both towers 151 and 150 should not be isolated, since the resulting triple-span is shown in Fig. 5.2 to be resonant at 705 kHz, which is too close to CHFA's 680 kHz. Thus the method of "suppression of resonances" indicates that towers 150, 153, 158, 161, 165, 168, 174, 176, 178, 182 and 184 should be isolated from the skywire.

Steps (iv) and (v) in the procedure outlined in the previous section call for the correlation of the towers chosen for isolation with the strength of the RF current flowing on the towers, with all towers connected to the skywire, which is given in Fig. 4.6(c). Thus the fifth column of Table 5.1 was derived from that figure by plotting the tower currents on an "asterisk" scale, using "*" to represent a current of between 5 and 10 mA, "**" for 10 to 20 mA, "***" for 20 to 40 mA and "****" for 40 to 80 mA. This "logarithmic" scale indicates at a glance which towers carry large currents and so are "problem" towers. The asterisks correlate well with the presence of resonant spans in column 2. The choice of towers for isolation in column 4 will evidently "treat" all of the towers carrying significant currents. To err on the side of caution, it was decided to isolate tower 167 in addition to tower 168, as these are the towers carrying the strongest RF currents. As previously mentioned, the resulting triple-span has an acceptable resonant frequency of 615 kHz. Thus column 5 of Table 5.1 accounts for both the estimated resonant behaviour of the power line and for the calculated RF current flow with all towers connected. Fig. 5.6(a) is a "resonance analysis diagram" of the power line with the towers listed in the last column of Table 5.1 isolated, and shows no resonances near 680 kHz.

TABLE 5.1

Selection of towers for isolation on the north line, by the method of suppression of resonances.

TOWER #	Resonant Frequencies Single Span	Resonant Frequencies Double Span	Isolate for Resonance Suppression	Tower Current	Augmented Selection for Isolation
185					
184		631 kHz	184	*	184
	678 kHz				
183		735		*	
	675				
182			182		182
181		738			
180					
179		634			
	733				
178			178	**	178
	685				
177		635		**	
176			176	***	176
	637				
175		690		**	
	646				
174			174	***	174
173		677		*	
172		668			
171		692		*	
170		713			
169		681		***	
168			168	****	168
	666				
167		676		****	167
166		733		***	

TABLE 5.1 Continued

TOWER #	Resonant Frequencies Single Span	Double Span	Isolate for Resonance Suppression	Tower Current	Augmented Selection for Isolation
165			165	***	165
	719				
164				**	
163		680		(*)	
162		655			
161		(744)	161	*	161
	666				
160		652			
159		652			
	674				
158		(619)	158	*	158
157		669			
156		633			
155		627			
154		(618)		*	
153			153	**	153
	735				
152		632		**	
151				***	
	660				
150			150	***	150
149					

Scale for representation of currents :

****	40 to 80 mA
***	20 to 40 mA
**	10 to 20 mA
*	5 to 10 mA
(*)	almost 5 mA

To test the effectiveness of isolating towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182, and 184, those towers were isolated in the computer model, which was then "run", resulting in the field strength in the protected arc shown in Fig. 5.6(b). There is a large improvement over the "all-connected" case. There is only one small excursion above the protection requirement, and that of small angular extent. The RF currents on the towers, shown in Fig. 5.6(c), are uniformly small. Thus the method of "suppression of resonances" systematically obtains a large reduction in the reradiation from the power line, and hence a greatly improved radiation pattern.

5.8 Selection of Towers for Detuning the Southeast Line

Table 5.2 sets out the steps in the selection of towers for isolation on the southeast line for the suppression of resonances. The resonance chart of Fig. 5.3 shows that the single spans 184-183-182, 181-180-179-178, 176-175, 167-166, 165-164, 161-160 and 158-157 have resonant frequencies close enough to CHFA's 680 kHz to be of concern. Column 3 lists the resonant freqencies of the double-spans whose bandwidth is estimated to include 680 kHz, as an aid in the selection of towers for isolation. To detune the spans from tower 184 to 183 and from tower 183 to 182, towers 184 and 182 were selected for isolation from the skywire, which creates a double-span resonant at 641 kHz, which is of borderline concern. An alternate choice would have been the isolation of tower 183 which creates a non-resonant double-span. No measures were taken to detune span 181-180 as its resonant frequency of 629 kHz is "borderline", although tower 181 could be safely selected for isolation. To detune spans 180-179 and 179-178, tower 179 is chosen for isolation, which creates a double-span resonant at 741 kHz, a "borderline" resonance not likely to be troublesome. Overall, an alternate choice would have been the isolation of towers 180 and 178, which creates only one "borderline" resonance. To detune span 176-175, tower 176 was selected for isolation. To detune span 167-166, tower 166 has been chosen for isolation, which also detunes the double-span 168-166. An alternate choice to detune span 167 to 166 is to isolate tower 167, which leaves the double-span 168-166 untreated. To detune span 161-160, tower 161 was chosen for isolation, and for span 158-157, tower 158 was selected for isolation. This completes the selection of towers for the "suppression of resonances".

TABLE 5.2

Selection of towers for isolation on the southeast line, by the method of suppression of resonances.

TOWER #	Resonant Frequencies Single Span	Resonant Frequencies Double Span	Isolate for Resonance Suppression	Tower Current	Augmented Selection for Isolation
190					
189		676 kHz			
188		738			
187		735			
186		(741)			
185					
184		641	184		184
	738 kHz				
183				**	
	676				
182		626	182	**	182
181				*	
	629				
180		734		*	
	726				
179		(741)	179	*	179
	639				
178				*	
177		715			
176			176	***	176
	645				
175				***	
174		(615)		*	174
173		620		*	
172		621		(*)	172
171		(617)		(*)	
170		646		(*)	

TABLE 5.2 Continued

TOWER #	Resonant Frequencies Single Span	Resonant Frequencies Double Span	Isolate for Resonance Suppression	Tower Current	Augmented Selection for Isolation
169		684			
168		682			
167		628			
	717				
166			166		166
165					
	738				
164		627			
163		663			
162		664			
161			161		161
	706				
160		(619)			
159		671			
158			158		158
	689				
157					
156					

Scale for representation of currents :

****	40 to 80 mA
***	20 to 40 mA
**	10 to 20 mA
*	5 to 10 mA
(*)	almost 5 mA

The RF current with all the towers connected to the skywire can be used to refine the choice of towers for isolation. Thus the current distribution of Fig. 4.9(a) was used to plot the tower currents in column 5 on the "asterisk" scale described above. Towers 176 and 175 carry the most current, but are adequately treated by isolating tower 176. Towers 169 to 156 lie progressively far into the minimum in CHFA's pattern and do not carry significant currents. Towers 174, 173, 172, 171 and 170 carry some RF current not treated by the tower selection for the suppression of resonances, and indeed the phase distribution of the skywire current in Fig. 4.9(b) does not indicate resonance on these spans. The small but significant currents seen on these towers can be "treated" by isolating towers 174 and 172, which does not create any undesirable double-span resonances. This is the "refined" selection given in column 6 of Table 5.2. Thus towers 158, 161, 166, 172, 175, 176, 179, 182 and 184 were selected for isolation. Fig. 5.7(a) shows the "resonance analysis" of the power line with this choice of towers for isolation from the skywire. The resulting power line is essentially non-resonant at 680 kHz. Fig. 5.7(b) shows the behaviour of the power line with this choice of towers for isolation. The field strength in CHFA's minimum has been reduced to a level below the protection requirement. Fig. 5.7(c) shows that the current flowing on most of the towers is small.

5.9 Isolating Fewer Towers

This section shows that a considerable improvement in the radiation pattern can be obtained by "detuning" only a small section of the line, carrying the largest currents. In Table 5.1, it is seen that towers 176, 174, 169, 168, 167, 166, 165, 151 and 150 carry large RF currents. Towers 174, 169, 168, 167, 166 and 165 are the "worst offenders" and are detuned by isolating tower numbers 165, 167, 168 and 174 from the skywire. If only this reduced set of towers is isolated, the resulting field strength in the minimum is shown in Fig. 5.8(a), and a large improvement has been achieved. However, there are still substantial excursions above the protection limit, from 185 to 210 degrees, and other smaller excursions are present as well. This illustrates the improvement to be expected from treating a few troublesome spans. The RF current distribution on the towers is shown in Fig. 5.8(b), and indicates that one span of the "untreated" portion of the power line is strongly resonant, namely that from tower 150 to tower 151. Fig. 5.8 shows that a substantial improvement in the radiation pattern is possible by only a few towers to suppress the largest RF currents.

TABLE 5.3

Classification of Towers for Isolation.
Group 1 Dominant towers.
Group 2 Secondary towers.
Group 3 Optional towers.

NORTH LINE

Tower	Group
184	3
182	3
178	2
176	2
174	2
168	1
167	1
165	1
161	2
158	2
153	2
150	2

SOUTHEAST LINE

Tower	Group
184	3
182	2
179	2
176	1
174	1
172	2
166	2
161	3
158	3

5.10 Classification of Towers for Isolation

The current distributions of Fig. 4.7(a) and Fig. 4.9(a) show that a few towers on each power line carry "strong" currents, others carry "significant" currents, and most carry "small" currents. The choice of which towers to isolate was made in the above such that all possible resonances of the power line are suppressed, regardless of whether each resonance is actually excited by the broadcast antenna. Fig. 5.8 demonstrates that by isolating only those few towers carrying "strong" currents, a large improvement in the radiation pattern can be achieved. Thus the towers designated for isolation which are associated with the "strong" currents on the power line will be classified as "Group

1" towers. Table 5.1 shows the currents of Fig. 4.7(a) on a logarithmic "asterisk" scale. The asterisks show that of the set of towers chosen for isolation on the north line, namely towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184, the "Group 1" towers are numbers 165, 167 and 168. A large improvement in the radiation pattern is obtained by isolating the "Group 1" towers. "Group 2" towers will be any others designated for isolation which carry "significant" currents, and includes towers number 150, 153, 158, 161, 174, 176 and 178. The remaining towers in the list, numbers 158, 161, 182 and 184, are towers of "dormant" resonant spans which are not excited significantly by the broadcast antenna, and will be designated "Group 3" towers. No great change in the radiation pattern is anticipated by isolating these towers. Table 5.3 summarizes the classification.

Fig. 4.9(a) or the "asterisk" scale in Table 5.2 should be consulted in order to classify the towers selected for isolation on the southeast power line. The group of towers isolated to obtain Fig. 5.7 will be chosen, namely towers 158, 161, 166, 172, 174, 176, 179, 182 and 184. To suppress the "strong" currents seen on towers 176 to 174, towers number 174 and 176 should be isolated, and these two constitute the "Group 1" towers. Towers number 166, 172, 179, and 182 form "Group 2", and towers 158, 161, and 184 make up "Group 3".

5.11 Detuning Both Lines Simultaneously

The above has examined each power line individually, and shown that, when the specified towers are disconnected from the skywire, CHFA operating near the "detuned" north line has a satisfactory azimuth pattern, and similarly CHFA operating near the "detuned" southeast line is satisfactory. In Sect. 4.7, a computer model of CHFA operating near both power lines at the same time was presented, and it was commented that the power lines interact significantly where they are closely parallel. Thus in general, detuning measures designed using computer runs of the individual power lines might not be satisfactory for the parallel sections. The parallel sections run eastward from tower number 174 on the north line, and from tower number 176 on the southeast line, as shown in Fig. 4.1. In the particular case of the power lines near CHFA, the dominant RF current flow is found on the widely separated portions of the power lines, with only a few towers carrying significant currents on the parallel portions, and so isolating towers as specified in Table 5.3 is expected to be satisfactory. To test this, the computer model of "both" lines discussed in Sect. 4.7 was used, including towers 157 to 180 on the north line, and 165 to 185 on the southeast. The towers specified in Table 5.4 were isolated from the skywire, to obtain the field strength in the restricted arc shown in

Fig. 5.9. It is seen that the isolation of these towers from the skywire effectively detunes the power lines, even when both lines are simultaneously included in the computer model. Fig. 5.10 compares the current flow at the bases of the power line towers before and after detuning. It is seen that isolating the specified towers achieves a substantial reduction of the RF current flow. On the widely separated sections of the power lines, the RF current on towers 164 through 169 of the "north" line, and on towers 174, 175 and 176 of the "southeast" line is substantially reduced. On the parallel sections of the power lines, detuning by isolating towers for the suppression of resonances is also successful. Thus the RF current flow on towers 174 through 177 of the "north" line and towers 182 through 185 of the "southeast" line are substantially reduced. It may be inferred that, although closely parallel power lines affect the excitation of current flow on one another, parallel power lines have about the same resonant behaviour as widely separated lines, and so detuning by suppression of resonances remains a useful technique.

TABLE 5.4
Towers isolated for the analysis of "both power lines together".

POWER LINE	TOWERS MODELLED	TOWERS ISOLATED
north	157-180	158,161,165,167,168,174,176,179
southeast	165-185	166,172,174,176,179,182,184

5.12 Conclusion

The set of towers specified for isolation in Table 5.3 were disconnected from the skywire by Trans-Alta in June and July of 1984, and a large reduction in the tower base currents on the power lines was reported by Til-Tek(36). Thus the technique of selecting towers for isolation for the "suppression of resonances", using the resonance chart as a guide, has been successful in reducing the tower base current flow on a real power line "in the field". Further investigation is required to compare the measured RF current flow at the tower bases reported in Ref. (36) with the computed current flow reported in this Chapter. It would be of interest to compare the CHFA pattern with power line towers isolated with that predicted by the computer model including both power lines.

The method of "suppression of resonances" does not require computer resources to implement. The resonance chart can be prepared with a simple calculator for as many towers of the power line for which base coordinates and heights are available, and thus the technique is not limited to the number of towers which can be analysed on the available computer. Thus the resonance chart is searched for resonant single spans, and towers are selected for isolation in order to "open" the resonant single-spans, without creating any resonant double- or triple-spans. The procedure results in a greatly improved radiation pattern without previous knowledge of the RF currents flowing on the towers with all towers connected to the skywire. Thus a simple means has been identified for selecting towers for isolation without the aid of a large digital computer. However, the resonance chart does not indicate which resonant spans are excited strongly enough to carry significant RF currents. A measured or computed set of tower base currents with all towers connected to the skywire can be used to identify strongly responding spans, and hence towers which carry large RF current flow. Thus resonant spans which are found to carry little RF current may not need to the "treated" by tower isolation.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This report has reviewed the basic methodology of the computer modelling of power lines, and then traced a power line reradiation problem through its "life cycle", from the early stage at which the power line is proposed for construction and must be evaluated as a potential reradiator, to the construction of the power line, which must then be analysed for resonant spans and strong tower currents, to the design of "detuning" for the power line, by choosing towers for isolation from the skywire by the method of "suppression of resonances". Throughout, the CHFA antenna was used as an example, and, in fact, provided two power lines to illustrate the "as-built assessment", and the design of detuning. This chapter reviews certain decisions which must be made along the way in this analysis process, reviews the simplifications inherent in the computer model, and then recommends areas of interest for further investigation.

6.2 Conclusions

At the "initial assessment" stage, a fundamental decision must be made about how many towers on the power line should be included in the computer model. The electric field excitation of a span decreases as 1. / distance, so spans "far enough away" will not be strongly excited even if resonant. The question of an adequate number of towers involves including all resonant spans which are close enough to make a significant contribution to the reradiated field. For "close" power lines, such as those near CHFA, a small number of spans very close to the antenna appear to be the primary reradiators, and so a reasonable estimate of the amount of reradiation is had by modelling only 15 or 20 spans on each power line. For a power line much farther away, such as the power line 15 km from station CBO, discussed in the Appendices, a very long run of power line is all about the same distance from the antenna, and appears to contribute to reradiation. Conversely, the inverse-distance relationship makes the excitation of the individual spans, and hence their response, small. No "in between" distance case has thus far been examined. If doubt arises as to whether a long enough section of the power line has been modelled, then more towers should be included and the behaviour re-examined.

At the "as-built assessment" stage, the locations of the towers are known, and hence the span lengths can be used to draw a "resonance chart" giving the estimate of the resonant frequency of each span. In general, all resonant spans which are sufficiently close to the antenna should be included. There is no simple criterion for determining how far away a span must be so that its contribution is "insignificant", so, once again, if doubt arises, a longer segment of power line should be analysed.

At the "initial assessment" stage, a "ballpark figure" concerning the amount of reradiation to be expected from the power line by constructing and analysing a hypothetical power line with uniformly-spaced towers. Such a power line should be analysed with NEC or AMPL using the "nominal" span length, and also using nearby resonant values of the span length. If a more accurate assessment of the level of reradiation must be obtained, then the statistical methods of Chapter 3 are recommended to account for the variability of the span length on the actual power line. Span lengths have a roughly "normal" probability distribution with a rather large standard deviation. Hence, on a power line with a given mean or nominal span length, there will be some resonant spans and some non-resonant spans, and it is the resonant spans that are the principal reradiators. It has been shown in Chapter 3 that if the span length is allowed to be highly variable, having a large standard deviation such as the value of 46 m on a mean span of 363 m found at the CHFA site, then the amount of reradiated field is also highly unpredictable, having a mean value of the about 30 mV/m above the protection limit, with a standard deviation of about 23 mV/m. Thus for most possible instances of power lines with the given span statistics, protection will be substantially exceeded, but there exists specific power lines for which protection will be met. The principal conclusion here is that if the span length is highly variable, then there will very likely be some resonant spans, and so very likely be a problem with reradiation. A non-resonant value for the nominal span length is no guarantee of low levels of reradiation.

For a site such as that of CHFA, where there is more than one power line, it is economical to analyse the power lines individually, rather than model both at the same time and incur long running times for the computer model. The results of Chapter 4 show that as long as the power lines are widely separated, then they may be investigated one at a time. But closely spaced, parallel power lines must be analysed all together because they interact significantly.

The method of detuning by isolating towers from the skywire has been found to be both economical and effective. Thus the technique of "suppression of resonances" described in Chapter 5 uses a pencil-and-paper analysis of the resonant frequencies of the power line to indicate which spans are resonant at the operating frequency and hence potentially reradiators, and, using the graphical aid called a "resonance chart", chooses towers for isolation from the skywire to "open circuit" those spans without creating any resonant double- or triple-spans. Computer analysis of the site with all towers connected indicates which of the resonant spans are strongly excited and respond with strong RF current flow on their towers, and so are the primary choices for isolation. The set of towers specified in Table 5.3 were isolated by Trans-Alta, and resulted in a substantial reduction in the level of reradiation from the power line, and so the method of "suppression of resonances" appears to be satisfactory for the full-scale power line as well as for the computer model.

6.3 Simplifications Inherent in the Computer Model

The computer model of the power line used in this Report is not perfectly accurate. Possible sources of error are reviewed in this section.

The degree of agreement expected between measured and computed results is illustrated by the comparison of the field strength in the minimum of CHFA's pattern, in Fig. 4.11(b). By including the effect of ground conductivity as a "footing impedance" at the base of each power line tower, the current flowing on the powerline towers would be somewhat reduced, and the agreement would be improved. In Fig. 4.11(b), there is a good general correspondence between the measured and computed curves, and both show that the primary effect of reradiation is seen from 185 to 220 degrees azimuth, where the field strength is well in excess of the protection requirement, but detailed point by point agreement cannot be claimed. Similarly, the comparison of measured against computed tower base currents in Fig. 4.13 shows good general agreement, which could be improved by modelling ground conductivity. The key point is that where a group of resonant spans have been identified by computation, it is expected that the measured currents will show resonance, although the magnitude of the current on the individual towers may be somewhat different than in the computation.

That exact point-by-point agreement between measurements and computations has not been obtained is due to simplifications inherent in the computer model. Among these may be cited :

(i) local perturbations of the antenna's field caused by free standing towers or buried pipelines ;

(ii) imperfect, and indeed, non-unifrom ground conductivity ;

(iii) deviation from flatness in the ground, due to rivers, gullies, highways, etc. ;

and (iv) sag in the skywire, and geometrical differences between corner towers and other towers.

This list is not intended to be complete.

Concerning obstacles such as other towers or buried pipelines, these themselves reradiate and so the power line "sees" the broadcast antenna's field perturbed by the reradiated field of these structures. Thus the map of Ref. (37) shows that buried oil and gas pipelines run parallel and very close to the southeast power line between towers 144 and 170. This change in the excitation field could affect the response of some of the spans.

Concerning ground conductivity, the computer model analysed with the NEC program in this report uses highly-conducting "perfect" ground to save computer costs. A realistic value of ground conductivity of the order of 10 millisiemens/metre, and a realistic relative permittivity of 15, makes the ground a "good conductor". The principal effect of such a ground is the reduction of the magnitude of resonance effects by introducing additional damping. Only a very small change in the frequency of resonance is seen when ground conductivity is modelled. Thus the perfect ground model represents the "worst case", in that the largest possible resonant response is obtained. It has been commented above that the NEC computation could be improved by including the "footing impedance" to model the effect of imperfect ground conductivity. The AMPL model includes the "footing impedance" at the base of each power line tower, and as shown in Fig. 2.19 gives rise to somewhat smaller tower currents and reradiated field. A larger "footing impedance" would match the measured currents of Fig. 4.13 more closely. At the present time, a systematic, reliable relationship between the tower geometry and the appropriate value of footing impedance has not been demonstrated.

Concerning local differences in topology, certain individual spans of the power line cross deep gullies, or cross highways raised above the general level of the ground. The deviation from the flatness of the ground may cause a shift in the resonant response of the ground, which could result in stronger currents than expected from the computer model if the resonance is shifted closer to the operating frequency. In the case of CHFA, the maps of Refs. (37) and (38) show that on the southeast line span 161 to 162 crosses the Whitemud Creek, and span 175 to 176, and 180 to 181 recross the creek. The span from tower 175 to 176, in particular, is the one which responds most strongly in Fig. 4,9(a), and so the response of this span on the real power line may be different. This may in part account for the difference in current on the bases of towers 175 and 176 in Fig. 4.13(b). On the north line, span 160 to 161 crosses the

North Saskatchewan River, and span 175 to 176 crosses the gully of Whitemud Creek. Fig. 4.13(a) shows a large difference between the measured and computed currents on span 175 to 176.

Concerning power line geometry, it should be pointed out that the computer model of type Z7S towers used here has not been "fine tuned" by comparison with scale-model measurements. The model was derived using the same principles as that of the type V1S tower, as described in Sect. 2.3, but that model was verified against scale model measurements at various frequencies over the one-wavelength and two-wavelength resonance frequency bands. The Z7S geometry is quite different, and such a validation against measured data would allow the radii of the wires of the tower model to be "finely adjusted" to match the bandwidth of the measured resonance. The ability of the computer model to respond with the same resonant frequencies and about the same bandwidth as the full scale power line is the basis of its usefulness in dealing with power line reradiation.

Another source of error in the computer model concerns the relative location of the CHFA broadcast array to the power lines. The position of each power line tower was determined from data supplied by Trans-Alta (32), which accurately locates each power line tower relative to the next one along the power line in terms of a distance and an angle. The position of the CHFA array was determined from the map of Ref. (38), on a scale of 1:25000, which shows the towers of the array, but not the power lines. The broadcast array's position was found from the map relative to a road junction which also appears on the Trans-Alta maps. The accuracy of this procedure is difficult to establish, but is likely to be of the order of the spacing of the CHFA towers. A surveyed position for CHFA relative to the closest towers of the southeast line would be useful. Errors in the broadcast antenna's location result in errors in the phase of the excitation of each tower of the power line, and thence lead to errors in the induced current flowing on the power line.

In spite of these sources of error, the computer model has proven useful in detuning the power lines near CHFA.

6.4 Recommendations for Further Work

The CHFA study used as an example in Chapters 3, 4 and 5 of this Report is at present incomplete. Trans-Alta agreed to isolate the towers recommended in Table 5.3 and this was carried out in June and July, 1984. Field measurements were made of the azimuth pattern with those towers isolated, and of the tower base currents on the power lines. The first recommendation for further work is to follow up these measurements by comparing the results with the computed tower base currents and with the computed azimuth pattern using a model including both power lines.

The second recommendation concerns the limited frequency range of the present computer models. Thus the "single wire tower" model used with the NEC program, which is also the tower model upon which the AMPL program is based, is limited in frequency to about 1100 kHz. It is recommended that a computer model be developed which extends this frequency range to 2000 kHz. Evidently, top-loading by the crossarms becomes an important consideration above 1100 kHz, and so the tower model to be used is probably quite dependent on the geometry of the actual tower being modelled. This might require that a tower model be developed for each tower type by comparison with scale model measurements.

The most promising avenue for the development of tower models for higher frequencies appears to be the measurement of skywire loop impedance. Ref. (4) showed that loop impedance is sensitive to the presence of crossarms on the tower, and that the frequency range of the computer model of the type V1S tower could be extended by adding a crossarm to the model. Therefore it is recommended that skywire loop impedance be measured over a wide frequency range for various new tower types, and that computer models be developed for each.

The concept of "footing impedance" was discussed in Sect. 2.6, where it was found to provide an economical alternative to the costly Sommerfeld-Norton ground model for including the effects of the ground conductivity in the computer model. In the comparison with full-scale measured currents with all the towers connected to the skywire, in Fig. 4.13, it was seen that the ground conductivity "damps out" the RF current flow on the towers, and so the computed RF current, using the perfect ground model, is too high. The agreement could be improved considerably by including the "footing impedance" in the computer model. It is recommended that the accuracy of the "footing impedance" concept be tested systematically against computations with the more accurate Sommerfeld-Norton ground model, in order to firmly establish the value of the "footing impedance" for modelling ground conductivity, and to identify its limitations.

In this Report, the AMPL program has proven an invaluable tool for "initial assessment" and "as-built assessment" because it requires only modest computer resources, and, indeed, could be run on a personal computer. It is recommended that the AMPL program be systematically evaluated relative to existing computations with the NEC program, in order to establish its ability to "predict" power line resonances, and in particular the bandwidth associated with each resonance. The prediction of double- and triple-span resonances should be checked as well. Circumstances in which AMPL might not be sufficiently accurate should be defined. The ability of AMPL to reproduce NEC computations including the effect of ground, lumped into the "footing impedance", should also be systematically tested.

The principal limitations of AMPL are that it is limited in frequency to perhaps 1100 kHz, and that it is at present unable to model detuning by tower isolation. It would be of interest to add to AMPL the ability to isolate towers from the skywire, so that AMPL could be used to test the effectiveness of isolating a specific set of towers from the skywire, without incurring the cost of a run of the NEC code. It may be possible to extend the frequency range of AMPL by adding a crossarm to the tower model.

This Report has attempted to generalize previous work by studying power lines with a realistic, non-uniform span length. It may be of interest to document the behaviour of a "typical" power line as a function of such parameters as the distance to the broadcast antenna, the orientation of the line relative to the broadcast antenna, and other factors. In a specific situation NEC or AMPL can be used to obtain an estimate of the level of reradiation to be expected, but at present there is only a small "experience base" on which an engineer can make a judgement about whether a given situation warrants further investigation. The objective might be to generate results for carefully chosen power line geometries which might serve as a sufficient "experience base".

This Report has presented a full "life cycle" of a reradiation problem for an actual situation of some complexity, and shown how the problem could be resolved by detuning. It cannot be claimed that any such problem could be treated and brought to a satisfactory conclusion, because of limitations in the computer models, and other considerations. Future work should remove many of the real difficulties that remain and provide the ability to resolve any reradiation problem involving power lines in an economical fashion.

LIST OF REFERENCES

1. C.W. Trueman and S.J. Kubina, "AM Reradiation Project", Final Report, Communications Research Centre Contract No. OSU79-00066, Technical Note No. TN-EMC-80-03, Dept. of Electrical Engineering, Concordia University, March, 1980.

2. C.W. Trueman and S.J. Kubina, "Prediction by Numerical Computation of the Reradiation from and the Detuning of Power Transmission Lines," Final Report, Communications Research Centre Contract No. OSU80-00121, Technical Note No. TN-EMC-81-03, Dept. of Electrical Engineering, Concordia University, May 13, 1981.

3. C.W. Trueman and S.J. Kubina, "Corrective Measures for Minimizing the Interaction of Power Lines with MF Broadcast Antennas," Final Report, Communications Research Centre Contract No. OSU81-00192, Technical Note No. TN-EMC-82-02, Dept. of Electrical Engineering, Concordia University, May 17, 1982.

4. C.W. Trueman and S.J. Kubina, "Recent Advances in the Computer Modelling of Type V1S Power Line Towers at MF Frequencies," Final Report, Communications Research Centre Contract No. OSU82-00157, Technical Note No. TN-EMC-83-04, Dept. of Electrical Engineering, Concordia University, Sept. 29, 1983.

5. C.W. Trueman and S.J. Kubina, "The Radiation Pattern of CHFA, Edmonton near the As-Built North and Southeast Power Lines and Their Detuning by Isolating Towers," Interim Report, Communications Research Centre Contract No. OST83-00290, Technical Note No. TN-EMC-84-01, Dept. of Electrical Engineering, Concordia University, Jan. 31, 1984.

6. C.W. Trueman and S.J. Kubina, "Analysis and Procedures for Detuning the Power Lines near CHFA, Edmonton, by Isolating Towers," Interim Report, Communications Research Centre Contract No. OST83-00290, Technical Note No. TN-EMC-84-03, Dept. of Electrical Engineering, Concordia University, May 31, 1984.

7. Til-Tek Limited, "Reradiation Measurements of CHFA's Signal at the TransAlta Utilities Power Line Towers," Final Report, CBC Contract No. E-32545, Til-Tek Limited, Kemptville, Ontario, July, 1984.

8. C.W. Trueman and S.J. Kubina, "Initial Assessment of Reradiation from Power Lines," 34th Annual Fall Broadcast Symposium, IEEE Broadcast Technology Society, Washington, D.C., Sept. 20-21, 1984.

9. C.W. Trueman and S.J. Kubina, "Initial Assessment of Reradiation from the Lennox-Merivale Power Line into the Pattern of Station CBO, Ottawa," Interim Report, Communications Research Centre Contract No. OST83-00290, Technical Note No. TN-EMC-84-05, Dept. of Electrical Engineering, Concordia University, Nov. 13, 1984.

10. C.W. Trueman and S.J. Kubina, "Initial Assessment of Reradiation from the Lennox-Merivale Power Line into the Night Pattern of Station CBO, Ottawa," Interim Report, Communications Research Centre Contract No. OST83-00290, Technical Note No. TN-EMC-85-08, Dept. of Electrical Engineering, Concordia University, May. 31, 1985.

11. C.W. Trueman, S.J. Kubina, R.C. Madge and D.E. Jones, "Comparison of Computed RF Current Flow on a Power Line with Full Scale Measurement," IEEE Trans. on Broadcasting, Vol. BC-30, No. 3, pp. 97-107, Sept. 1984.

12. M.A. Tilston and K.G. Balmain, "A Microcomputer Program for Predicting AM Broadcast Re-Radiation from Steel Tower Power Lines," IEEE Trans. on Broadcasting, Vol. BC-30, No. 2, pp. 50-56, June, 1984.

13. Canadian Broadcasting Corporation, "Guidelines for the Measurement of Reradiation of MF Broadcast Stations," Draft 1, CBC Technical Report to the Working Group on Reradiation Problems in AM Broadcasting, November, 1982.

14. J. Provost, "Measurement Guide," Division Equipement, Equipment de Telecommunications, Planification, Hydro-Quebec, Montreal, June 1982.

15. C.W. Trueman, S.J. Kubina and J.S. Belrose, "Corrective Measures for Minimizing the Interaction of Power Lines with MF Broadcast Antennas," IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-25, No. 3, pp. 329-339, August 1983.

16. G.J. Burke, A.J. Poggio, J.C. Logan and J.W. Rockway, "NEC - Numerical Electromagnetics Code for Antennas and Scattering", 1979 IEEE International Symposium on Antennas and Propagation Digest, IEEE Publication No. 79CH1456-3AP, Seattle, Washington, June, 1979.

17. R. Mittra, editor, "Computer Techniques in Electromagnetics," Pergammon Press, 1973.

18. C.W. Trueman and S.J. Kubina, "Numerical Computation of the Reradiation from Power Lines at MF Frequencies," IEEE Trans. on Broadcasting, Vol. BC-27, No. 2, pp. 39-45, June 1981.

19. D.L. Jaggard, "An Application of Isoperimetric Inequalities to the Calculation of Equivalent Radii," Proc. of the National Radio Science Meeting, Boulder, Colorado, Nov. 1979.

20. C.R. Paul and S.A. Nasar, "Introduction to Electromagnetic Field Theory," McGraw-Hill, 1982.

21. J.N. Brittingham, E.K. Miller, and J.T. Okada, "SOMINT : An Improved Model for Studying Conducting Objects near Lossy Half Spaces," Lawrence Livermore Laboratory Report No. UCRL-52423, Feb. 24, 1978.

22. G.J. Burke, E.K. Miller, J.N. Brittingham, D.L. Lager, R.J. Lytle, and J.T. Okada, "Computer Modelling of Antennas Near the Ground," Lawrence Livermore Laboratory Report No. UCID-18626, May 13, 1980.

23. G.J. Burke and A.J. Poggio, "Numerical Electromagnetics Code - Method of Moments," Technical Document No. 116, prepared for the Naval Electronic Systems Command, (ELEX 3041), Jan. 2, 1980.

24. K.A. Norton, "The Propagation of Radio Waves over the Surface of the Earth and in the Upper Atmosphere, Part II", Proc. IRE, Vol. 25, No. 9, pp. 1203-1236, Sept. 1937.

25. A. Banos, "Dipole Radiation in the Presence of a Conducting Half-Space," Pergamon Press, New York, 1966.

26. M.M. Silva, K.G. Balmain and E.T. Ford, "Effects of Power Line Re-Radiation on the Pattern of a Dual-Frequency MF Antenna," IEEE Trans. on Broadcasting, Vol. BC-28, No. 3, Sept. 1982.

27. G.D. Monteath, "Applications of the Electromagnetic Reciprocity Principle," Pergammon Press, New York, 1973.

28. I. Miller and J.E. Freund, "Probability and Statistics for Engineers," Prentice-Hall, New Jersey, 1977.

29. M. Abramowitz and I.A. Stegun, editors, "Handbook of Mathematical Functions," Dover, New York, 1972.

30. C.W. Trueman and S.J. Kubina, "Analysis of Reradiation from the Southeast Route Power Line into the Restricted Arc of the Pattern of CHFA, Edmonton," Report No. CHFA-1, prepared for the Canadian Broadcasting Corporation, Sept. 25, 1980.

31. C.W. Trueman and S.J. Kubina, "Analysis of Reradiation from the Northern Route Power Line into the Restricted Arc of the Pattern of CHFA, Edmonton," Report No. CHFA-2, prepared for the Canadian Broadcasting Corporation, Nov. 25, 1980.

32. P.L. Barry, private communication (to P. Cahn, CBC), TransAlta Utilities Corporation, Calgary, Alberta, June 28, 1983.

33. J. Litchfield and P. Cahn, private communication, Canadian Broadcasting Corporation, Montreal, Quebec, Nov. 1983.

34. Til-Tek Limited, "Reradiation Measurements of CHFA's Signal at the TransAlta Utilities Power Line Towers," Final Report, CBC Contract No. E-31786, Til-Tek Limited, Kemptville, Ontario, April, 1984.

35. M.A. Tilston and K.G. Balmain, "Medium Frequency Reradiation from a Steel Tower Power Line with and without a Detuner," IEEE Trans. on Broadcasting, Vol. BC-30, No. 1, pp. 17-26, March, 1984.

36. Til-Tek Limited, "Reradiation Measurements of CHFA's Signal at the TransAlta Utilities Power Line Towers," Final Report, CBC Contract No. E-32545, Til-Tek Limited, Kemptville, Ontario, July, 1984.

37. Map of Whitemud Creek, Alberta, scale 1:25000, map number 83H/5h Edition 3, Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa.

38. Map of Woodbend, Alberta, scale 1:25000, map number 83H/5g Edition 2, Surveys and Mapping Branch, Department of Energy, Mines and Resources, Ottawa.

Fig. 2.1 Type V1S power line tower.

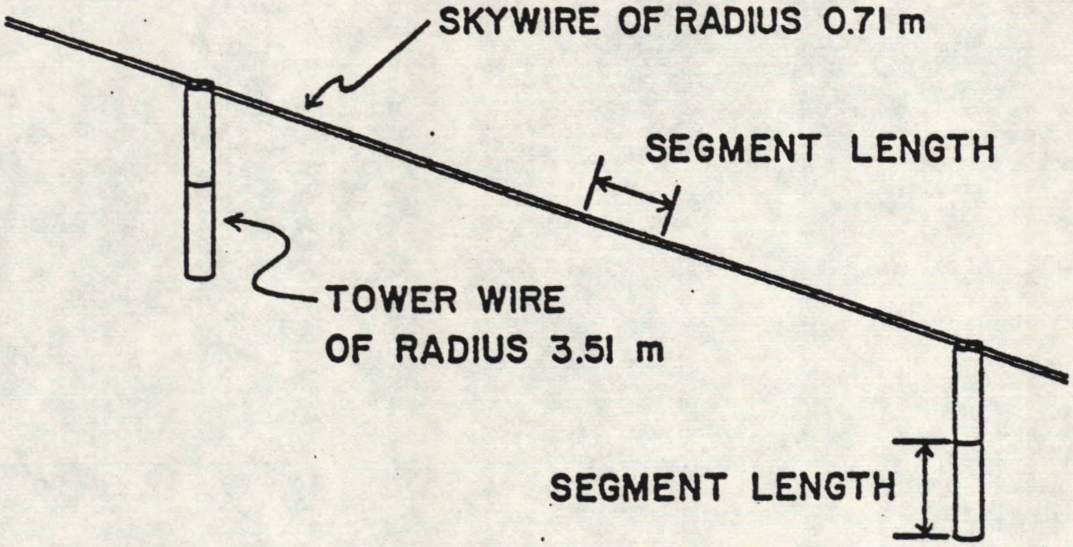


Fig. 2.2 One span of the "single wire tower" computer model of the power line, showing the radii of the wires and the lengths of the segments.

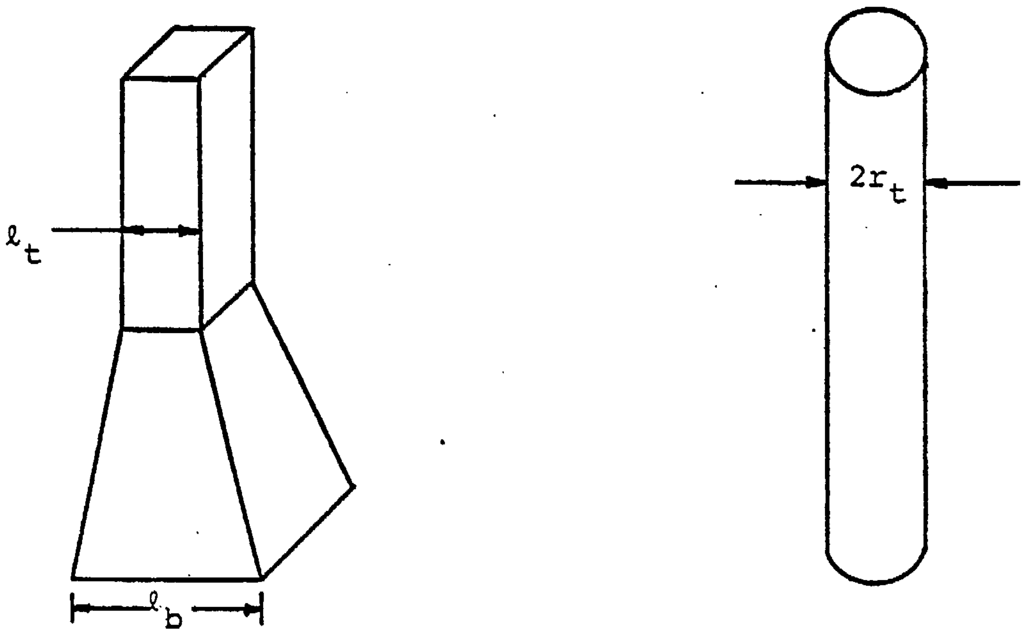


Fig. 2.3 Replacement of the tower by an "equivalent" wire.

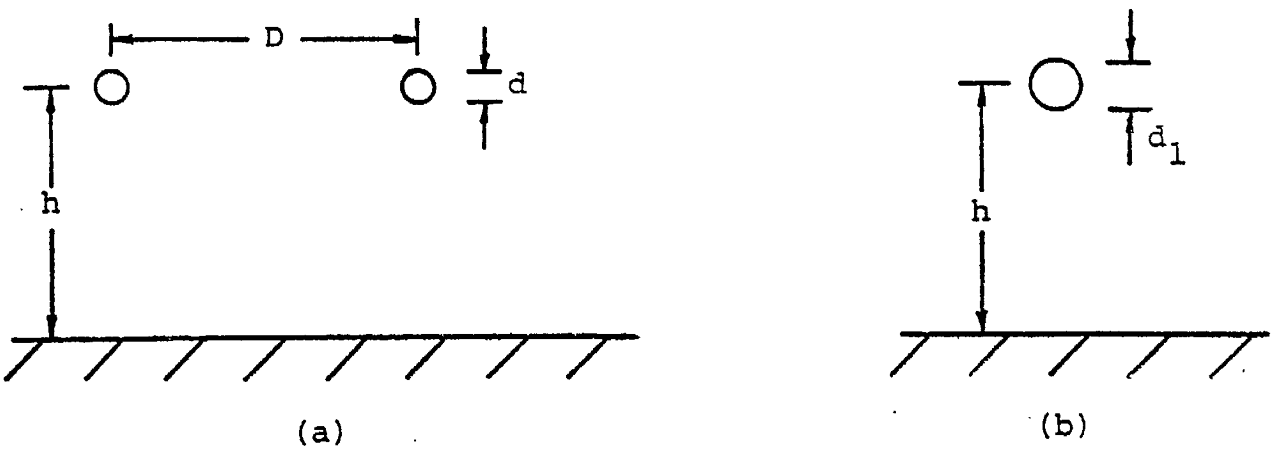


Fig. 2.4 Replacement of the pair of skywires by a single skywire.

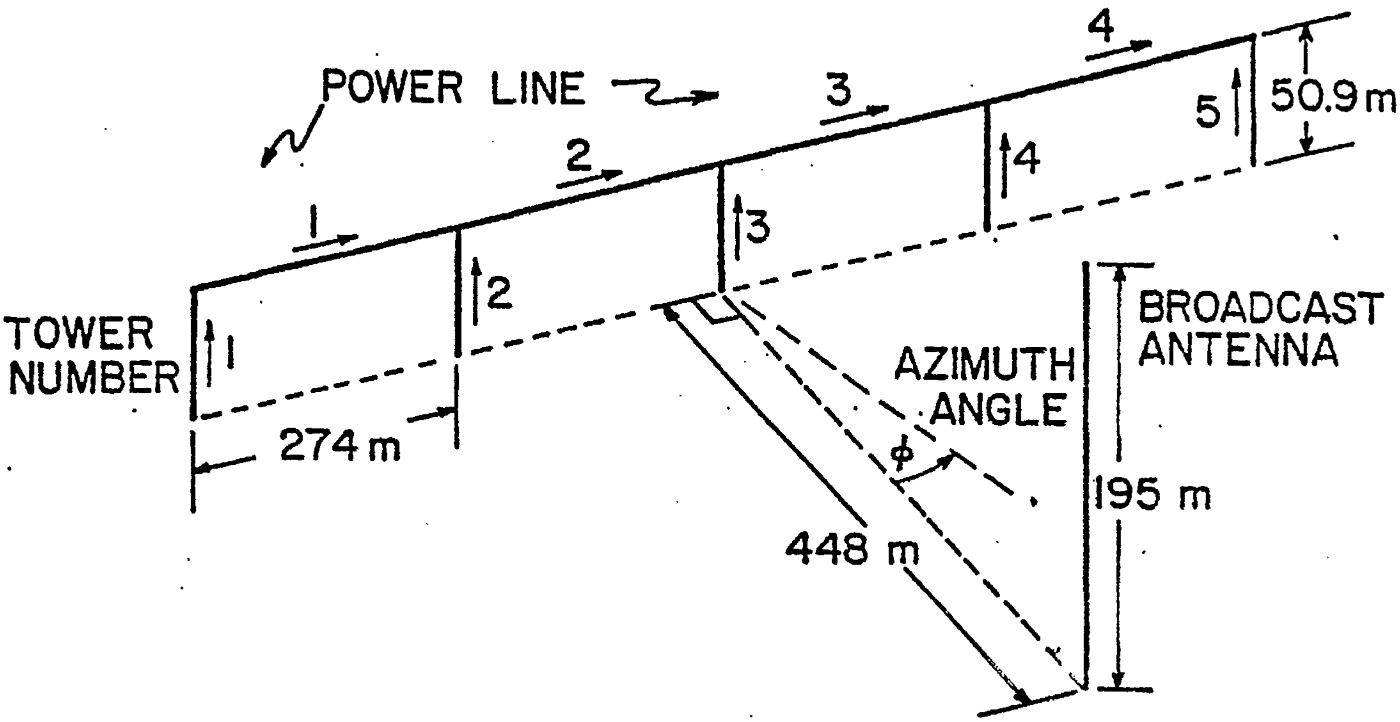


Fig. 2.5 Dimensions of the evenly-spaced power line, which was used with 13 towers to determine the resonant behaviour of a power line below 1000 kHz.

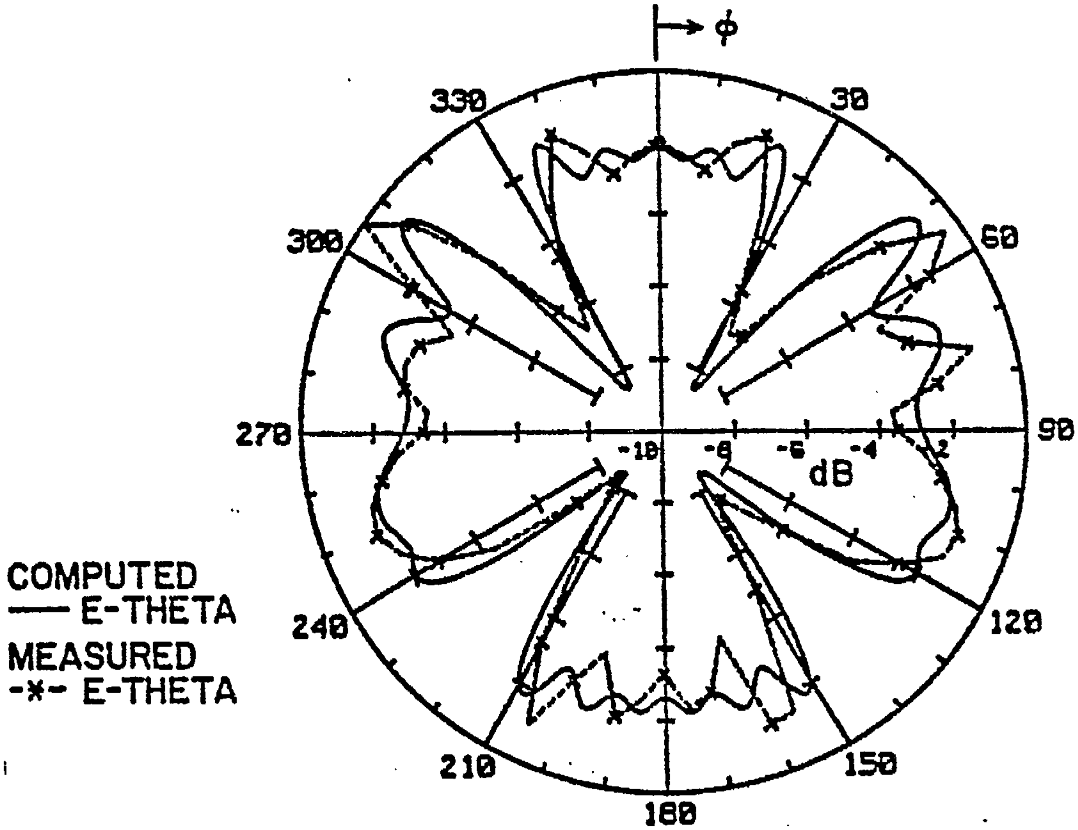


Fig. 2.6 The azimuth pattern at 860 kHz of the power line of Fig. 2.5 with 13 towers. The figure compares a computed pattern with a measured pattern using 600 scale factor towers over a highly-conducting ground plane.

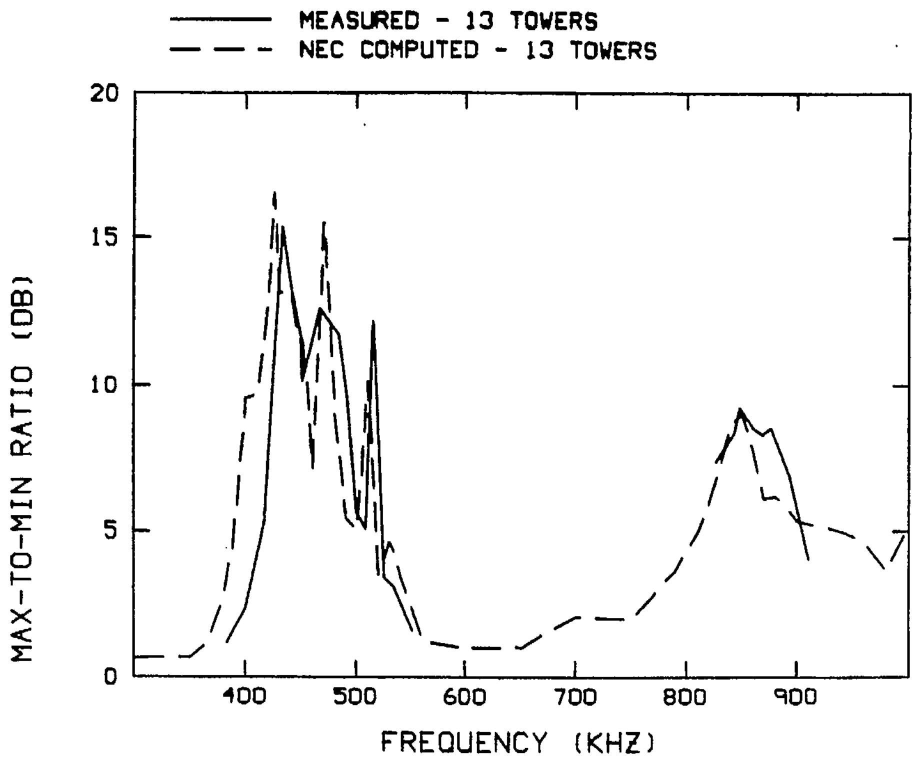


Fig. 2.7 The "max-to-min" ratio of the azimuth pattern of the power line of Fig. 2.5 with 13 towers, showing a resonance band between 380 and 530 kHz and a second resonance band from 760 to at least 1000 kHz.

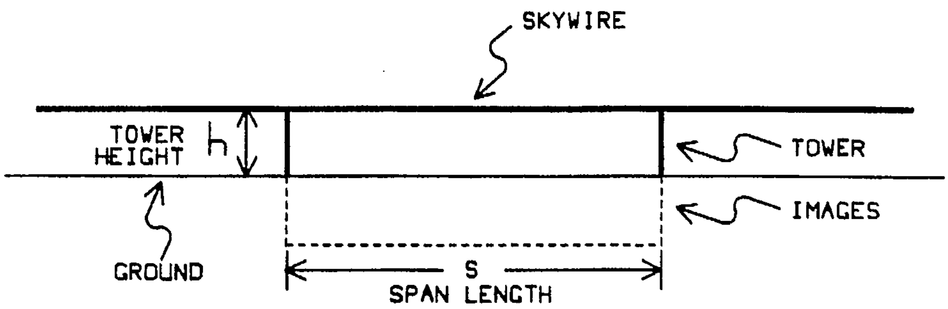


Fig. 2.8 The resonant path consists of two towers with their interconnecting skywires, and a return path on the images in the ground.

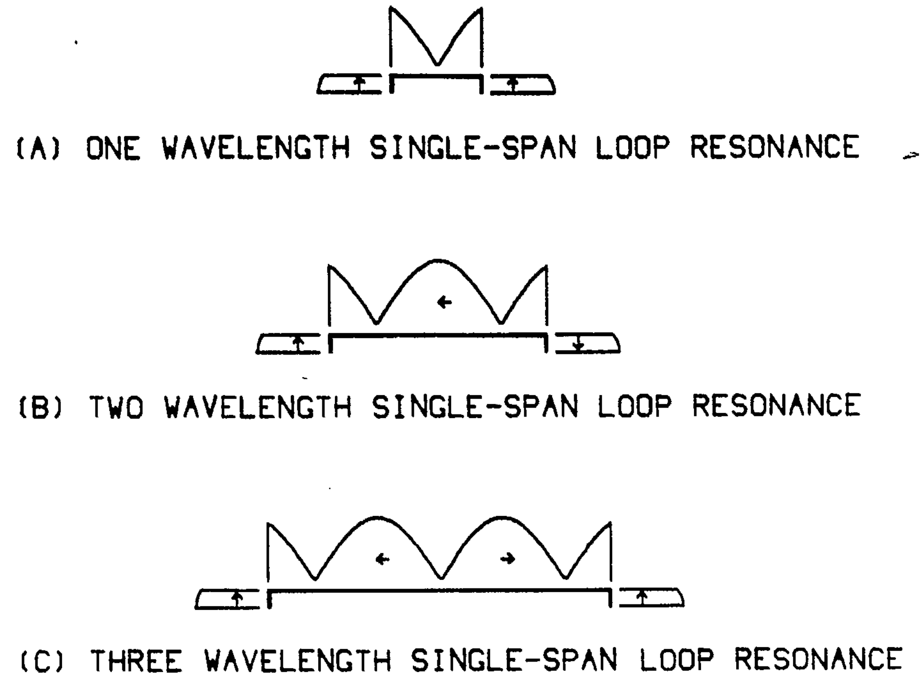


Fig. 2.9 Single-span loop resonance modes.

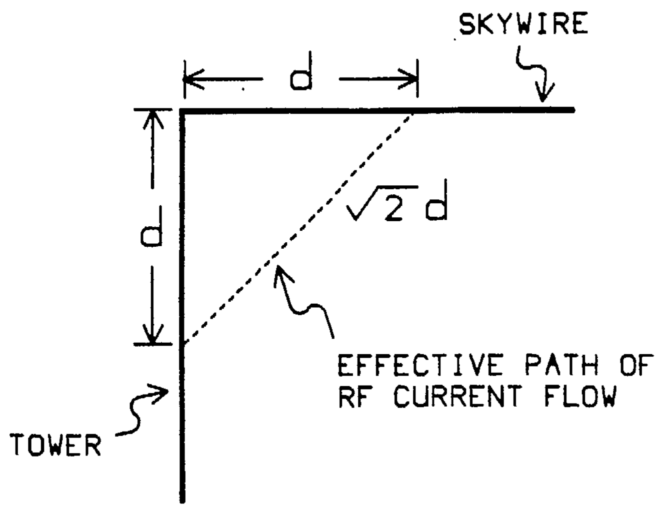
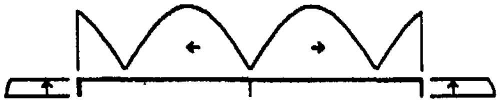
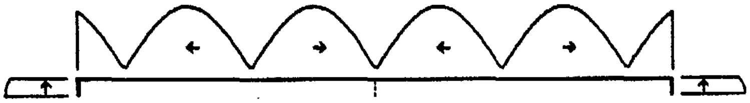


Fig. 2.10 Path length correction for the "cut-corner" estimate of resonant frequencies.



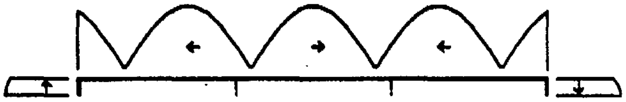
(A) THREE WAVELENGTH DOUBLE-SPAN LOOP RESONANCE

(B) FOUR WAVELENGTH DOUBLE-SPAN LOOP RESONANCE



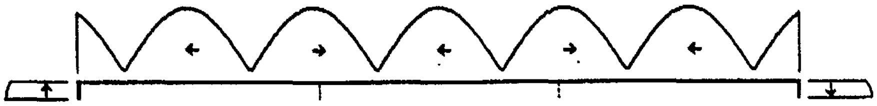
(C) FIVE WAVELENGTH DOUBLE-SPAN LOOP RESONANCE

Fig. 2.11 Double-span loop resonance modes.



(A) FOUR WAVELENGTH TRIPLE-SPAN LOOP RESONANCE

(B) FIVE WAVELENGTH TRIPLE-SPAN LOOP RESONANCE



(C) SIX WAVELENGTH TRIPLE-SPAN LOOP RESONANCE

Fig. 2.12 Triple-span loop resonance modes.

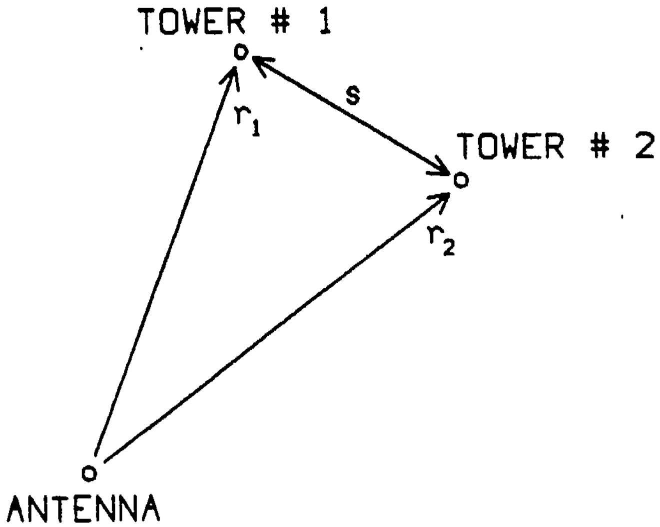


Fig. 2.13 Geometrical distances used to analyse the span excitation.

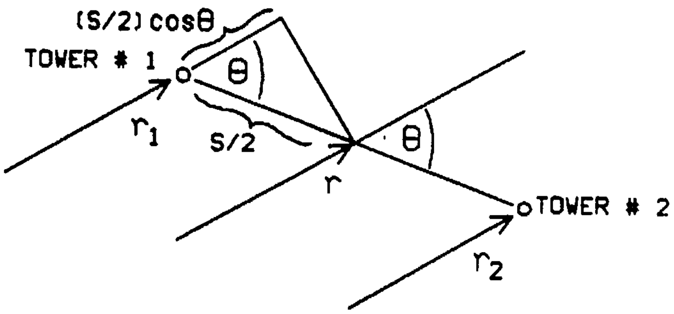


Fig. 2.14 Comparison of distances for $r \gg s$.

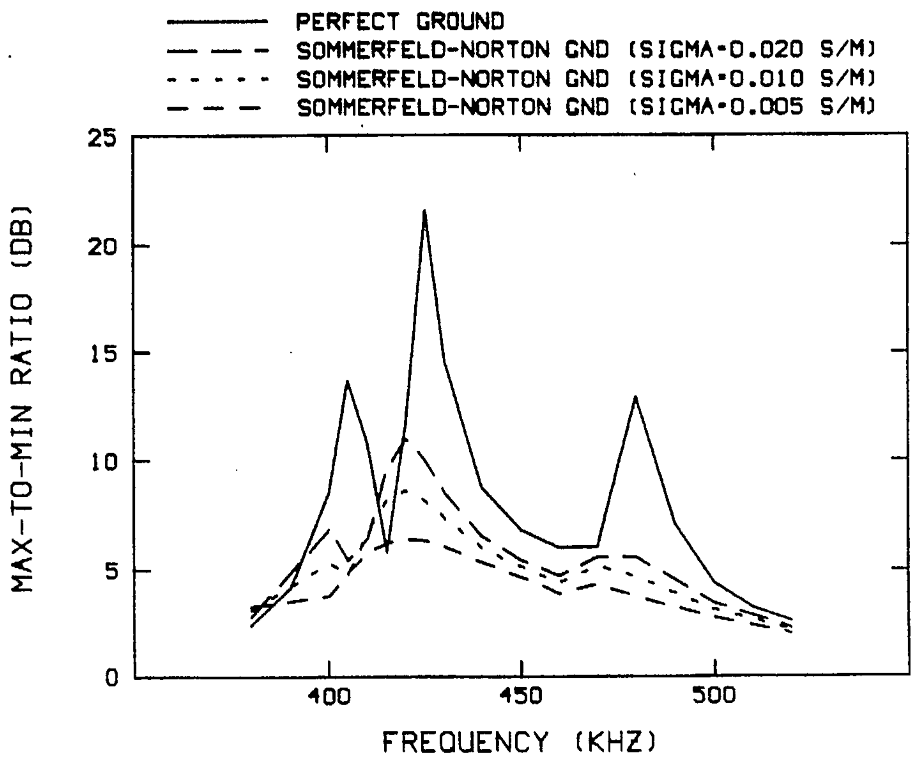


Fig. 2.15 Max-to-min ratio of the azimuth pattern for various ground conductivities using the Sommerfeld-Norton ground model, in comparison to the perfect ground model, in the frequency range of one wavelength loop resonance.

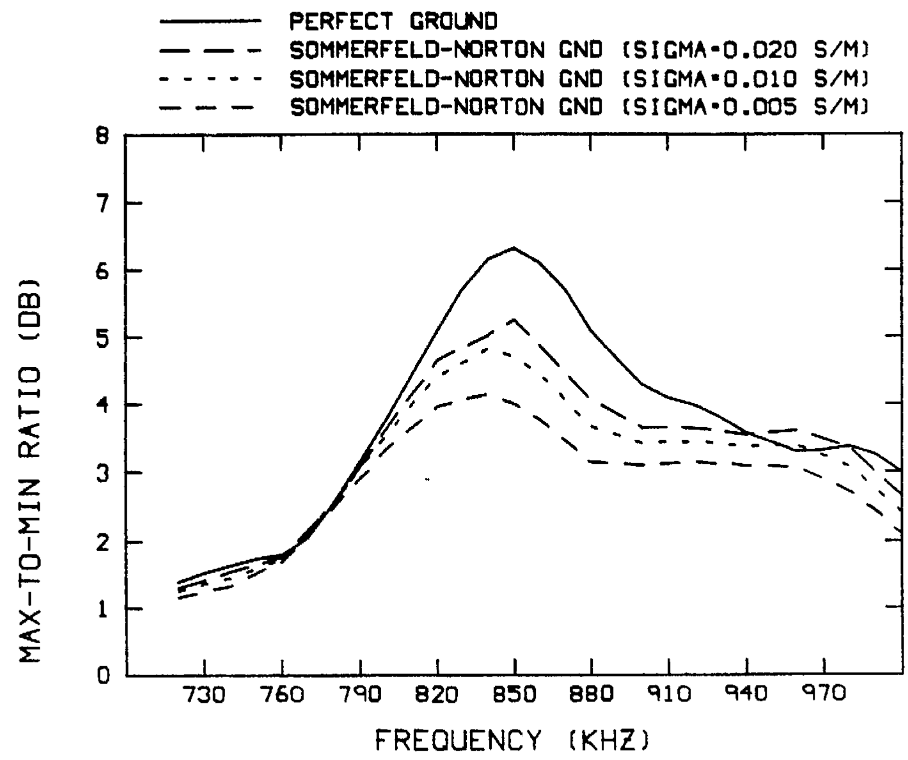


Fig. 2.16 Max-to-min ratio of the azimuth pattern for various ground conductivities using the Sommerfeld-Norton ground model, in comparison to the perfect ground model, in the frequency range of two wavelength loop resonance.

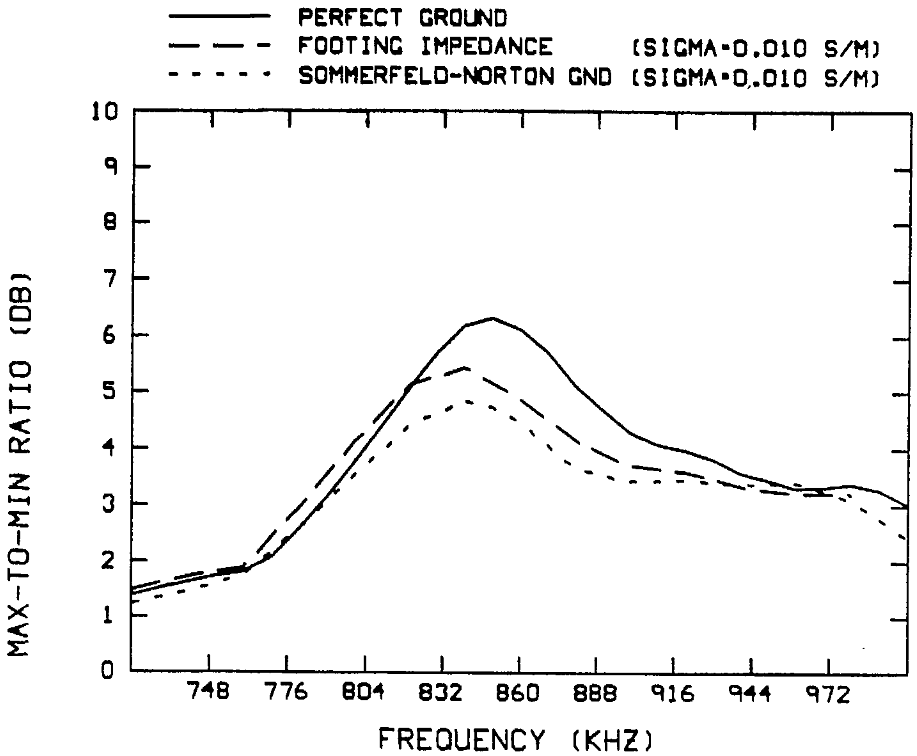


Fig. 2.17 Max-to-min ratio of the azimuth pattern for ground conductivity 10 mmho/m, comparing the "footing impedance" model with the Sommerfeld-Norton ground model and the perfect ground model, in the frequency range of two wavelength loop resonance.

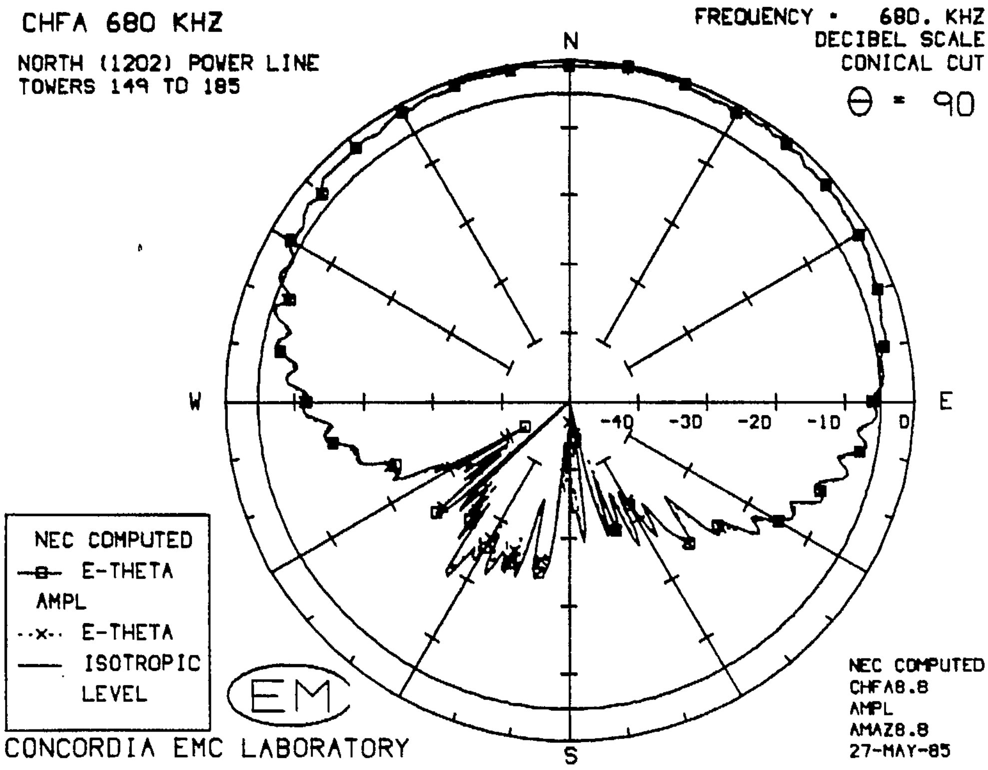


Fig. 2.18 Comparison of the azimuth pattern for the CHFA antenna near the ""north" power line of Fig. 4.4, as computed using the AMPL program against that computed with the NEC program.

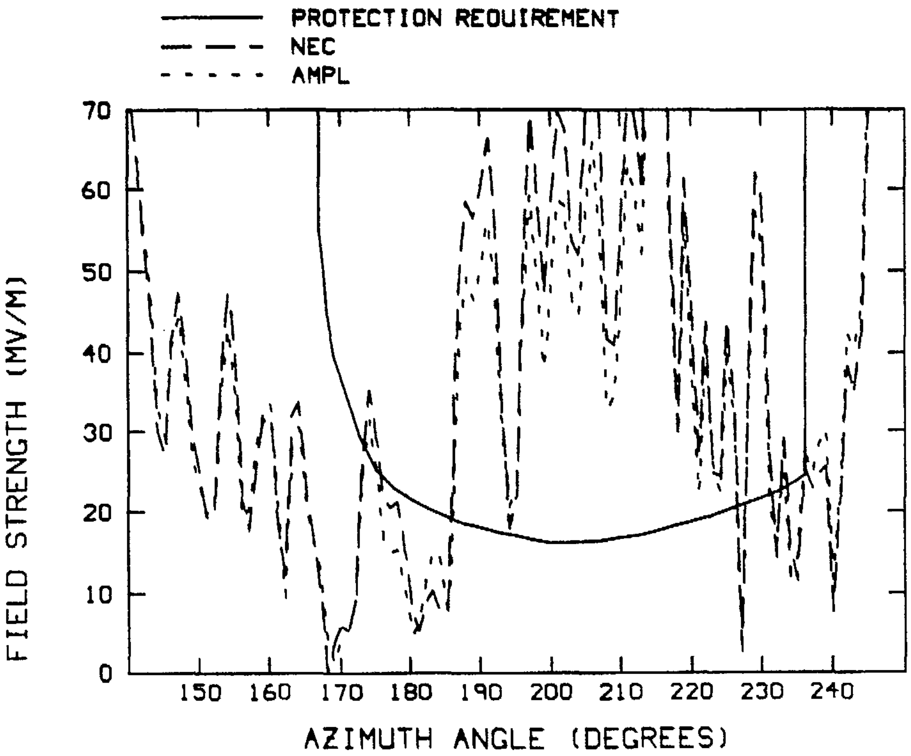
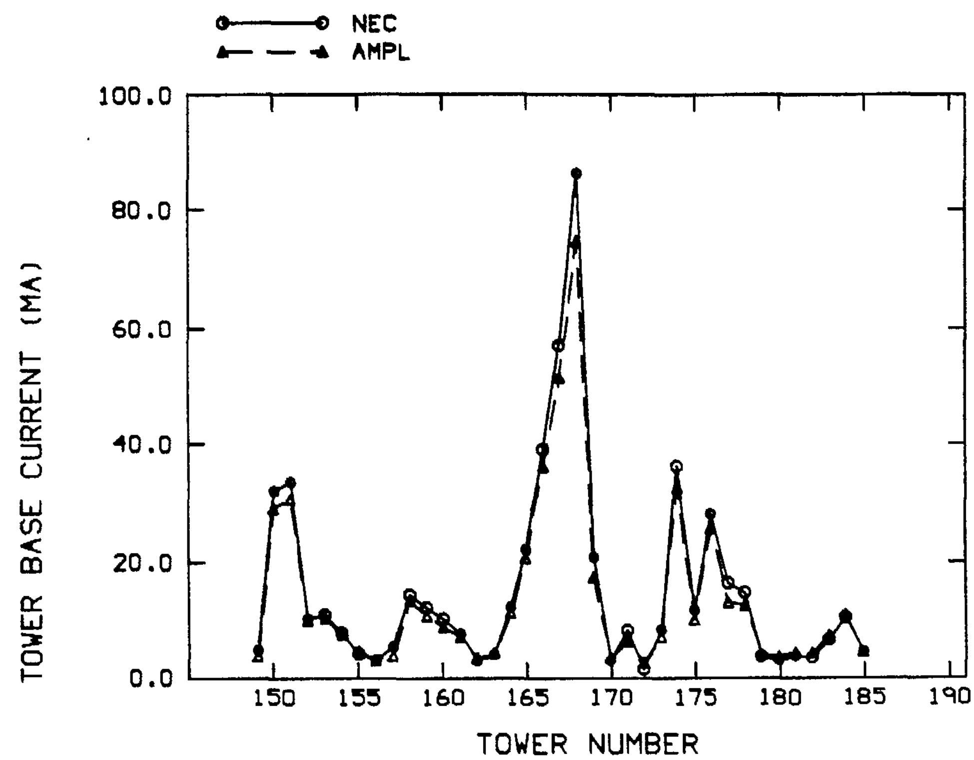
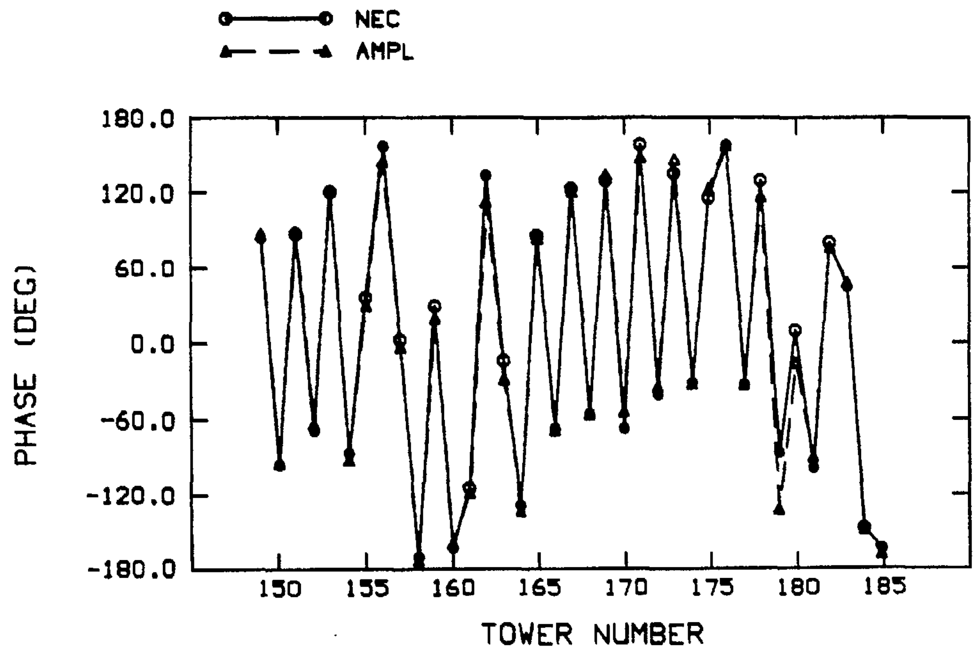


Fig. 2.19 Comparison of the field strength in the protected arc of the pattern of the CHFA antenna near the ""north" power line of Fig. 4.4, as computed using the AMPL program against that computed with the NEC program.



(a) Magnitude of the RF current flow.



(b) Phase of the tower base currents.

Fig. 2.20 The RF current flowing at the bases of the towers of the power line of Fig. 4.4 excited by the CHFA antenna, as computed by AMPL and by NEC.

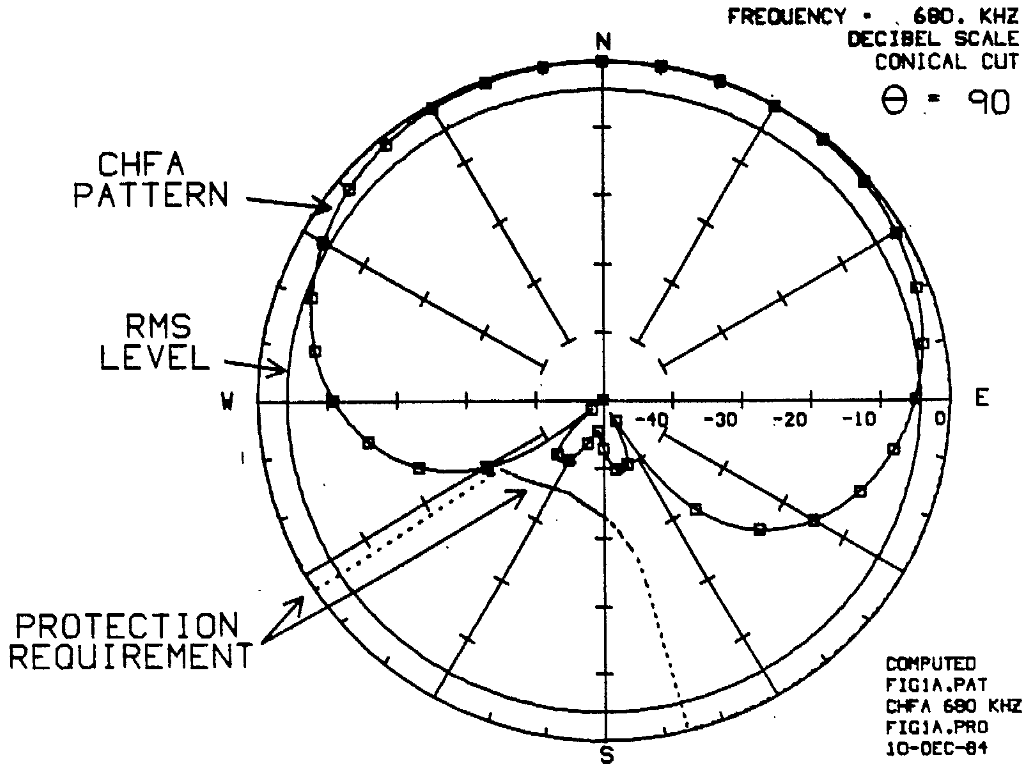


Fig. 3.1 (a) Azimuth pattern of the CHFA broadcast array, showing the protection requirement, plotted on a decibel scale.

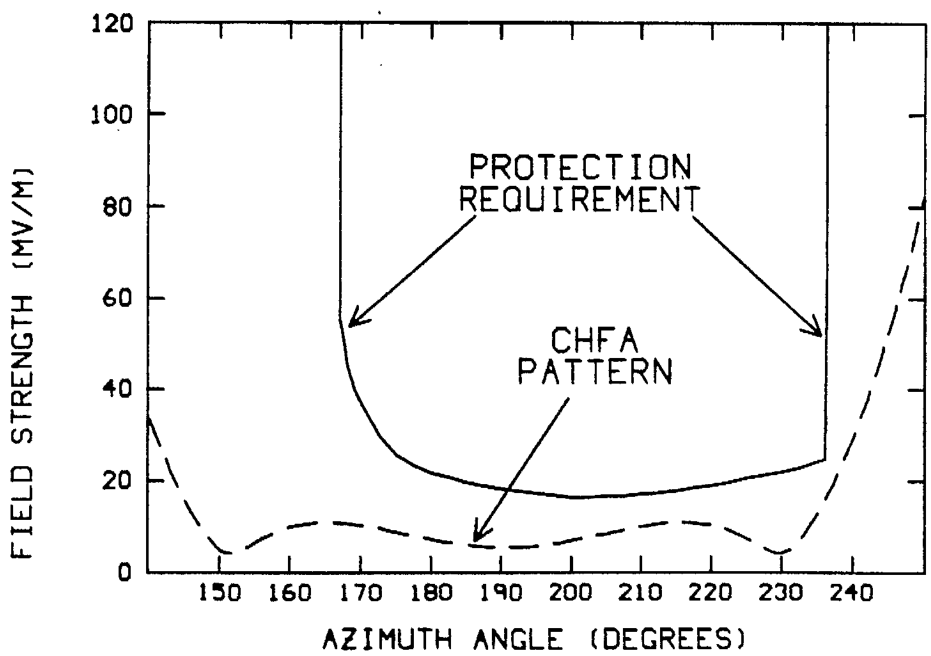


Fig. 3.1 (b) The field strength of the CHFA array over the restricted arc, showing the protection requirement. The effective field strength of the antenna is 590 mV/m at one mile.

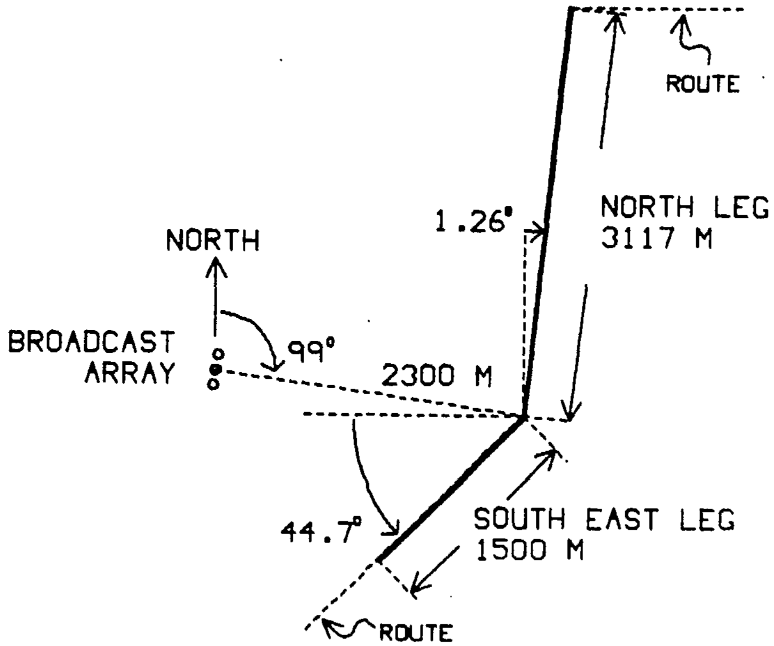


Fig. 3.2 The route of the "proposed" southeast power line. The section of the power line included in the computer model is indicated with solid lines, and dashed lines show the sections not represented.

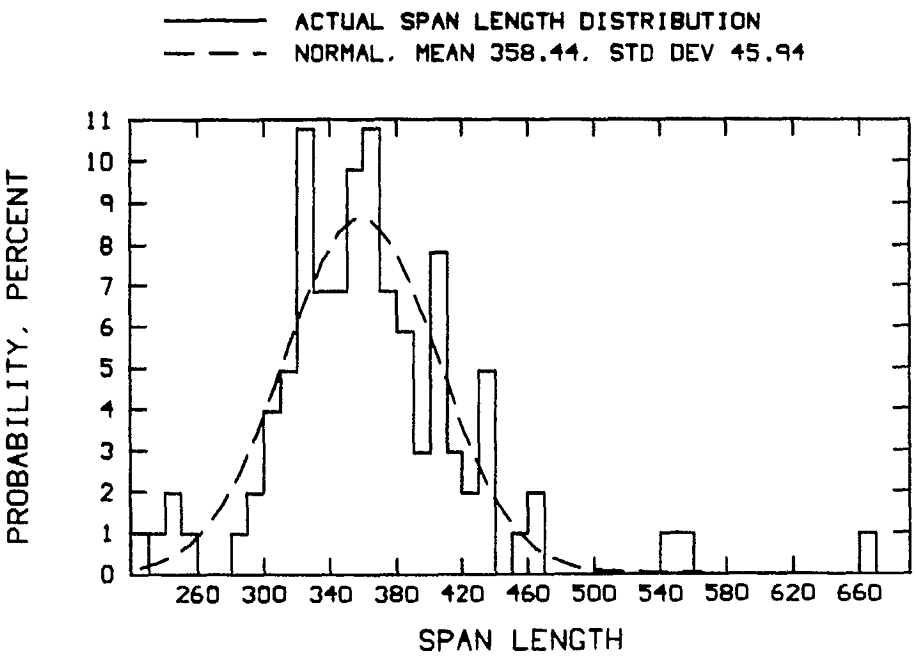


Fig. 3.3 The probability that the span length lies between s-5 and s+5 as a function of s. The actual distribution of span lengths for the power lines built near CHFA is compared with a "normal" probability distribution with mean 358.4 m and standard deviation 45.9 m.

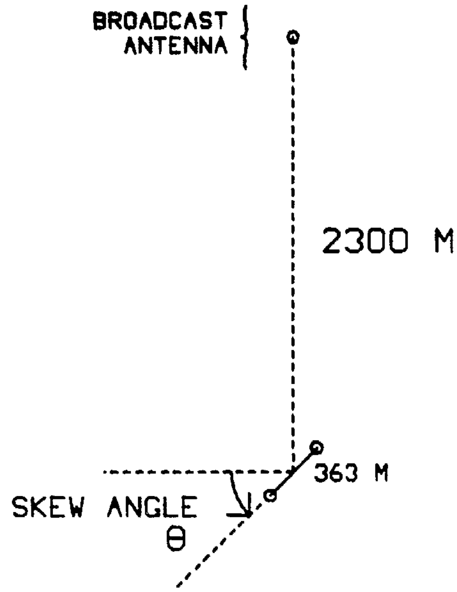


Fig. 3.4 An omnidirectional antenna illuminating one isolated span of a power line.

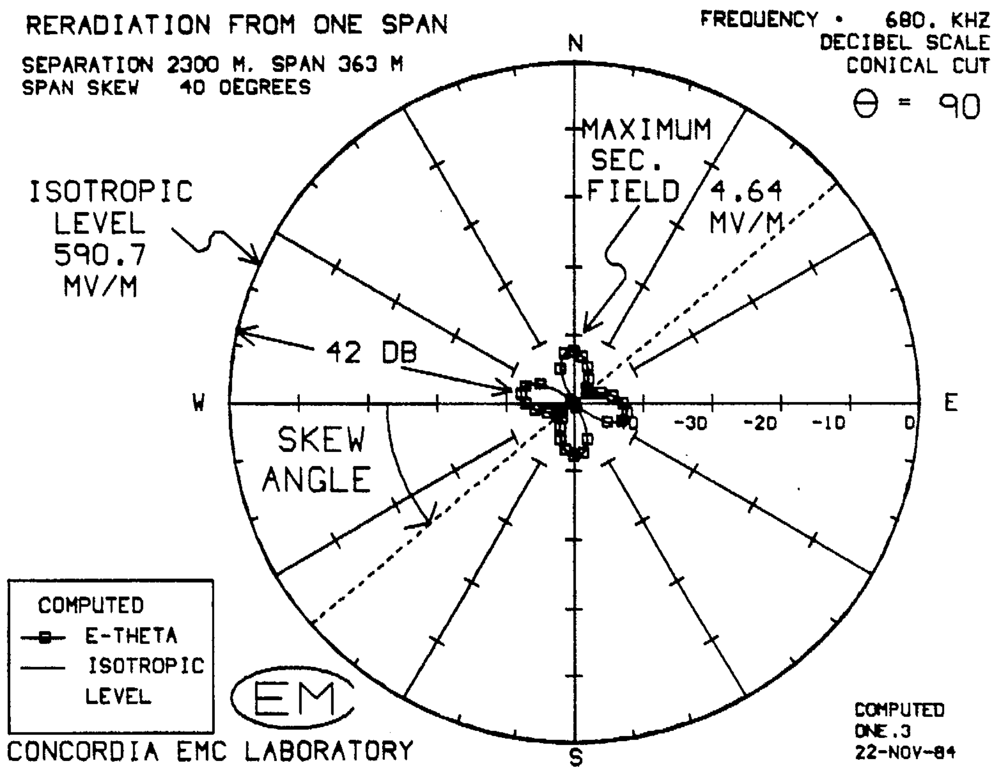


Fig. 3.5 The azimuth pattern of the reradiated field from one isolated span of length 363 m and skew angle 40 degrees. The maximum reradiated field is 4.6 mV/m at one mile compared to the antenna's field of 590.7 mV/m.

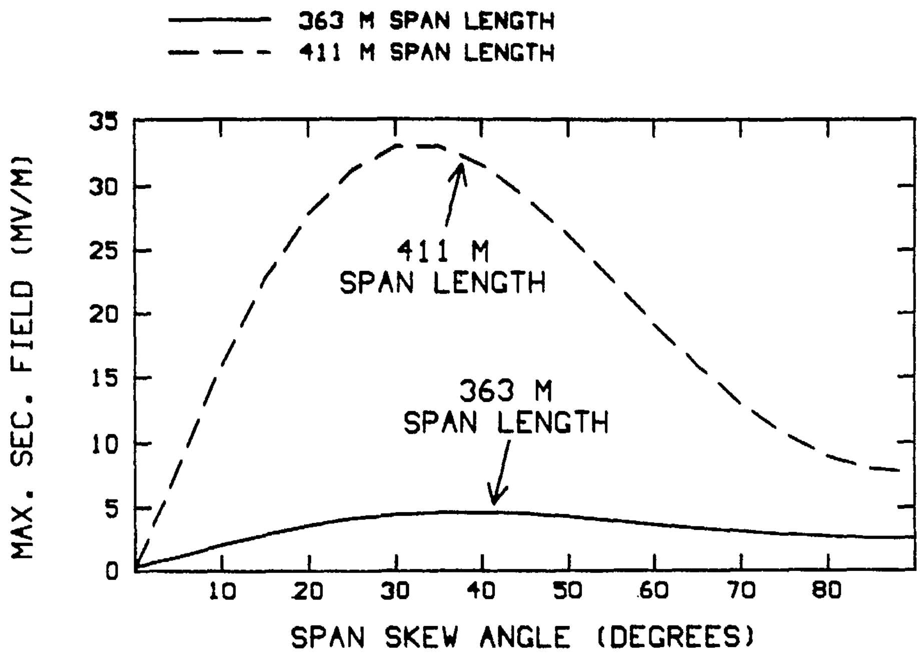


Fig. 3.6 The maximum value of the field reradiated from one isolated span as a function of the skew angle of the span, for two values of the span length.

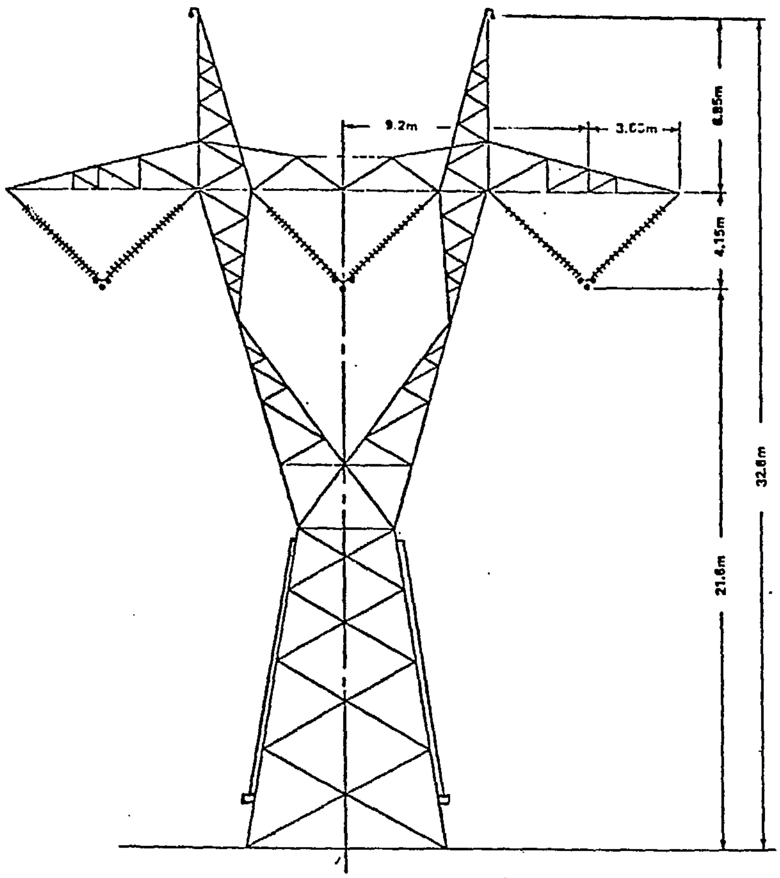


Fig. 3.7 (a) A type Z7S power line tower.

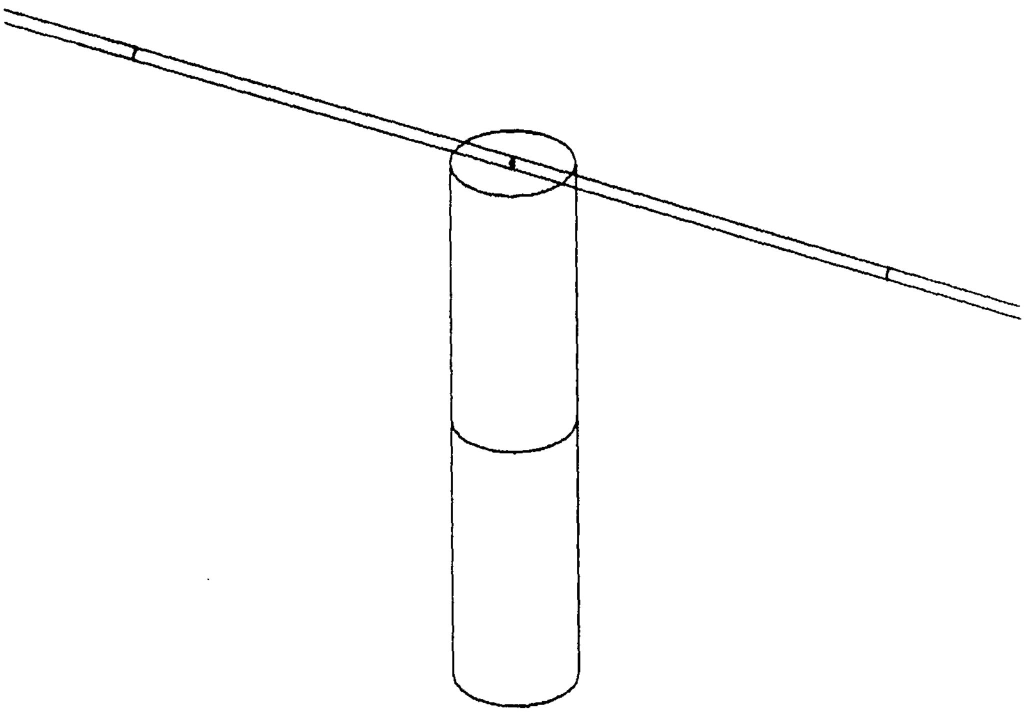


Fig. 3.7 (b) The computer model used to analyse reradiation from a type Z7S tower. The tower wire has a radius of 4 m, and the skywire radius is 0.76 m.

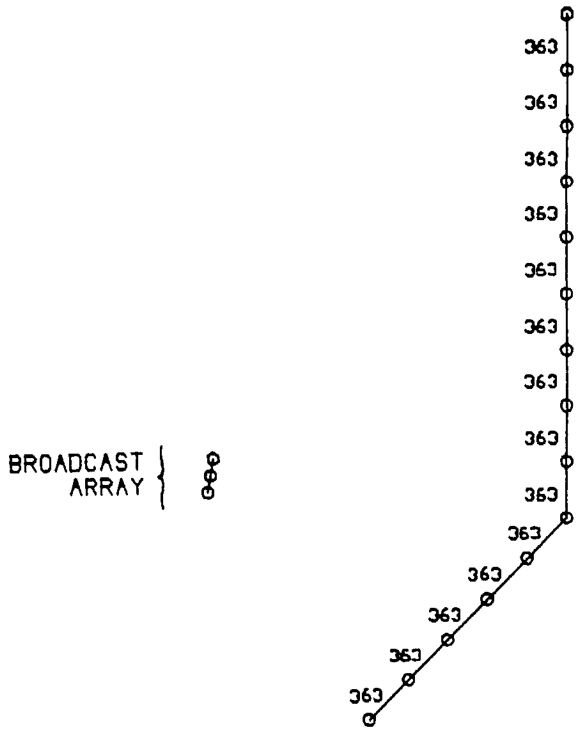


Fig. 3.8 A power line with uniformly-spaced towers 363 m apart, following the route of Fig. 3.2.

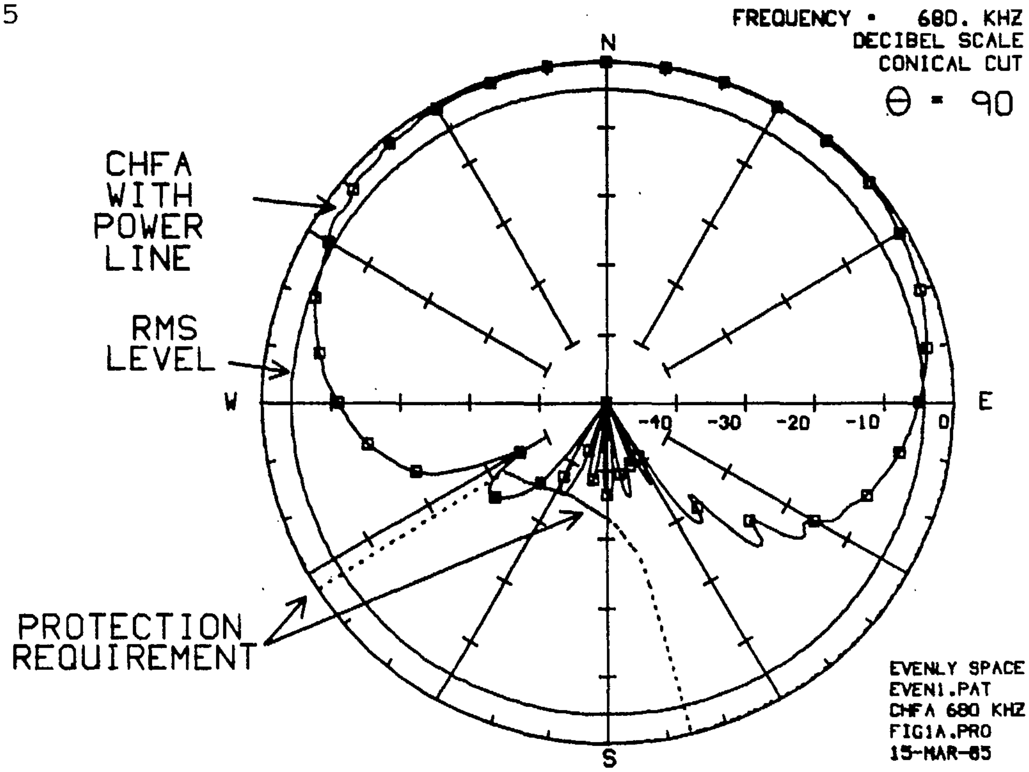


Fig. 3.9 (a) The azimuth pattern of the CHFA array operating near the power line of Fig. 3.8, with uniformly-spaced towers 363 m apart.

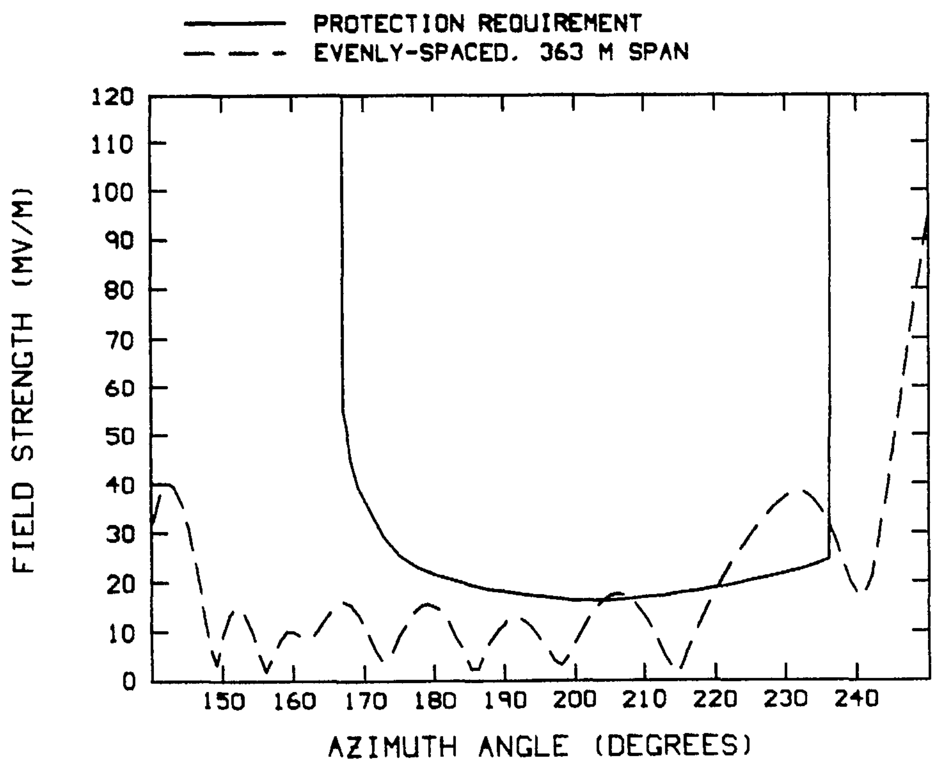


Fig. 3.9 (b) The field strength over the restricted arc of the CHFA array operating near the power line of Fig. 3.8. The protection requirement is exceeded by about 16 mV/m at about 232 degrees.

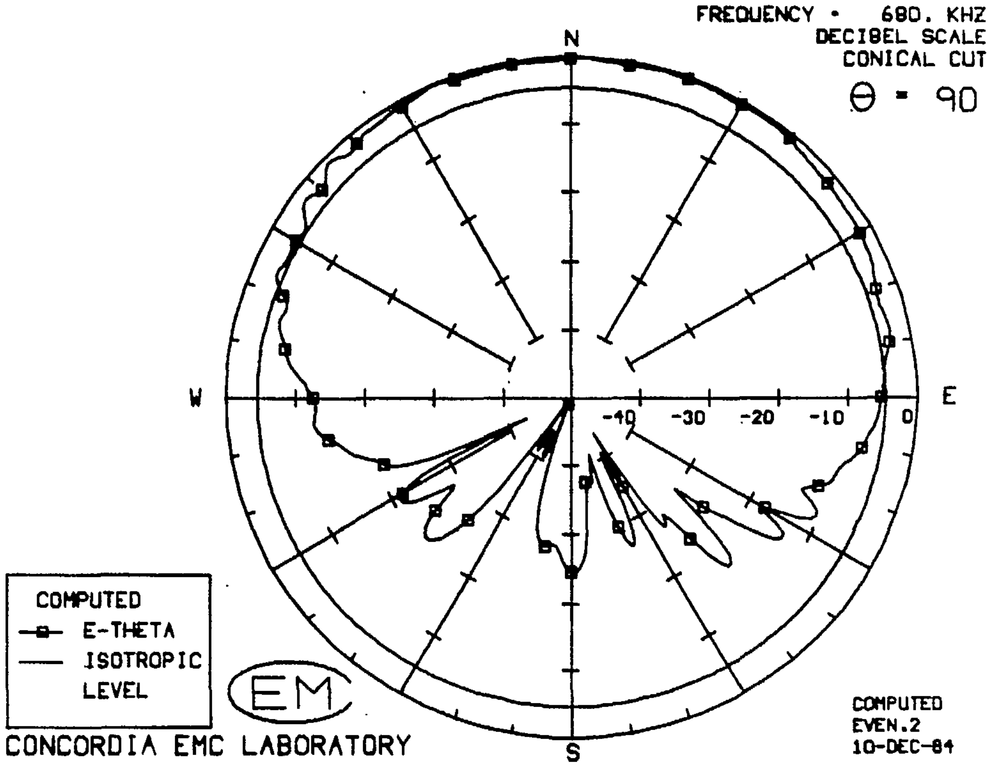


Fig. 3.10 (a) The azimuth pattern of the CHFA array operating near a power line with uniformly-spaced towers 411 m apart.

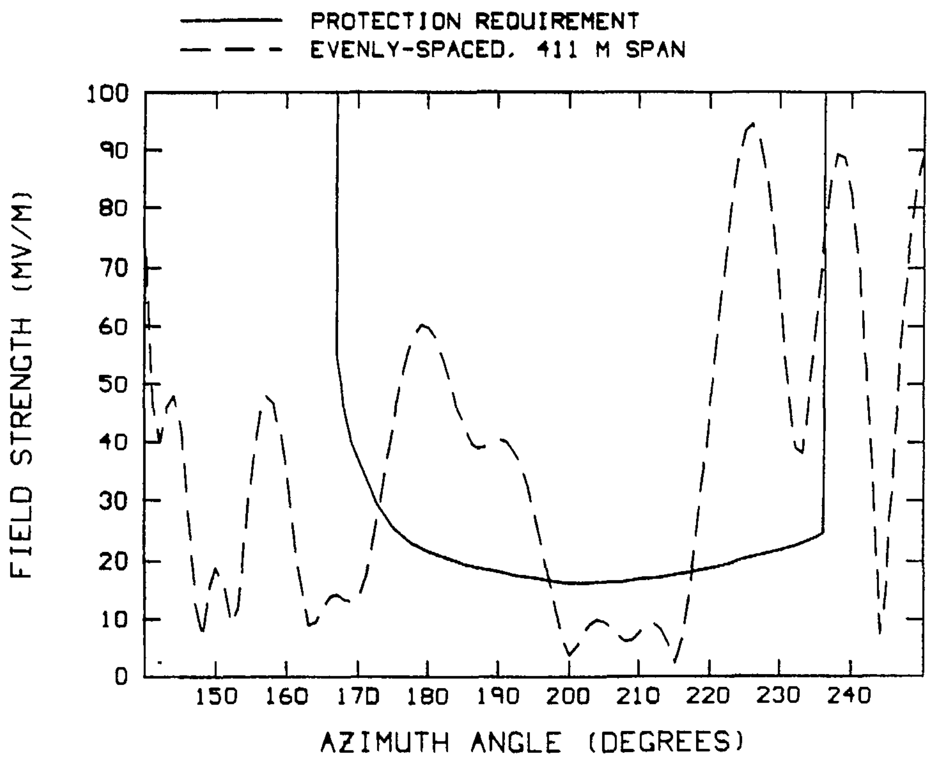


Fig. 3.10 (b) The field strength over the restricted arc. The protection requirement is exceeded by about 74 mV/m at about 227 degrees.

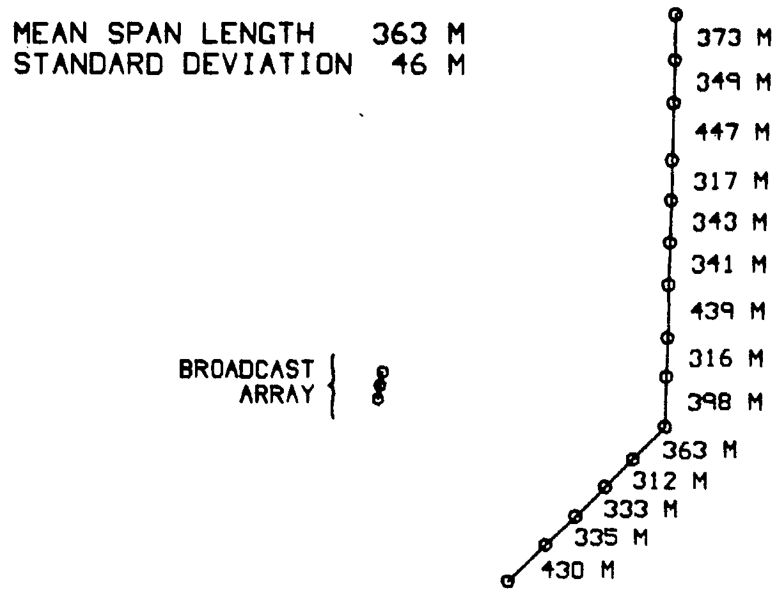


Fig. 3.11 (a) A power line following the route of Fig. 3.2, with span lengths randomly chosen to be "normally" distributed with a mean value of 363 m and a standard deviation of 46 m.

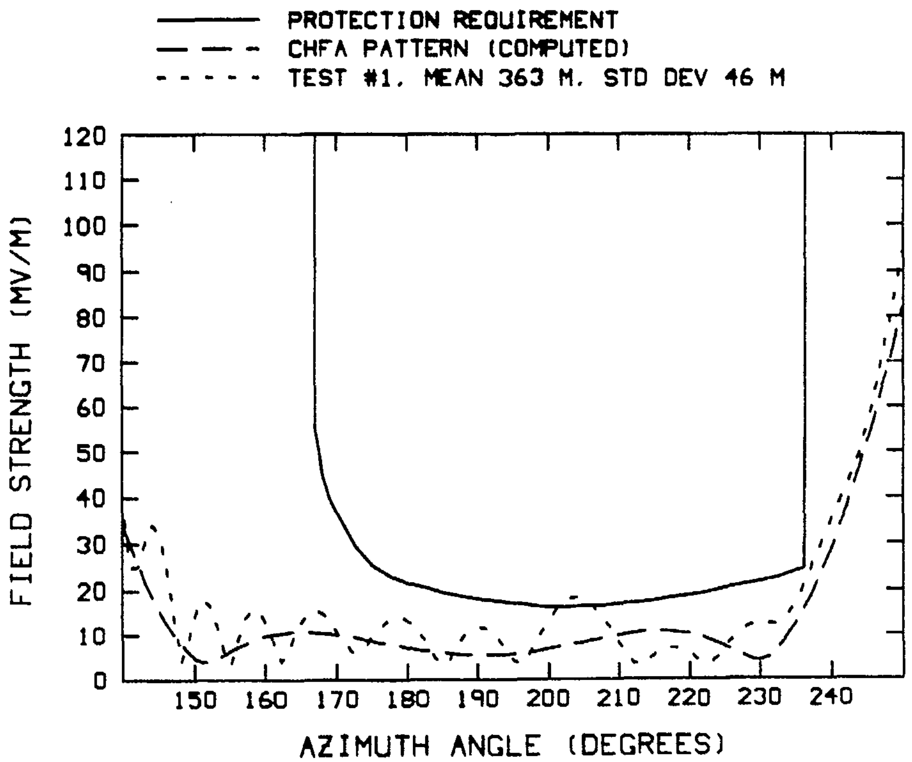


Fig. 3.11 (b) The field strength over the restricted arc of the CHFA array operating near the power line of part (a). The protection requirement is exceeded by 1.7 mV/m.

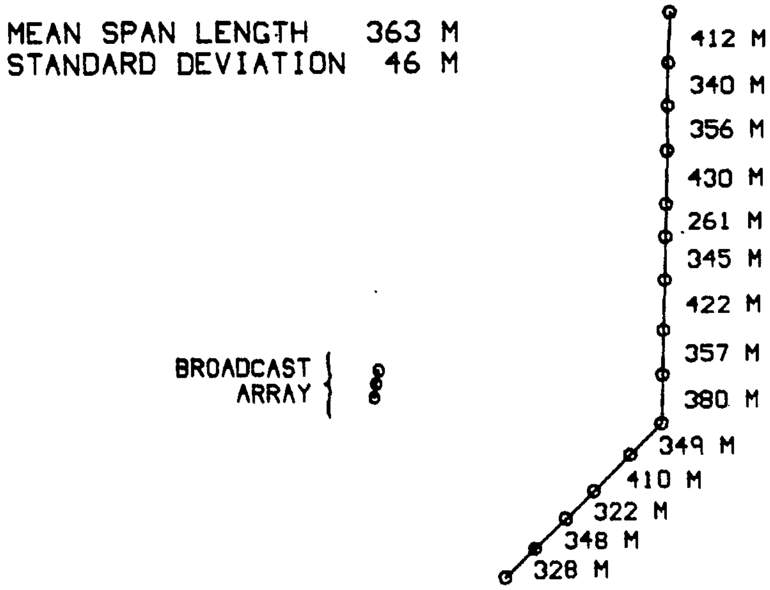


Fig. 3.12 (a) A power line following the route of Fig. 3.2, with span lengths randomly chosen to be "normally" distributed with a mean value of 363 m and a standard deviation of 46 m.

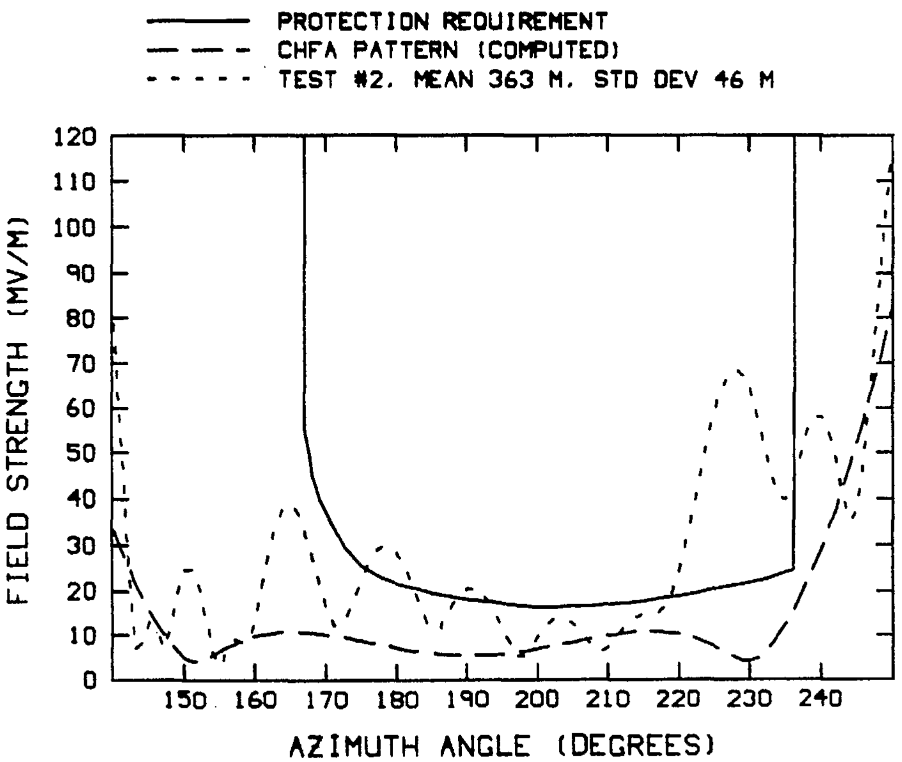


Fig. 3.12 (b) The field strength over the restricted arc of the CHFA array operating near the power line of part (a). The protection requirement is exceeded by 47 mV/m.

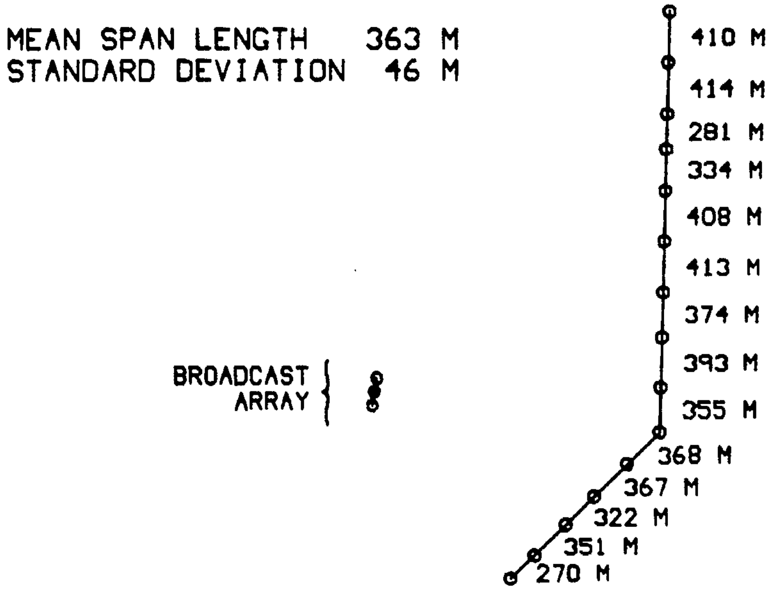


Fig. 3.13 (a) A power line following the route of Fig. 3.2, with span lengths randomly chosen to be "normally" distributed with a mean value of 363 m and a standard deviation of 46 m.

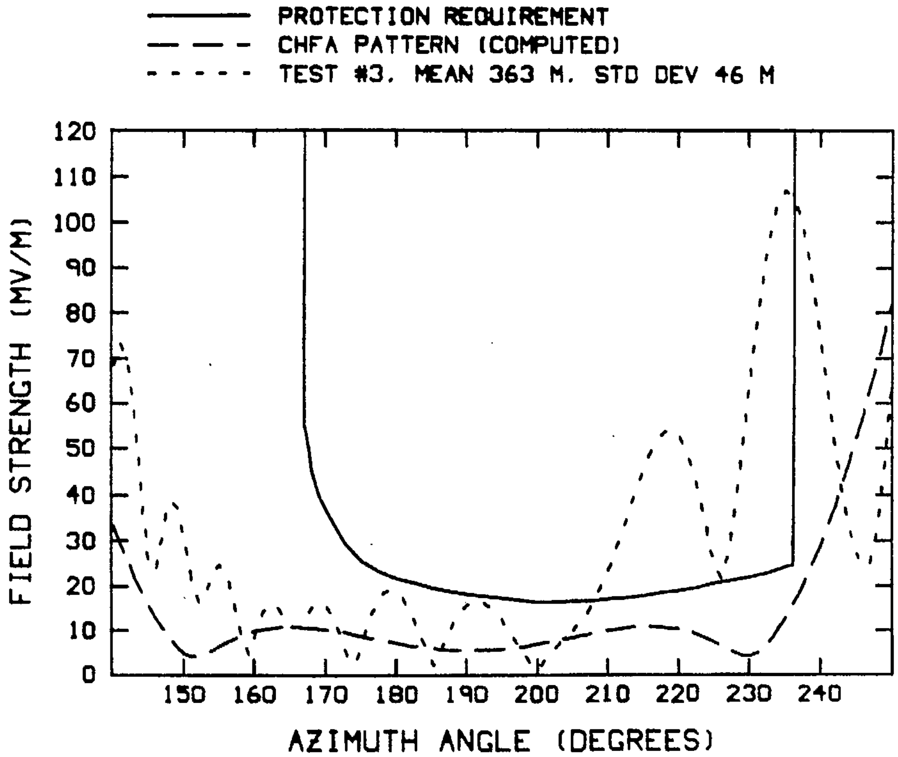


Fig. 3.13 (b) The field strength over the restricted arc of the CHFA array operating near the power line of part (a). The protection requirement is exceeded by 83 mV/m.

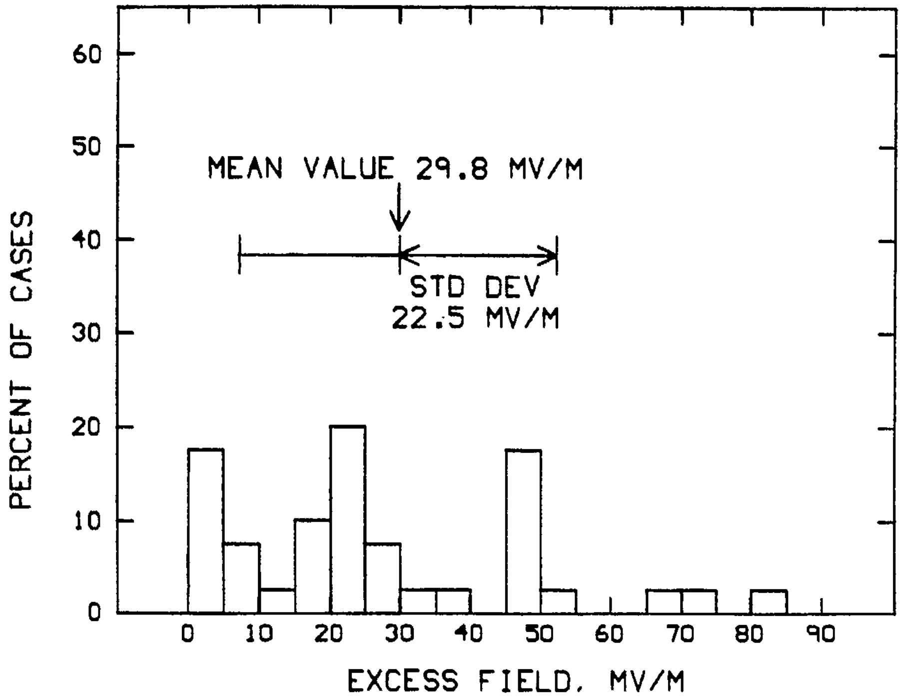


Fig. 3.14 Bar graph showing the distribution of the excess field values obtained for 40 cases of the CHFA antenna operating near each one of 40 different "test" power lines, with "normally" distributed span lengths with mean value 363 m and standard deviation 46 m.

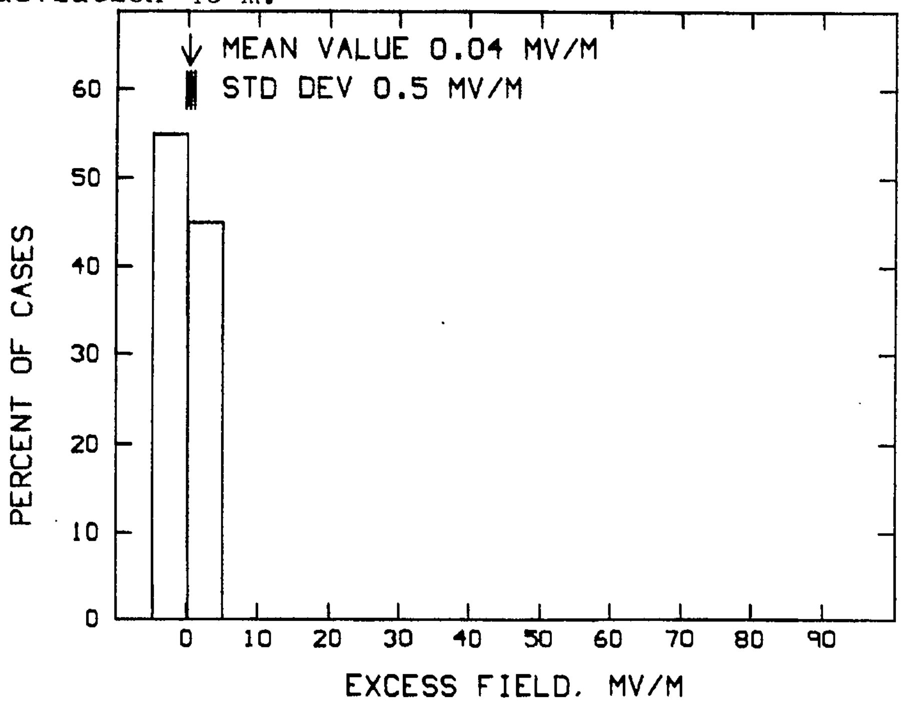


Fig. 3.15 Bar graph showing the distribution of the excess field values obtained from 20 cases of CHFA operating near a power line with mean span length 292 m, and standard deviation 10 m.

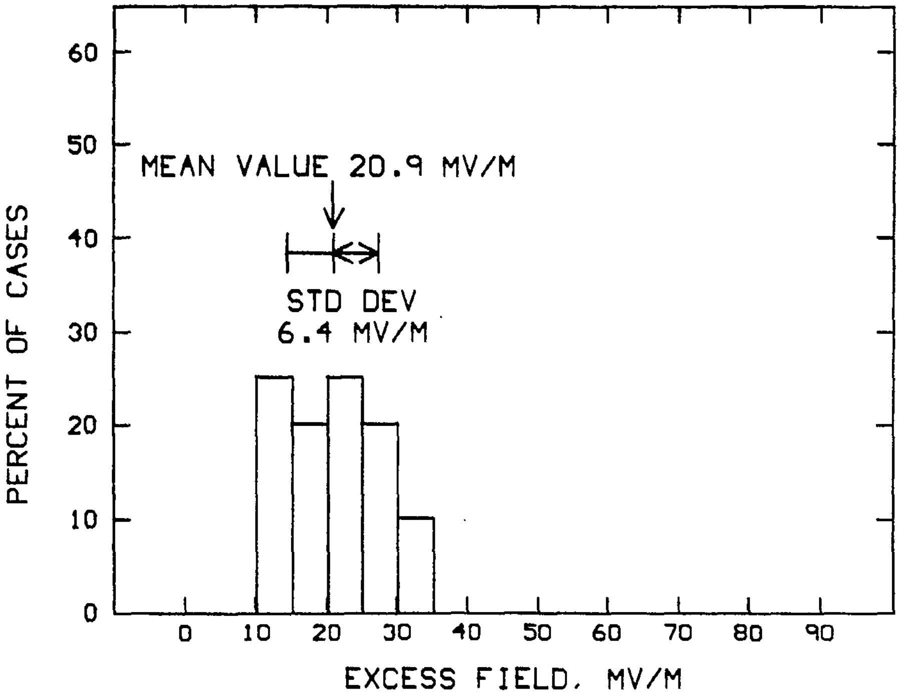


Fig. 3.16 Bar graph showing the distribution of the excess field values obtained from 20 cases of CHFA operating near a power line with mean span length 363 m, and standard deviation 10 m.

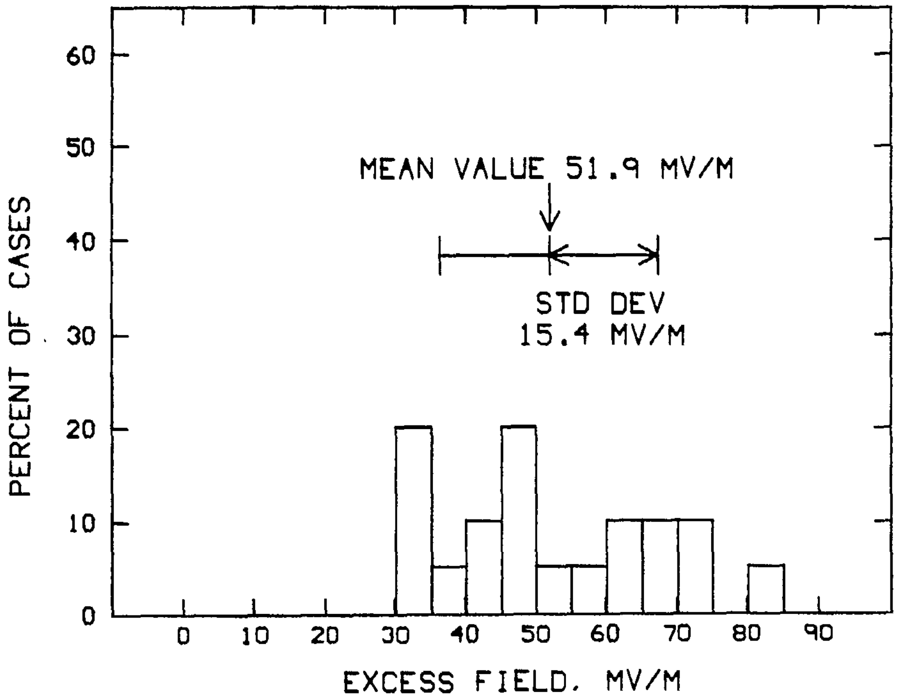


Fig. 3.17 Bar graph showing the distribution of the excess field values obtained from 20 cases of CHFA operating near a power line with mean span length 411 m, and standard deviation 10 m.

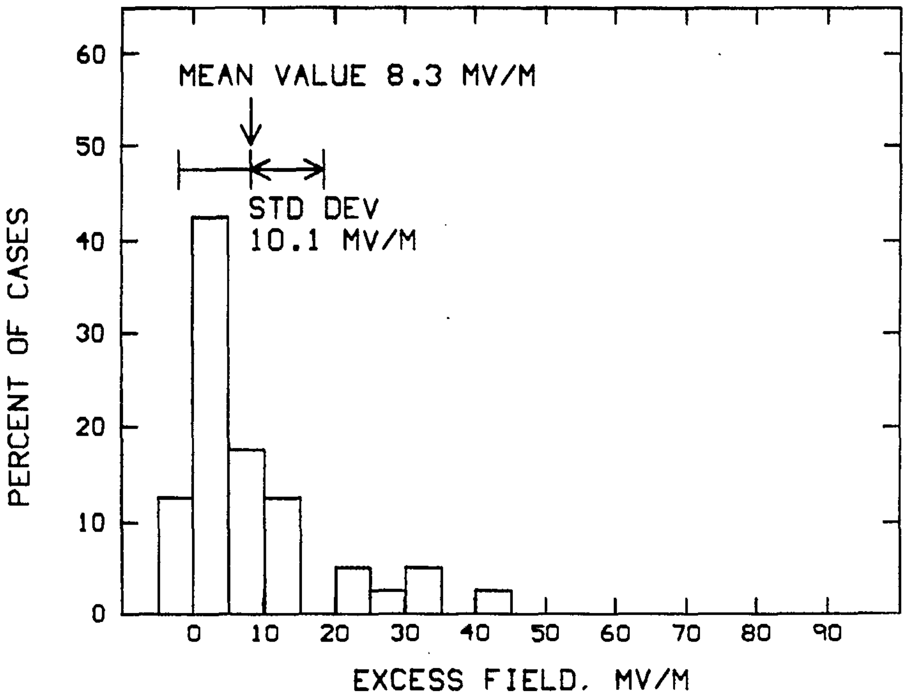


Fig. 3.18 Bar graph showing the distribution of the excess field values obtained from 40 cases of CHFA operating near a power line with mean span length 292 m, and standard deviation 46 m.

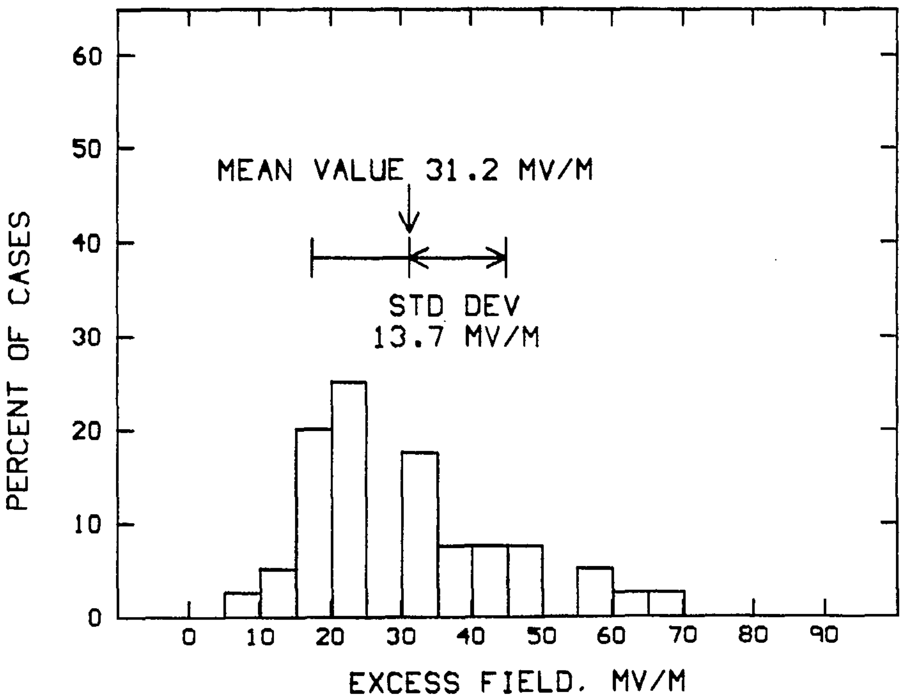


Fig. 3.19 Bar graph showing the distribution of the excess field values obtained from 40 cases of CHFA operating near a power line with mean span length 411 m, and standard deviation 46 m.

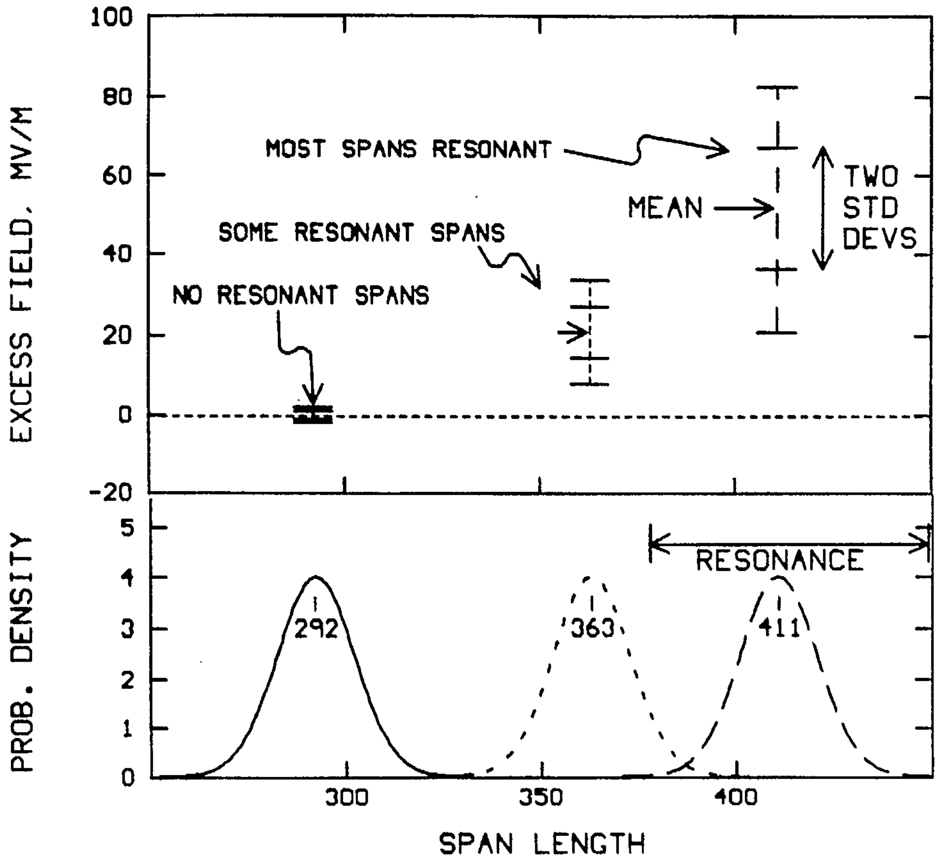


Fig. 3.20 The lower portion of this graph shows the "normal" probability density curve expressed as a percentage, for standard deviation 10 m, and for mean value 292, 363 and 411 m. The span lengths are tightly custered around the mean value. The upper part of the curve shows the distribution of the excess field values obtained from power lines with these span statistics, using a vertical bar four standard deviations wide centered on the mean value of the excess field.

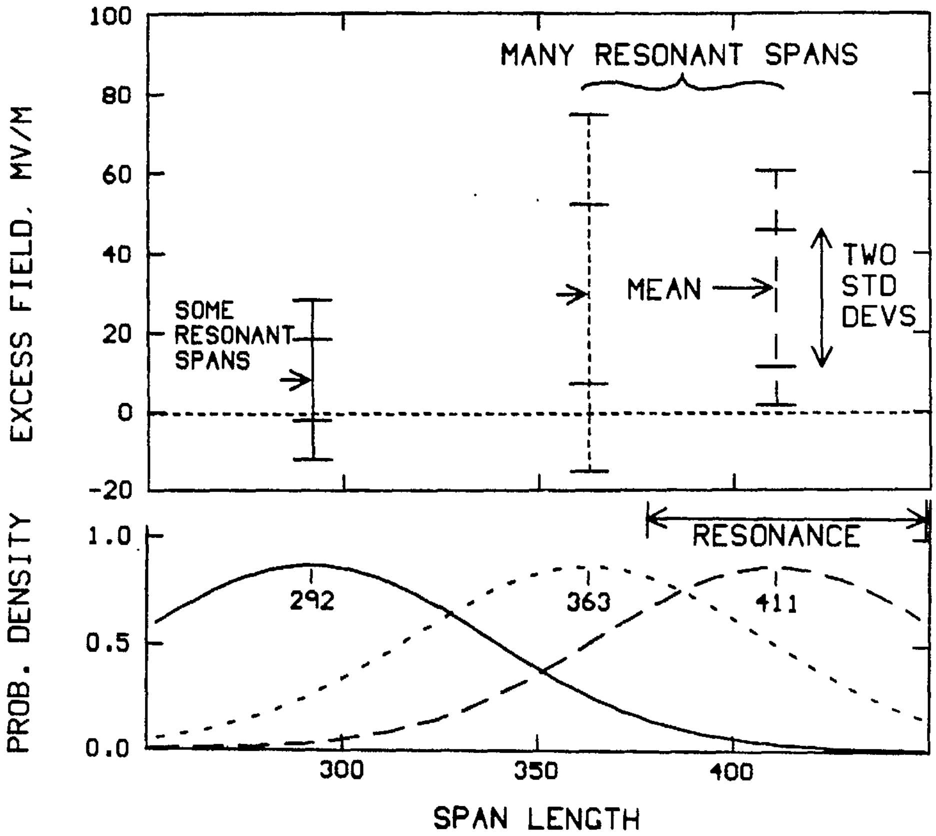


Fig. 3.21 The lower portion of this graph shows the "normal" probability density curve expressed as a percentage, for standard deviation 46 m, and for mean value 292, 363 and 411 m. The span lengths are widely spread. The upper part of the curve shows the distribution of the excess field values obtained from power lines with these span statistics, using a vertical bar four standard deviations wide centered on the mean value of the excess field.

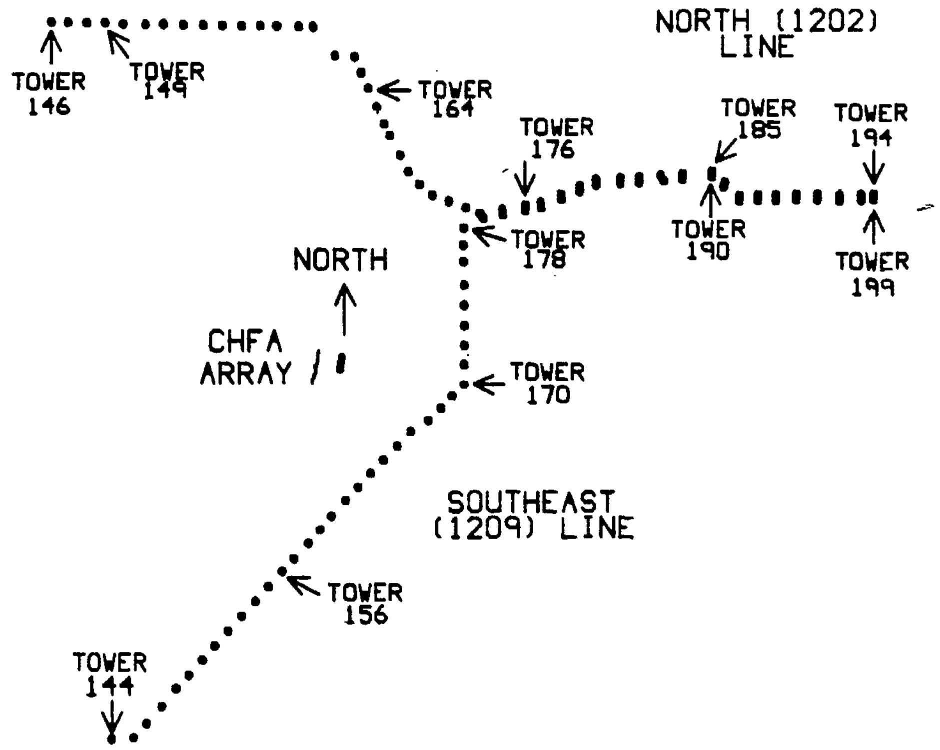


Fig. 4.1 (a) Plan view of the CHFA array and the "north" and the "southeast" power lines. The closest towers on the "north" line are 3.5 km distant, and the closest towers on the "southeast" line are 1.8 km away.

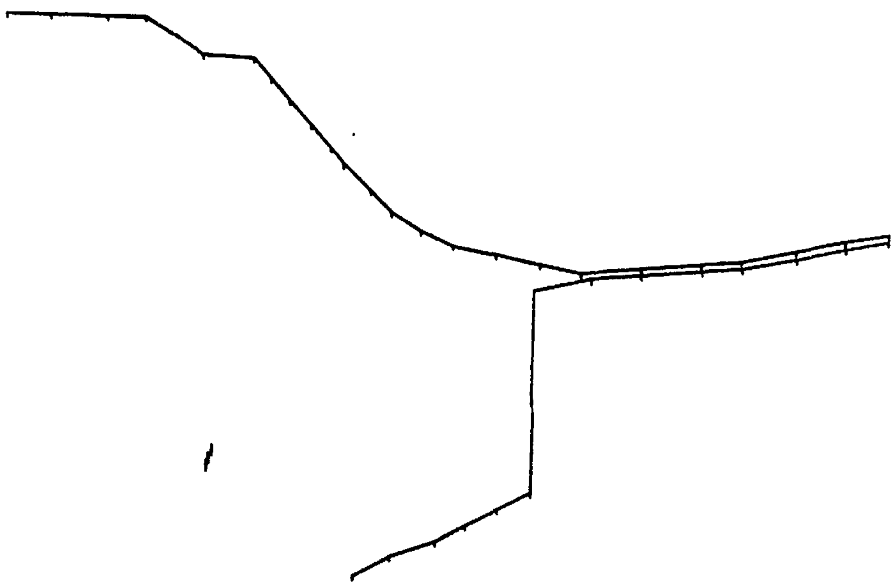


Fig. 4.1 (b) Computer generated view of the model of the power lines used to analyse reradiation.

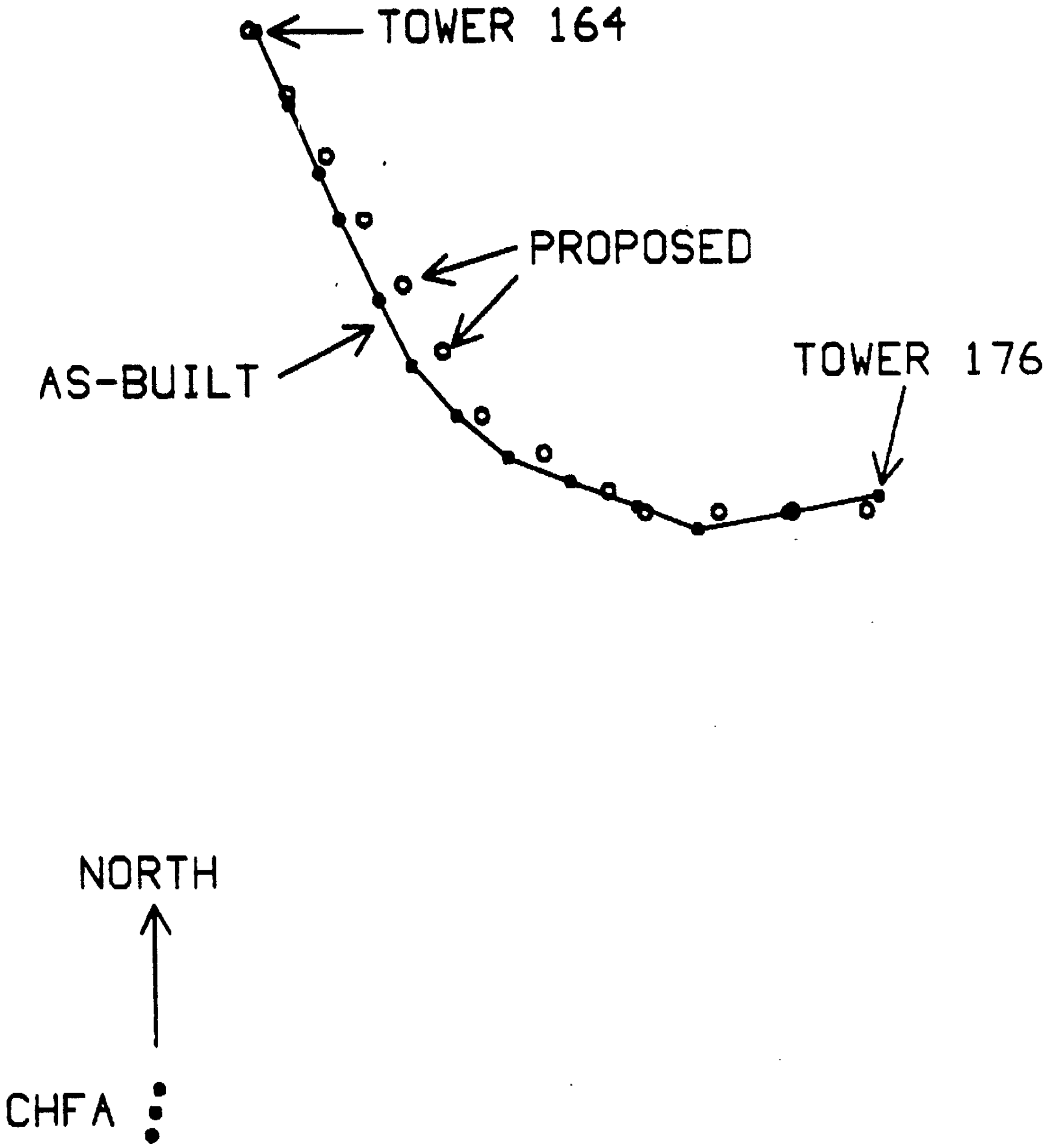


Fig. 4.2 Comparison of the "proposed" tower locations of the "north" line with the "as-built" locations.

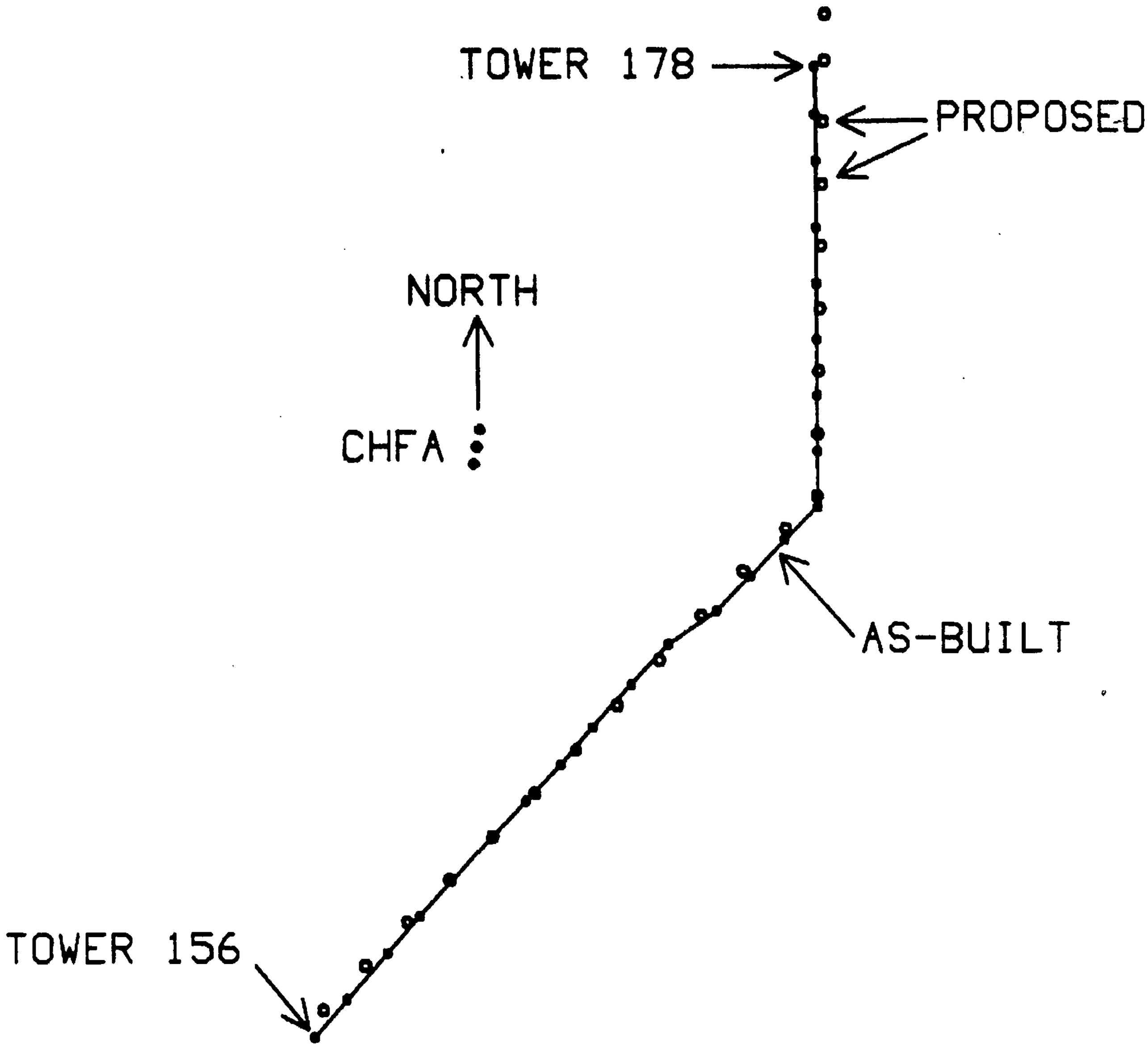


Fig. 4.3 Comparison of the "proposed" tower locations of the "southeast" line with the "as-built" locations.

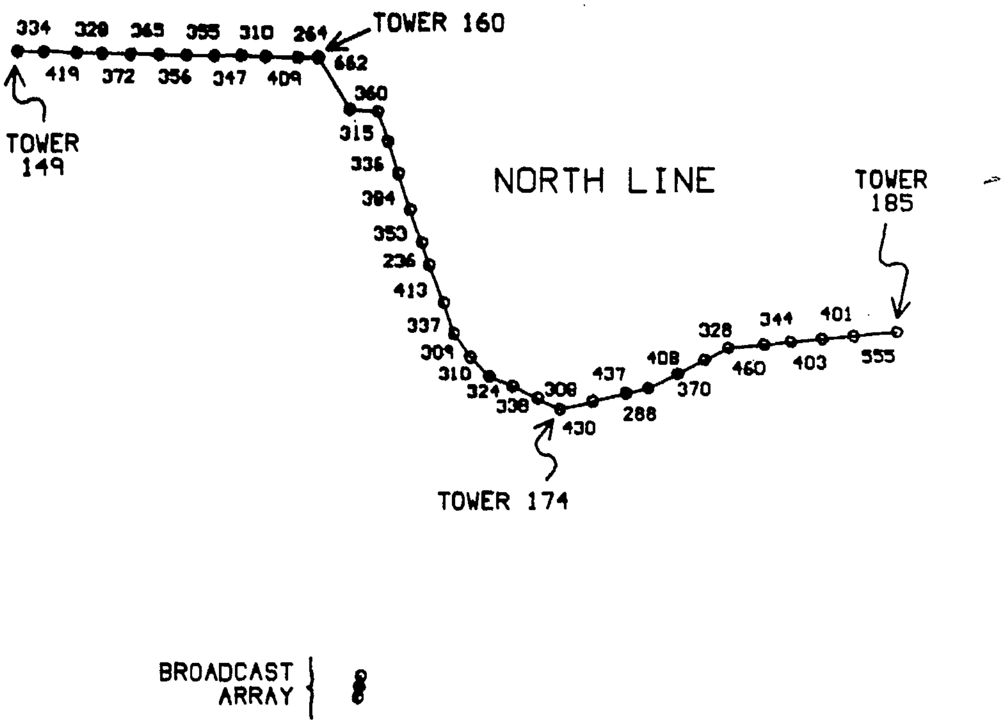


Fig. 4.4 Plan showing the span lengths on the "as-built" north power line.

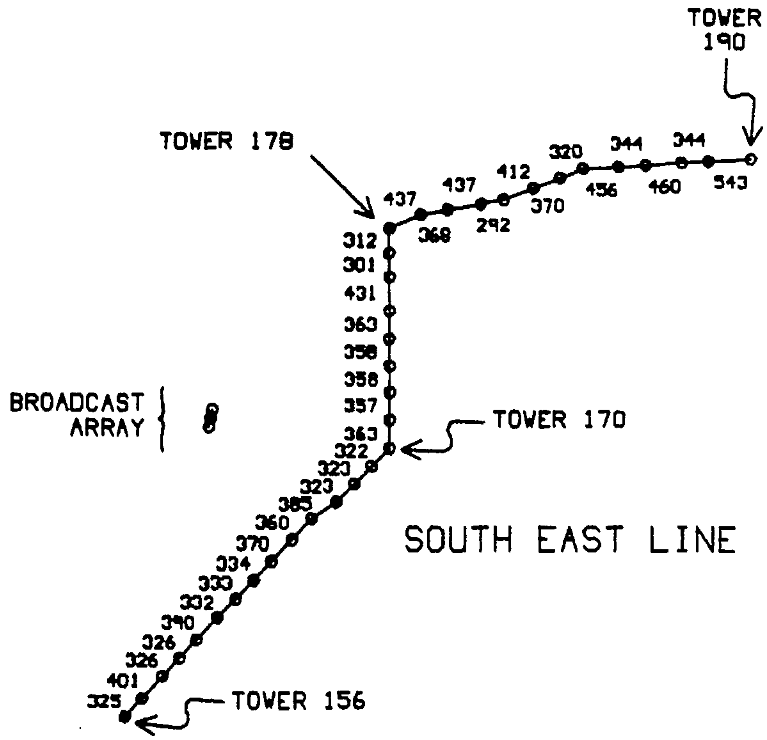


Fig. 4.5 Plan showing the span lengths on the "as-built" southeast power line.

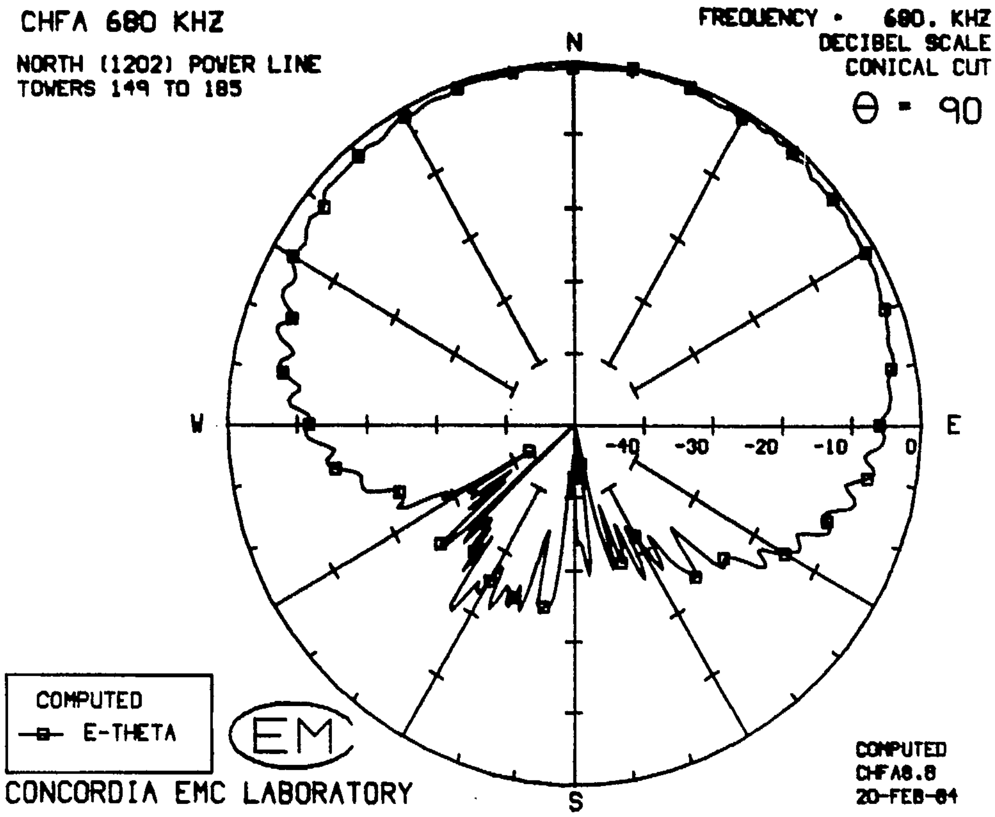


Fig. 4.6 (a) Radiation pattern of the CHFA array operating near a section of the "north" power line including towers 149 to 185.

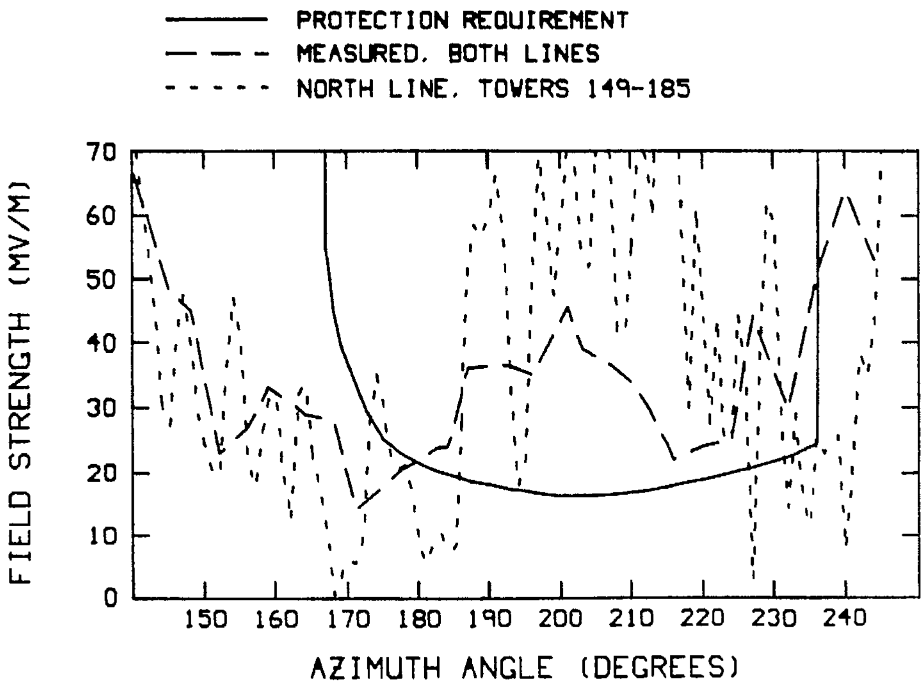


Fig. 4.6 (b) Field strength in the restricted arc.

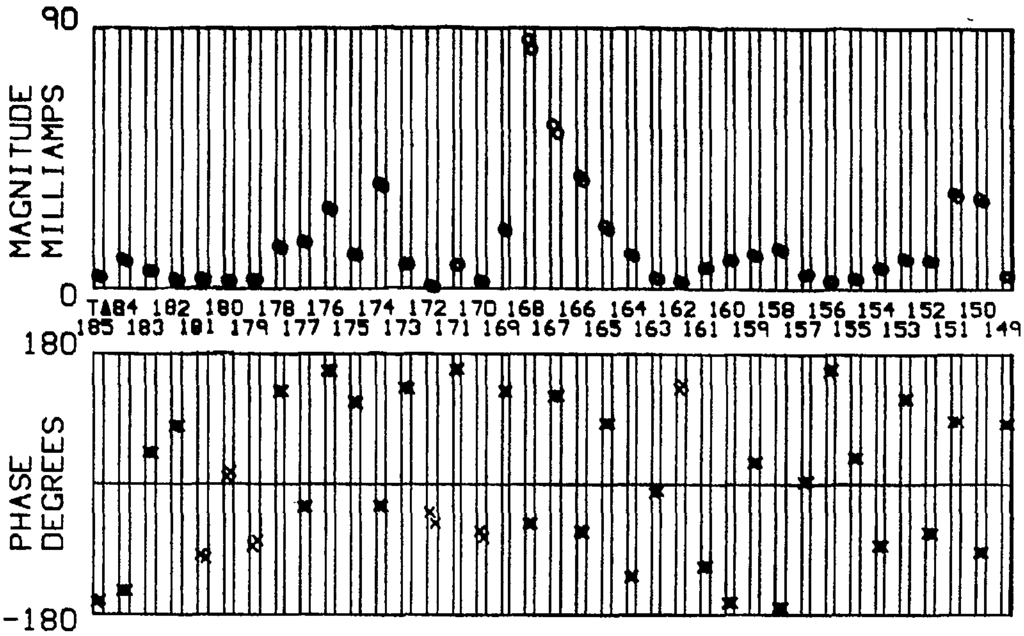


Fig. 4.7 (a) The RF current flowing on each power line tower of the "north" line.

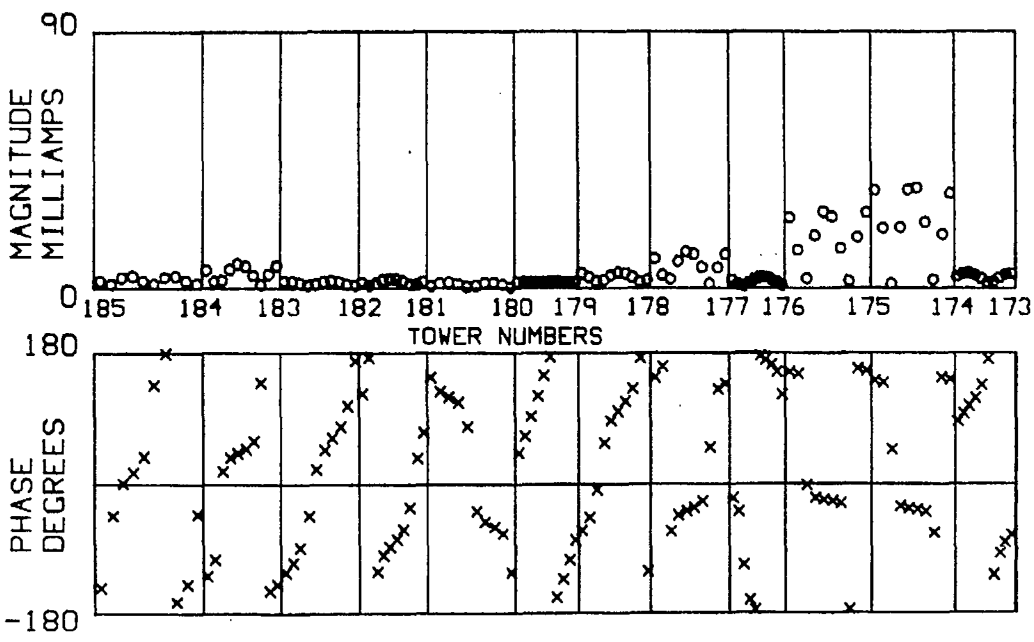


Fig. 4.7 (b) The RF current flowing on the skywires of the "north" power line.

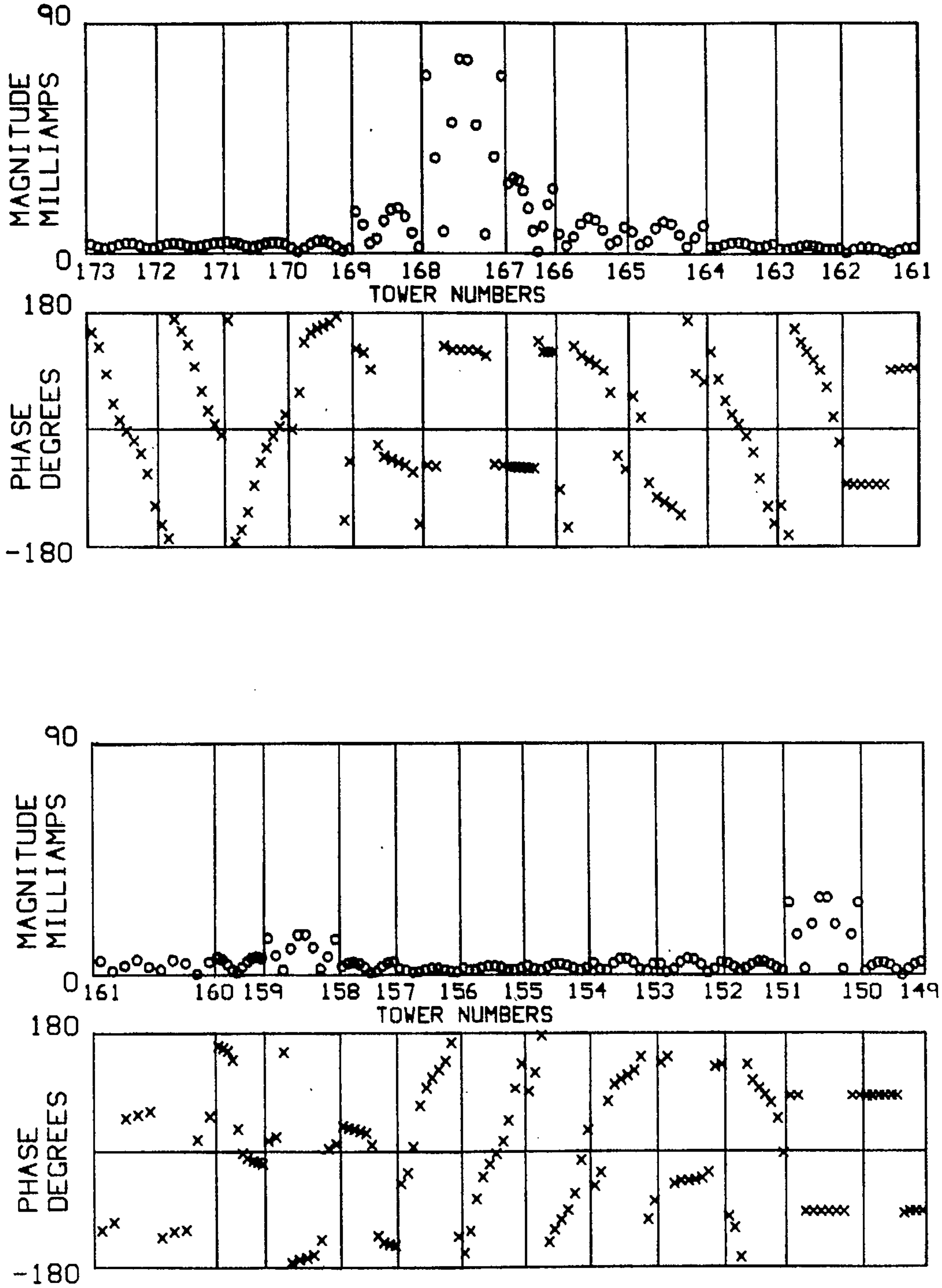


Fig. 4.7 (b) continued

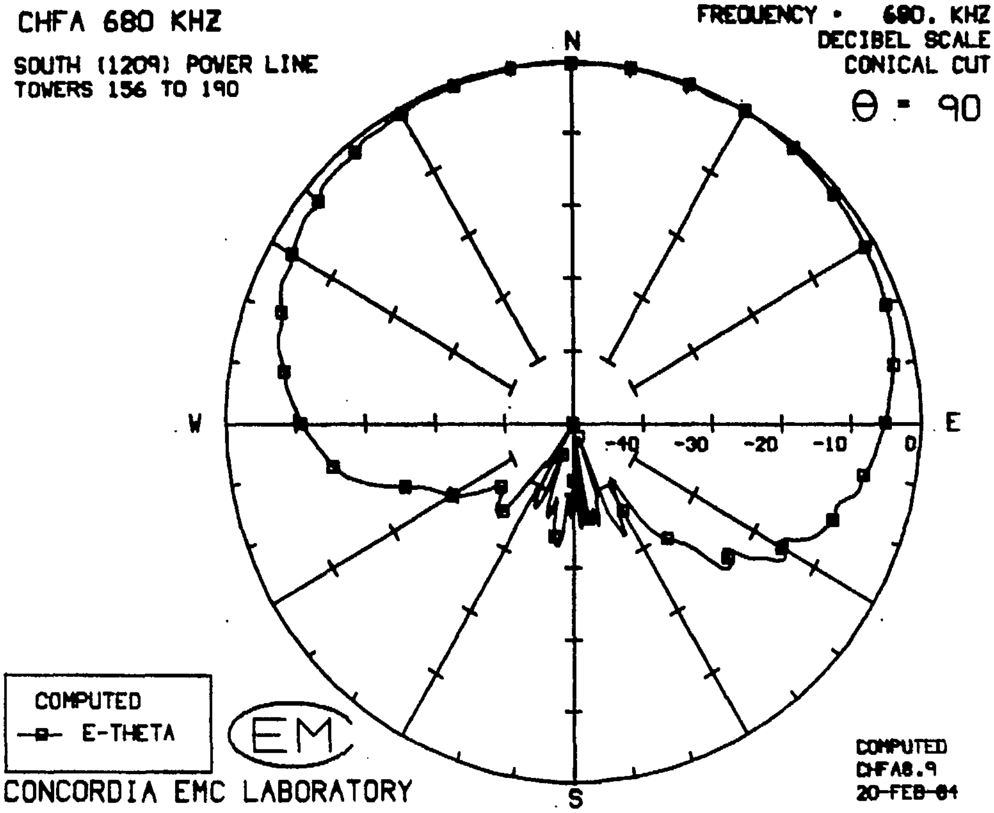


Fig. 4.8 (a) Radiation pattern of the CHFA array operating near a section of the "southeast" power line including towers 156 to 190.

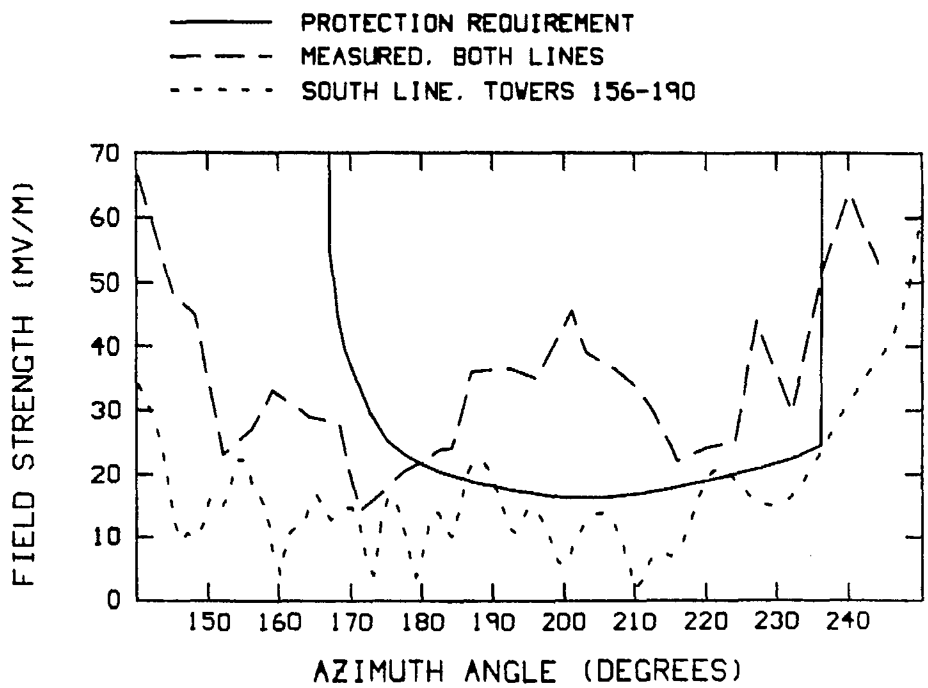


Fig. 4.8 (b) Field strength in the restricted arc.

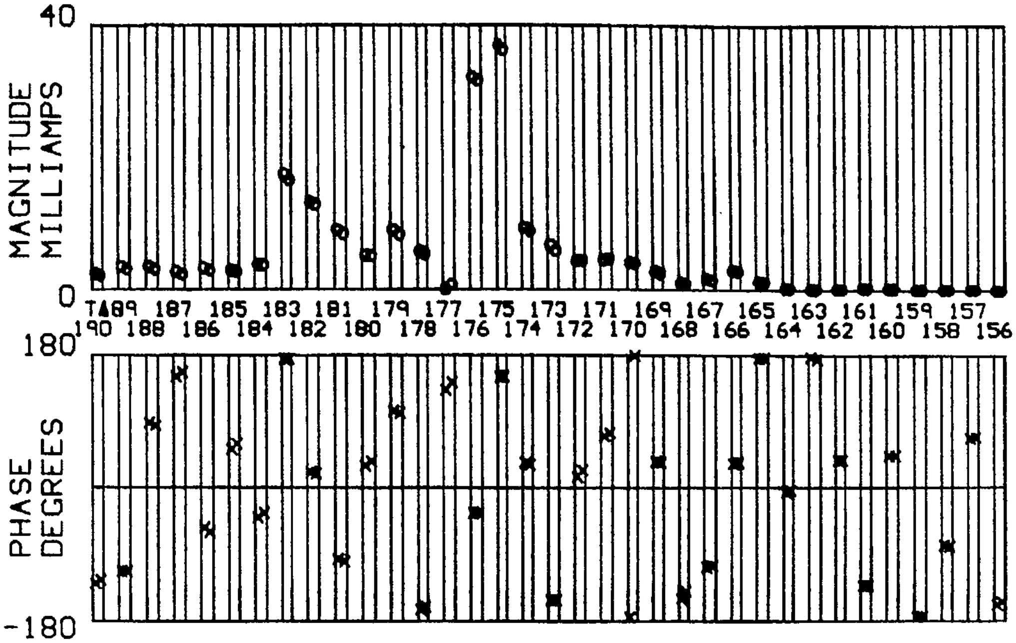


Fig. 4.9 (a) The RF current flowing on each power line tower of the "southeast" line.

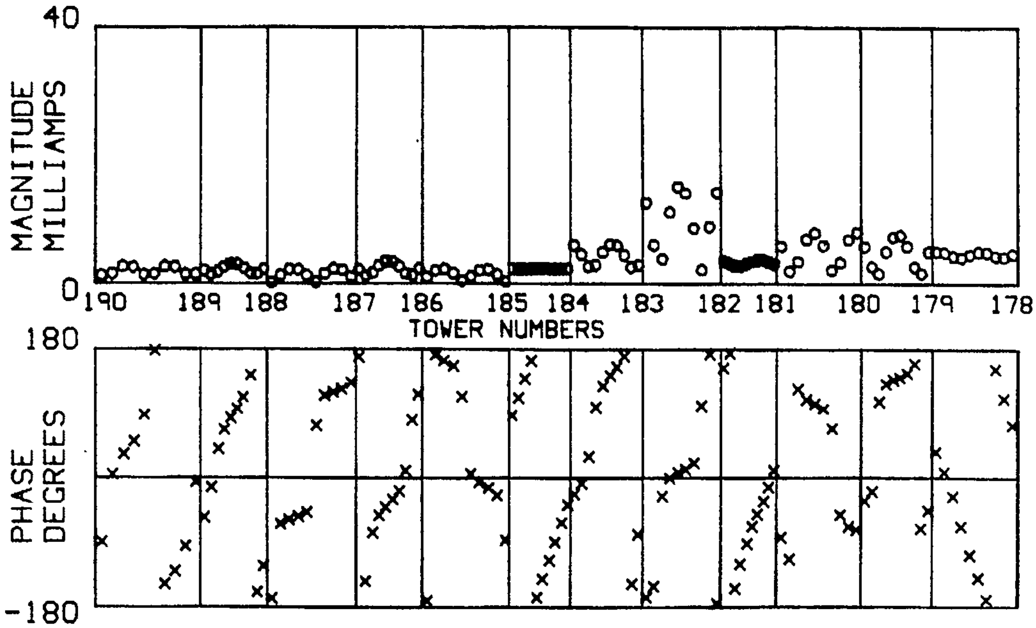
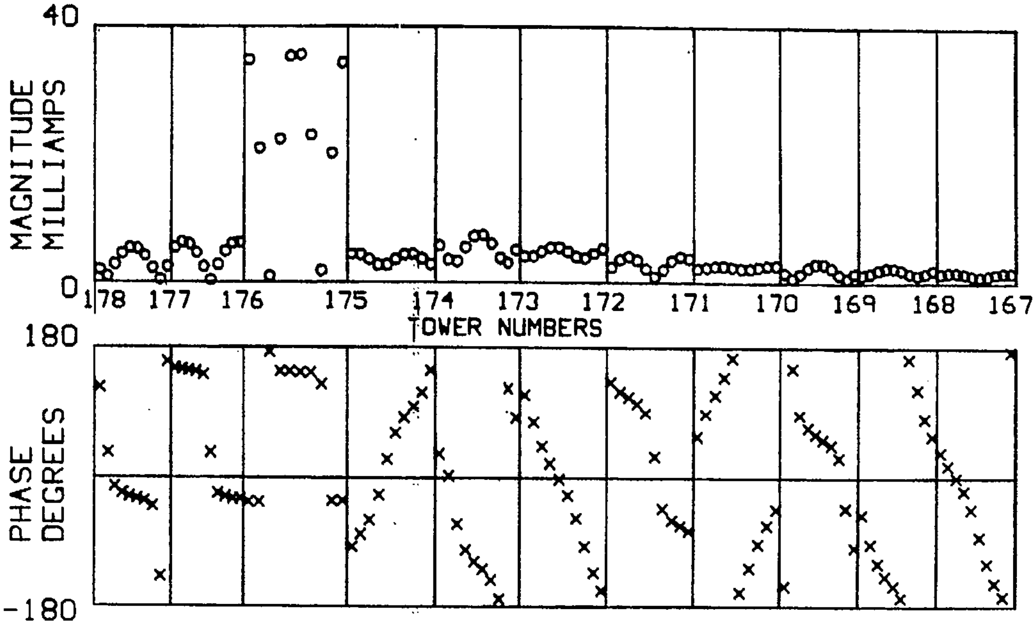


Fig. 4.9 (b) The RF current flowing on the skywires of the "southeast" power line.



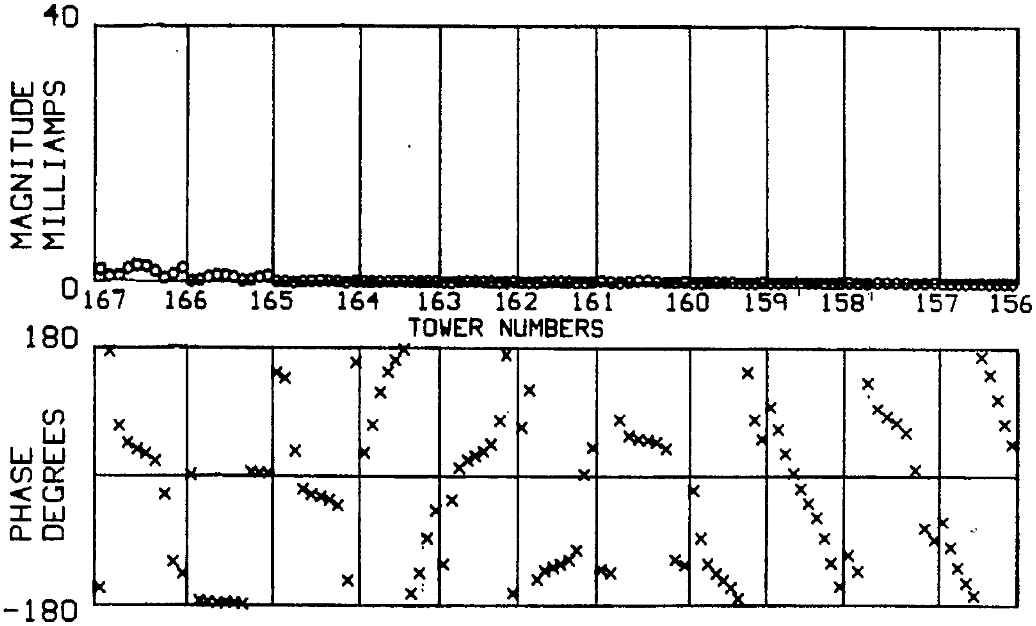


Fig. 4.9 (b) continued

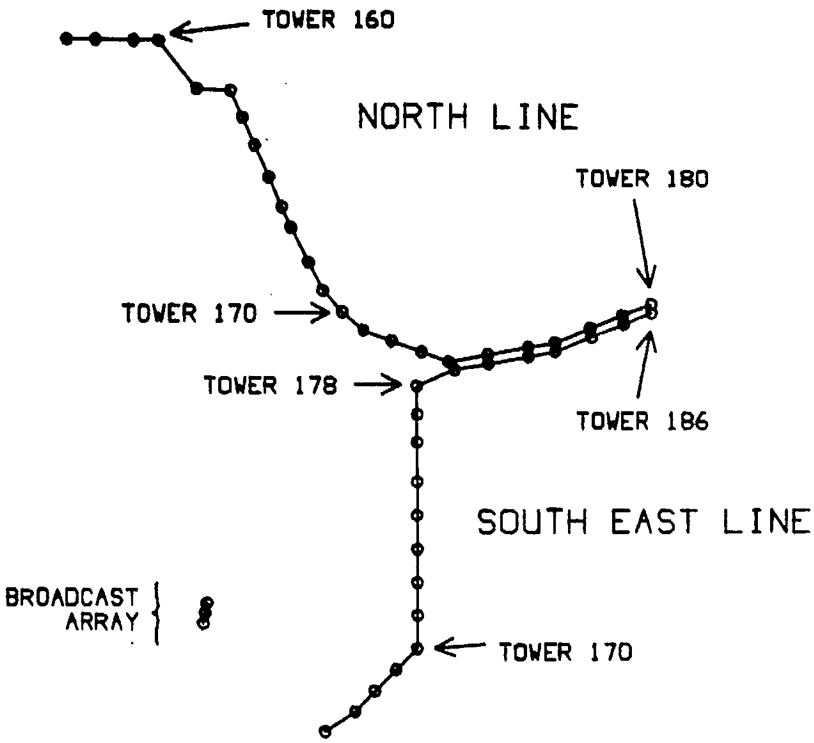


Fig. 4.10 Plan view of the model used to analyse both power lines together, including towers 156 to 180 of the "north" line and towers 165 to 186 of the "southeast" power line.

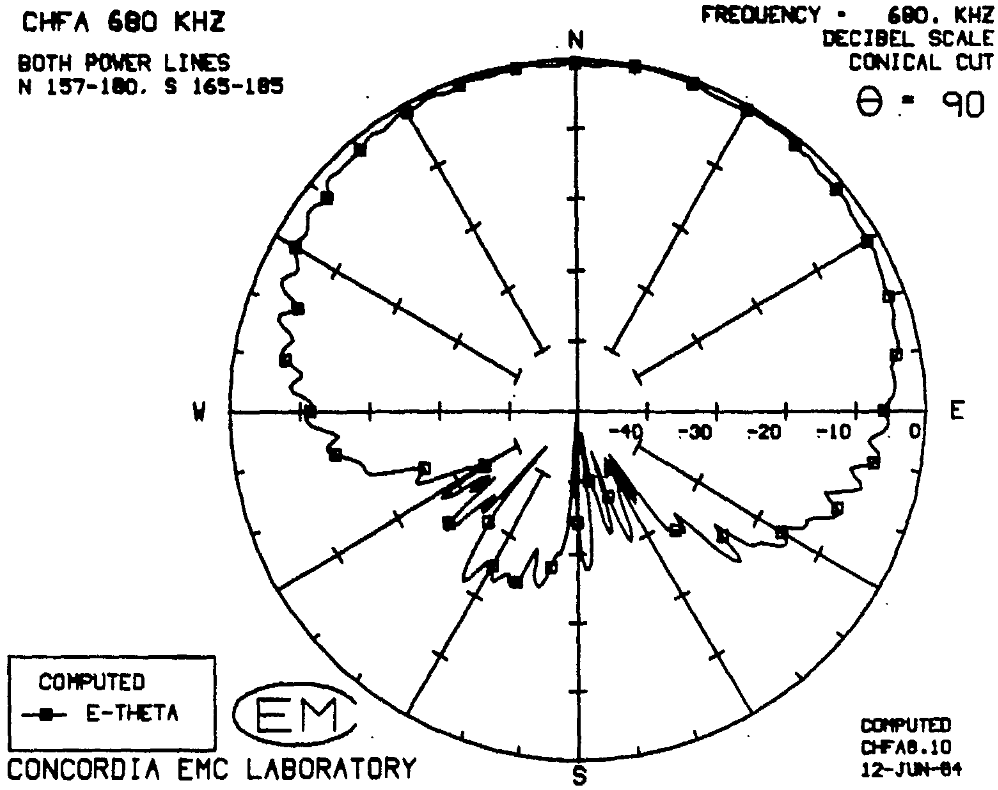


Fig. 4.11 (a) Azimuth pattern of the CHFA array operating near both power lines together, including the towers shown in Fig. 4.10.

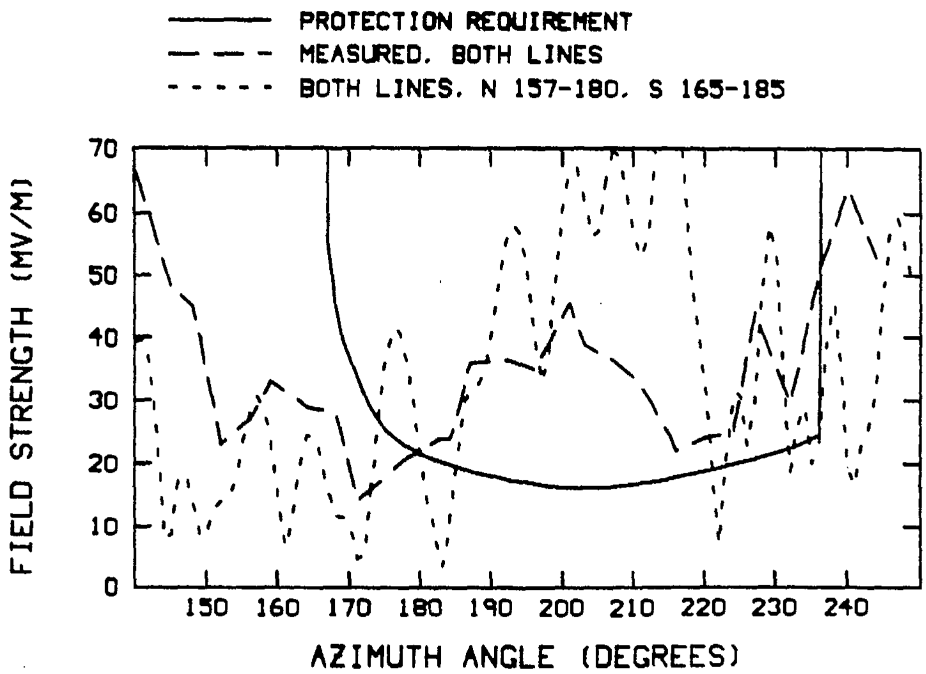


Fig. 4.11 (b) Field strength in the restricted arc.

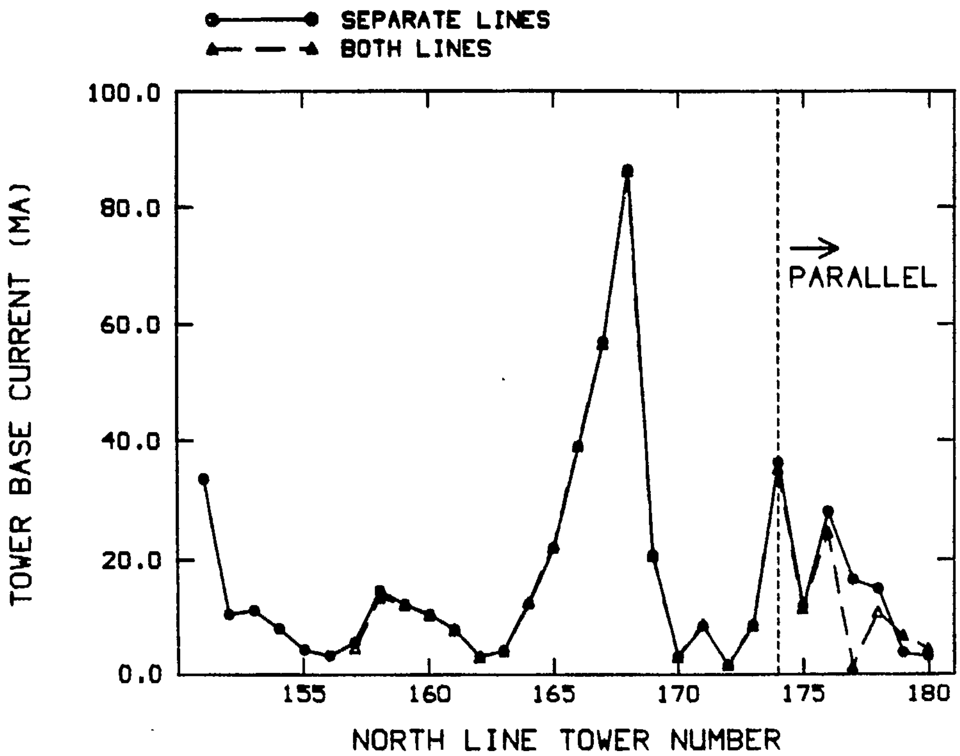


Fig. 4.12 (a) Comparison of the tower base currents computed for CHFA operating near the "north" line only, with those computed for CHFA operating near both power lines together.

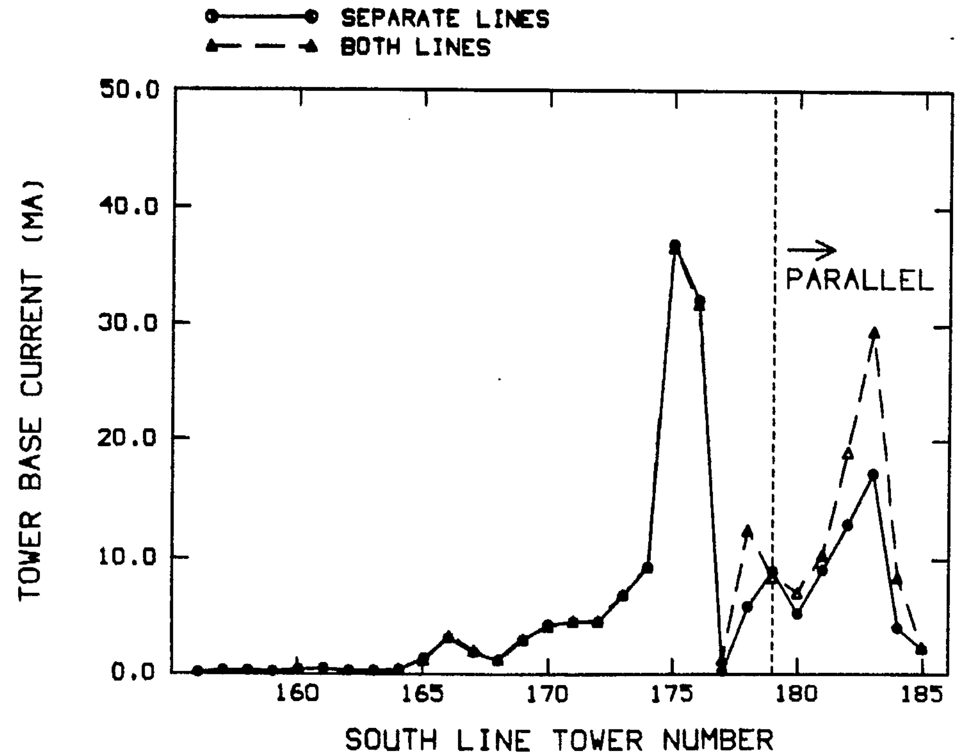


Fig. 4.12 (b) Comparison of the tower base currents computed for CHFA operating near the "southeast" line only, with those computed for CHFA operating near both power lines together.

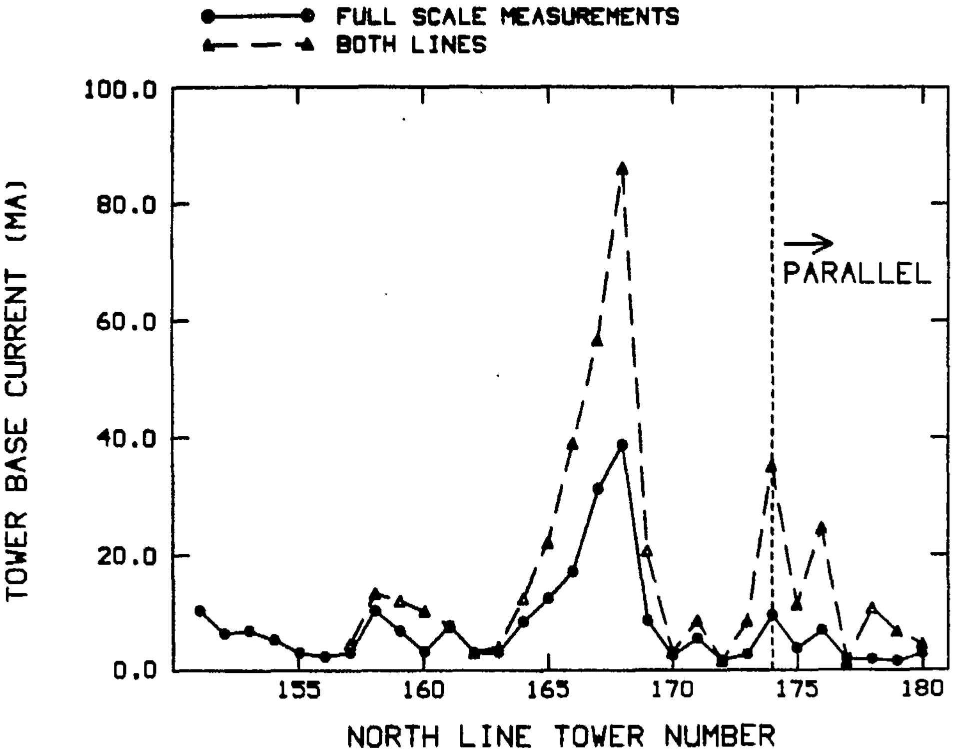


Fig. 4.13 (a) Comparison of the tower base currents measured on the "north" power line by Til-Tek with those computed for CHFA operating near both lines together.

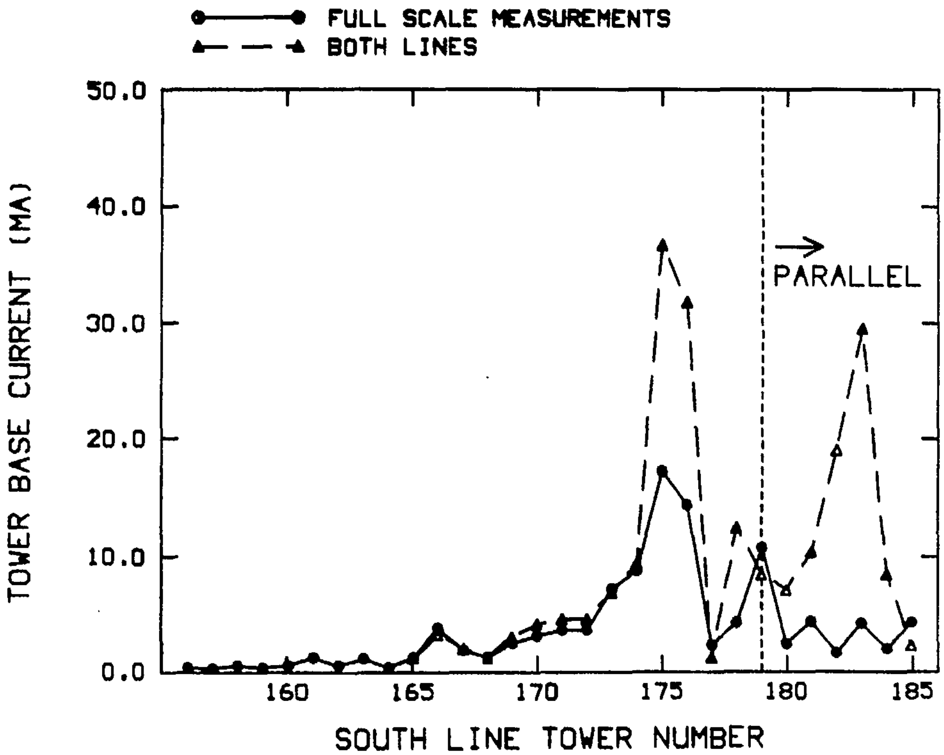


Fig. 4.13 (b) Comparison of the tower base currents measured on the "southeast" power line by Til-Tek with those computed for CHFA operating near both lines together.

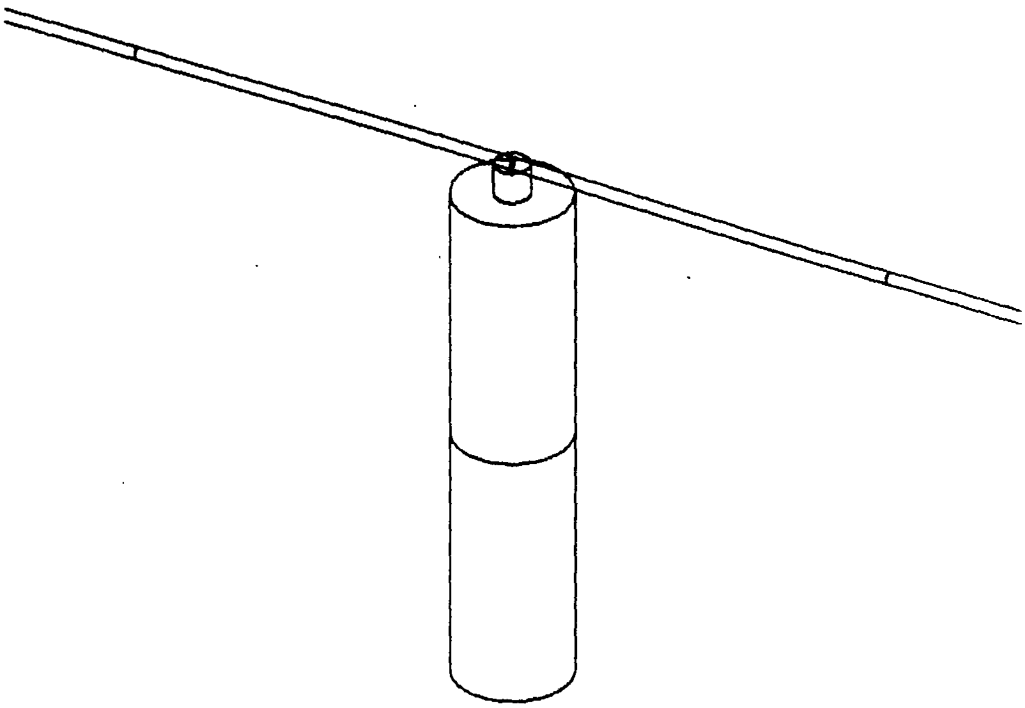


Fig. 5.1 The computer model of the tower of Fig. 3.7(b) modified to include an "insulator" modelled as a short segment between the tower top and the skywire, which is loaded with a large series resistor in parallel with a 27 pf capacitor.

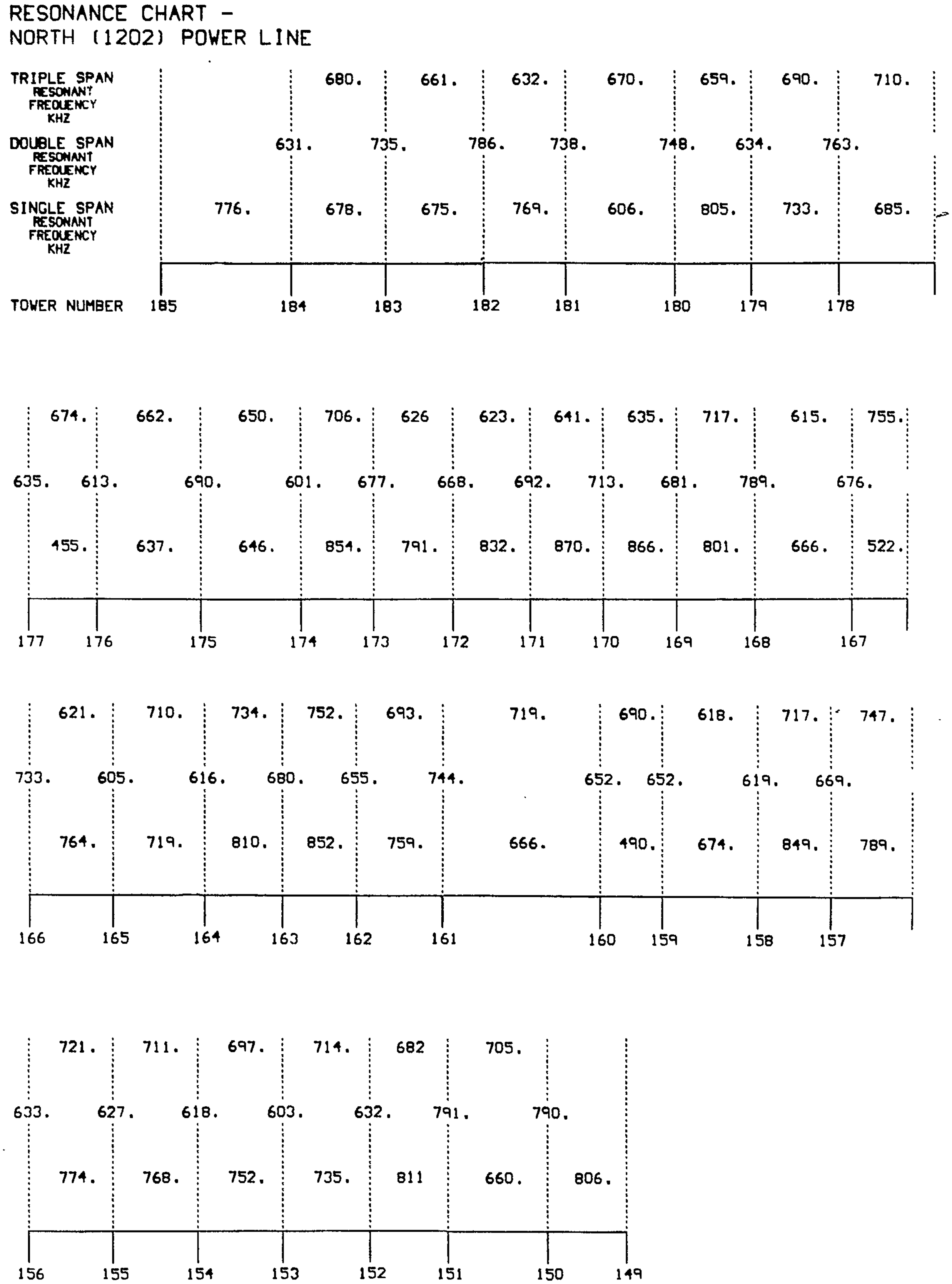


Fig. 5.2 Resonance chart for the "north" power line.

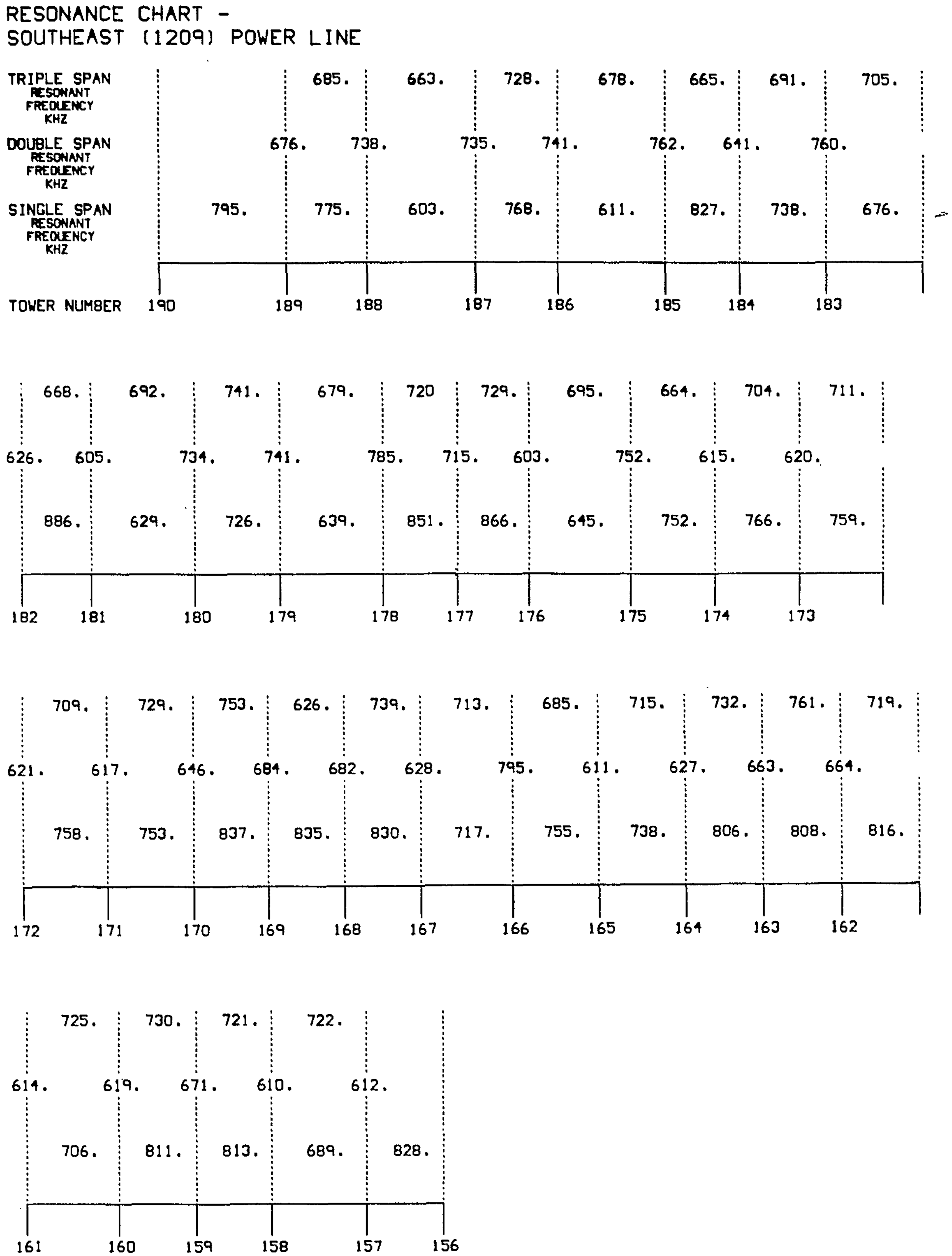


Fig. 5.3 Resonance chart for the "southeast" power line.

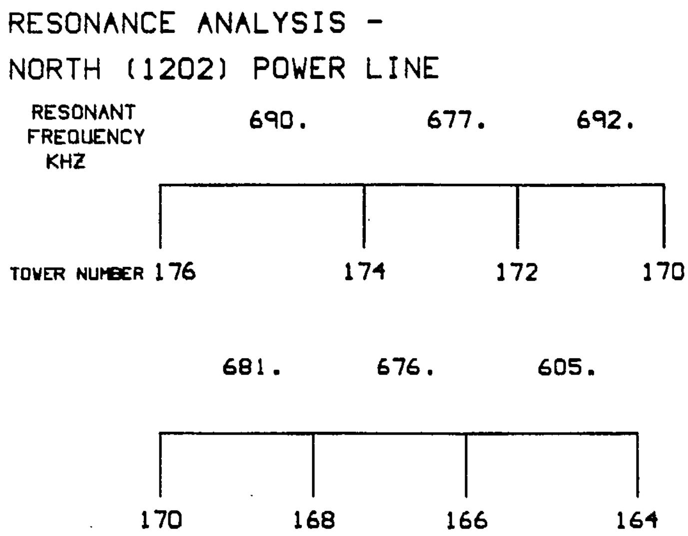


Fig. 5.4 (a) Resonance analysis of the "north" power line with every second tower isolated from the skywire.

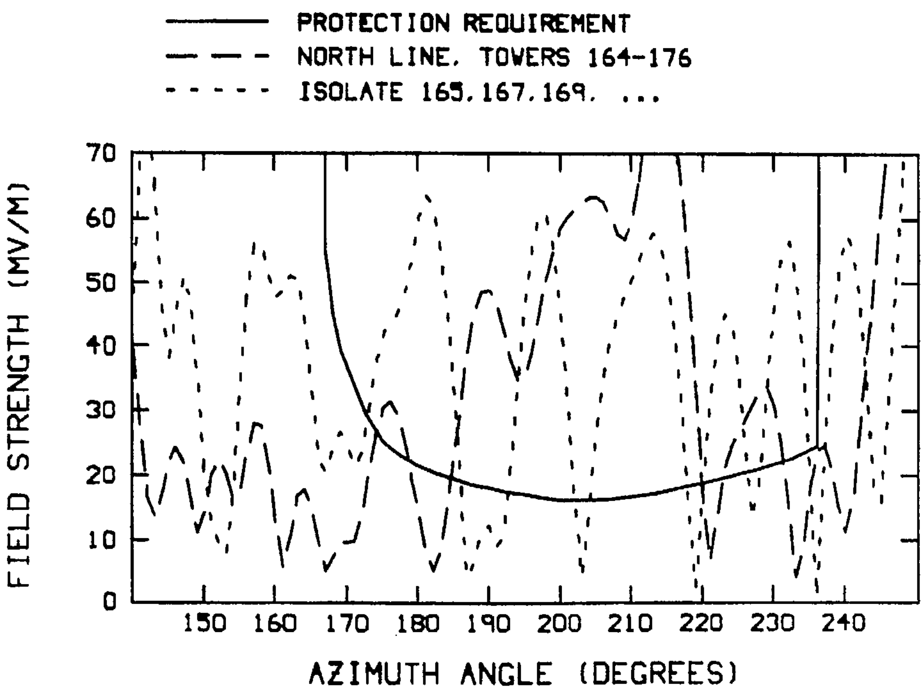


Fig. 5.4 (b) Field strength in the restricted arc with towers 165, 167, 169, 171, 173 and 175 isolated from the skywire.

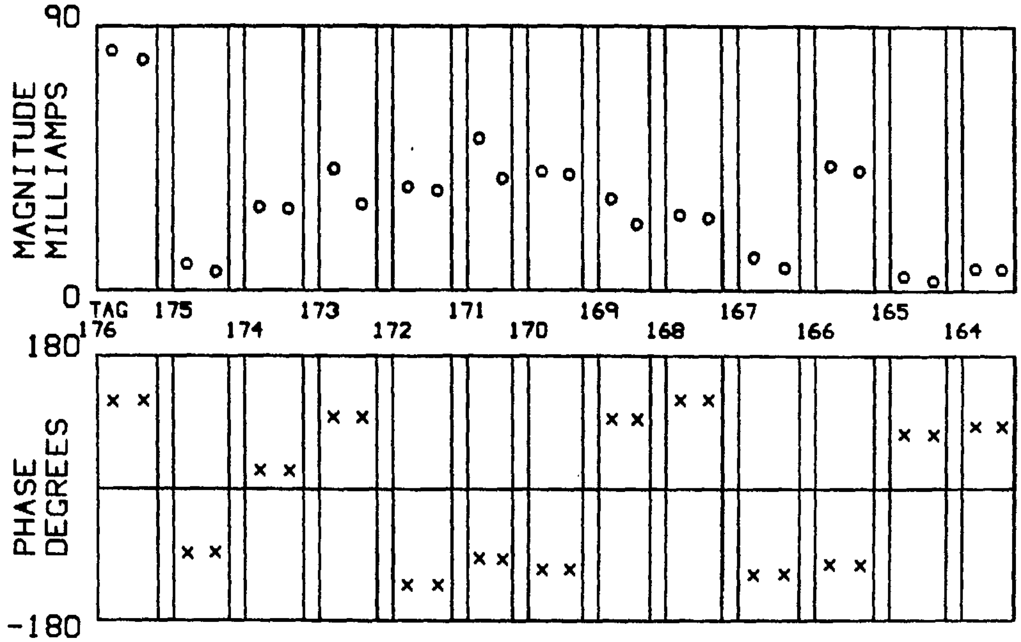


Fig. 5.4 (c) Tower base currrents with towers 165, 167, 169, 171, 173 and 175 isolated from the skywire.

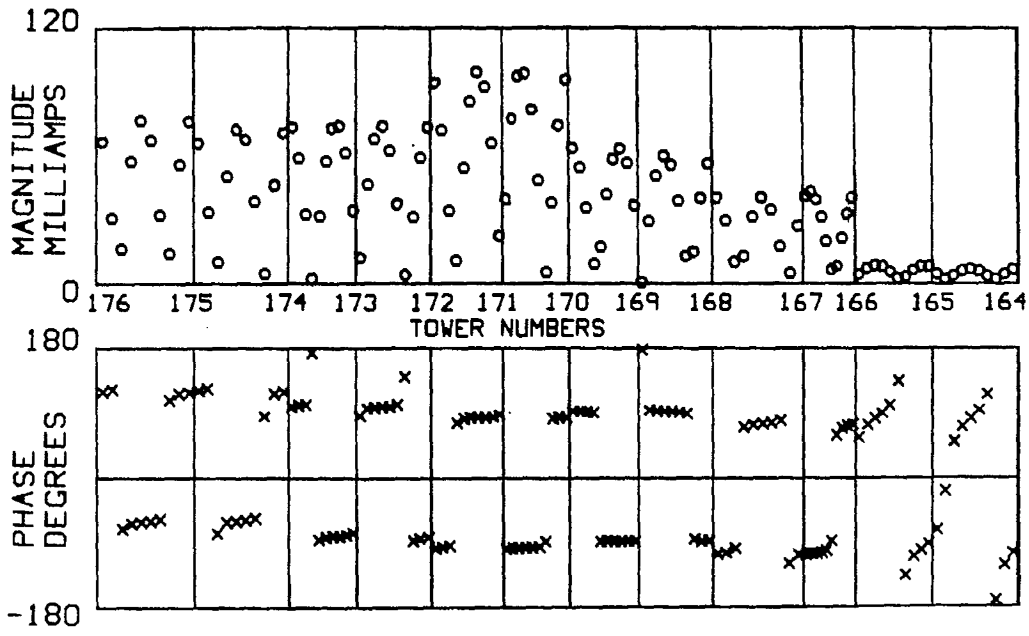


Fig. 5.4 (d) Skywire current distribution.

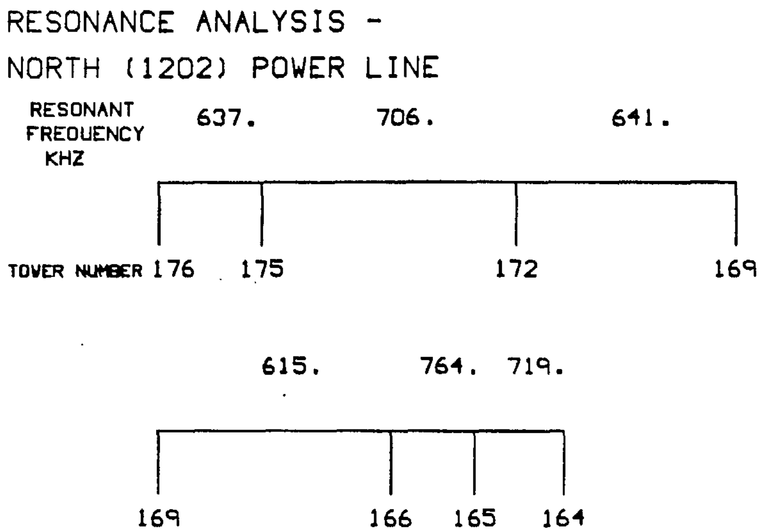


Fig. 5.5 (a) Resonance analysis of the "north" power line with two out of every three towers isolated from the skywire.

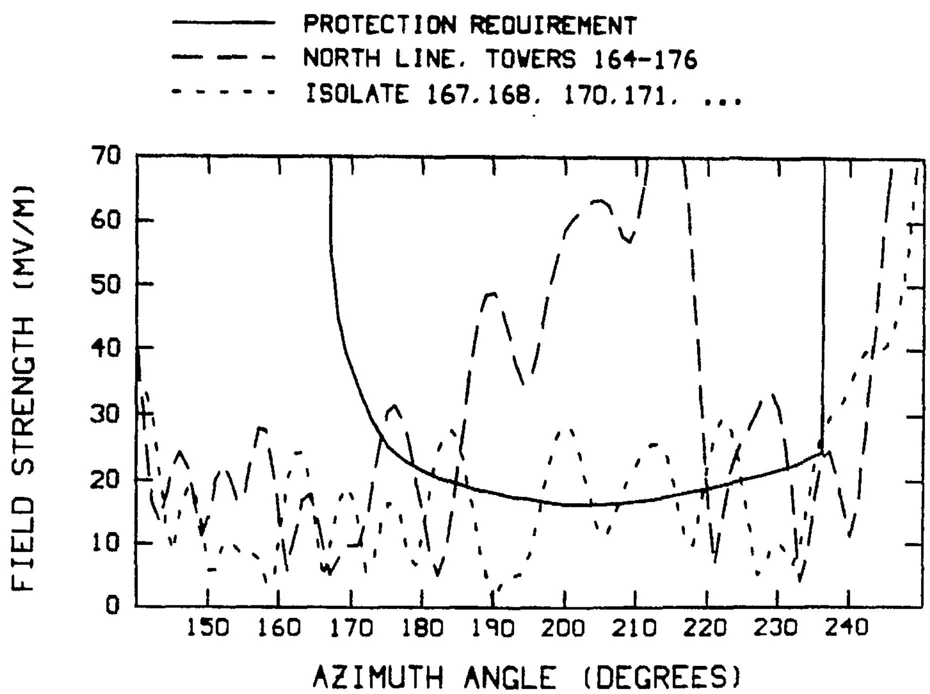


Fig. 5.5 (b) Field strength in the restricted arc with towers 167 and 168, 170 and 171, and 173 and 174 isolated from the skywire.

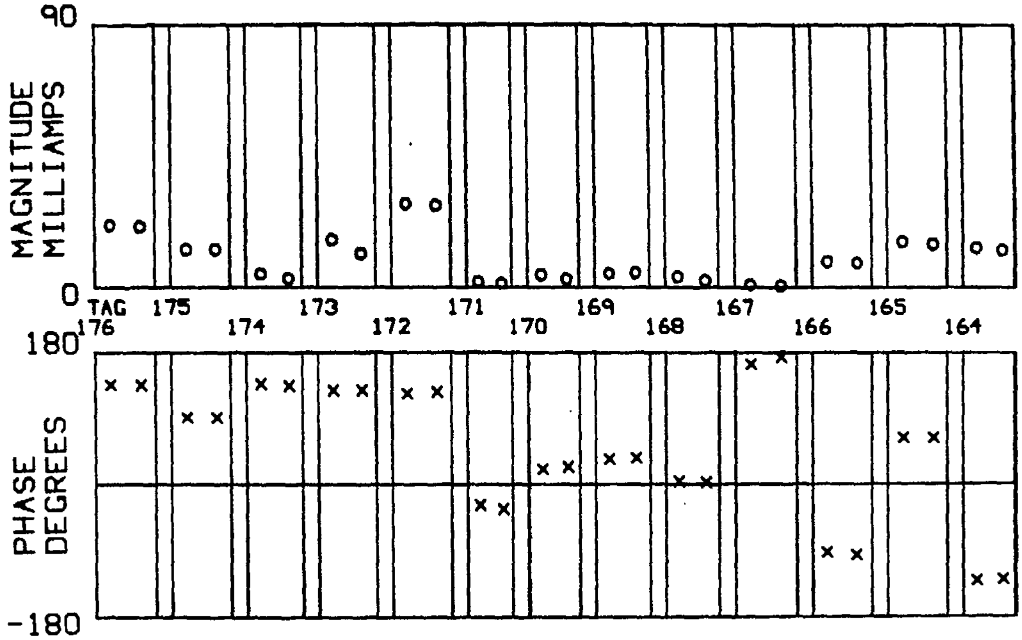


Fig. 5.5 (c) Tower base currrents with towers 167 and 168, 170 and 171, and 173 and 174 isolated from the skywire.

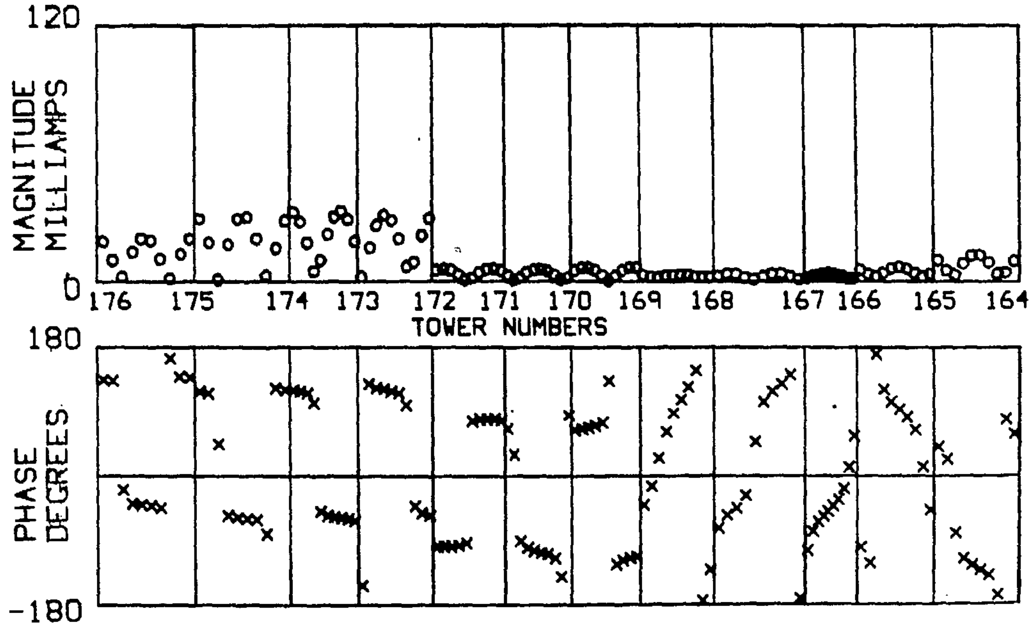


Fig. 5.5 (d) Skywire current distribution.

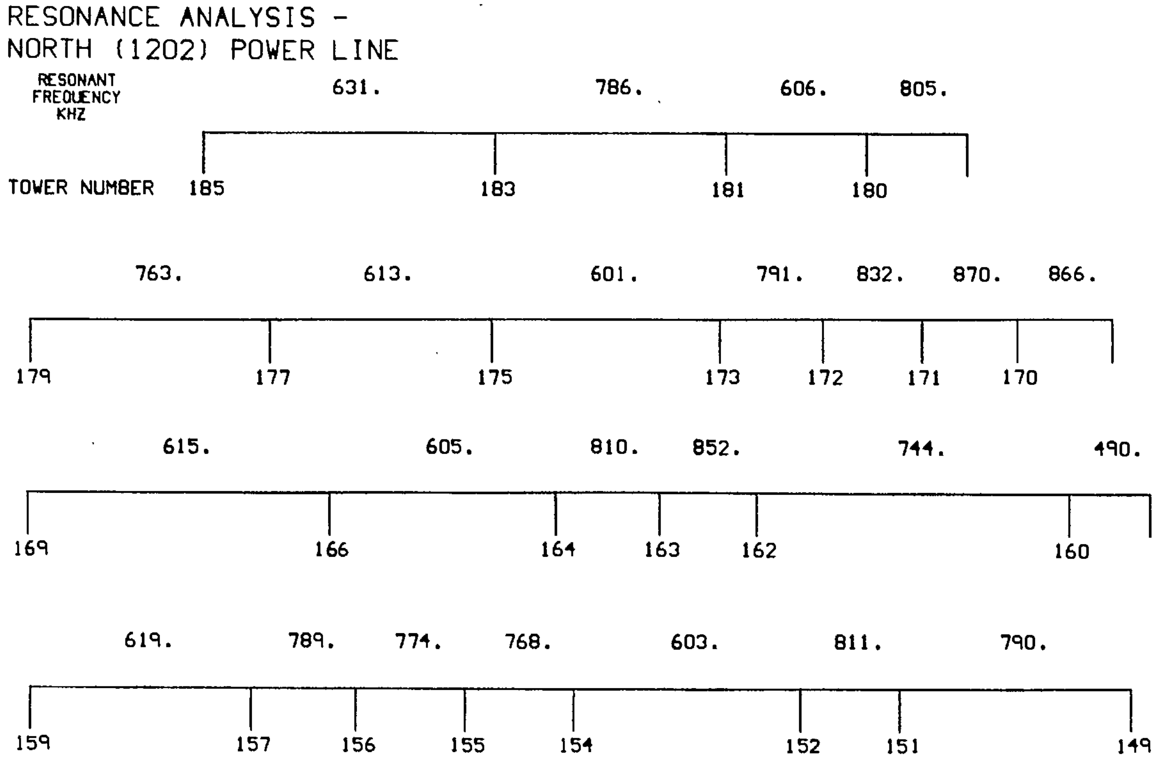


Fig. 5.6 (a) Resonance analysis of the "north" power line with towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184 isolated from the skywire.

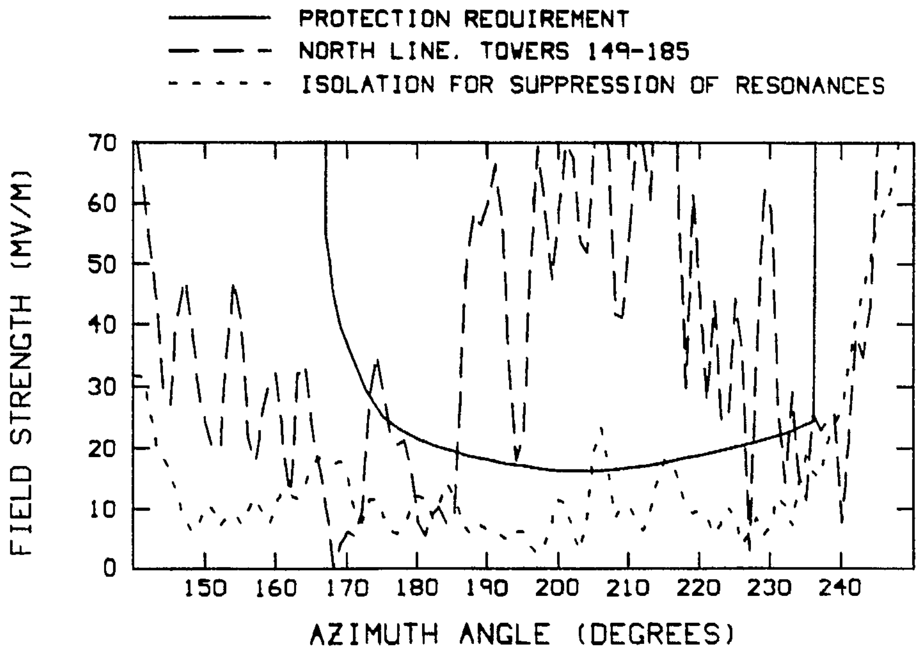


Fig. 5.6 (b) Field strength in the restricted arc for CHFA operating near the "north" power line with towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184 isolated from the skywire.

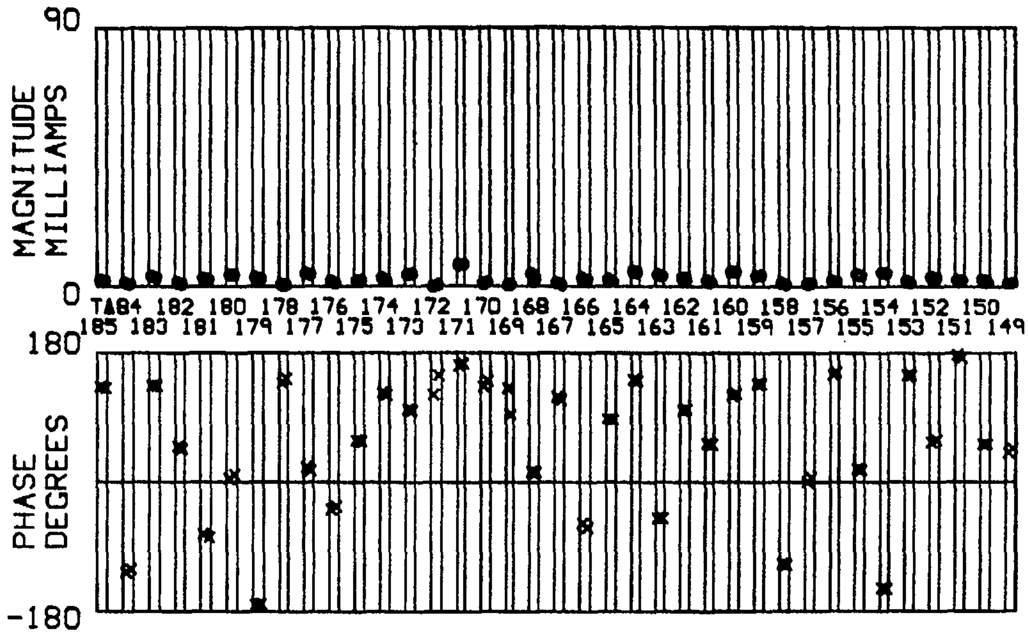


Fig. 5.6 (c) Tower base currents on the "north" power line with towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184 isolated from the skywire.

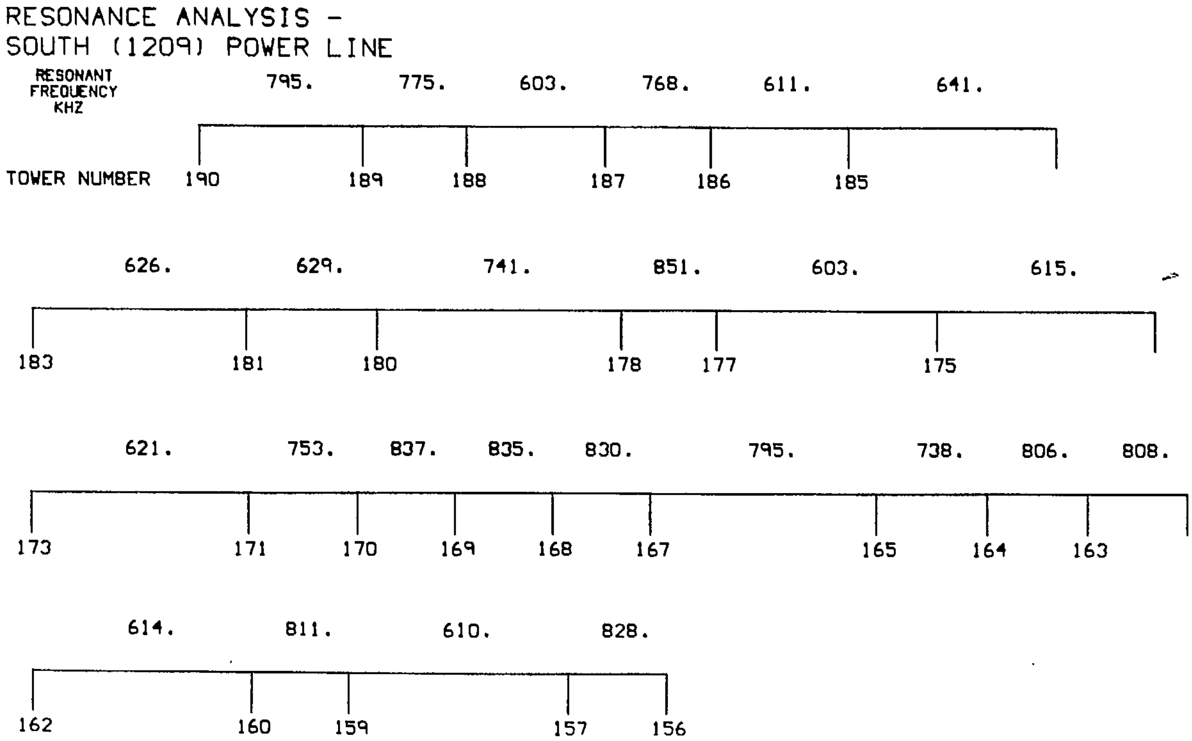


Fig. 5.7 (a) Resonance analysis of the "southeast" power line with towers 158, 161, 166, 172, 174, 176, 179, 182 and 184 isolated from the skywire.

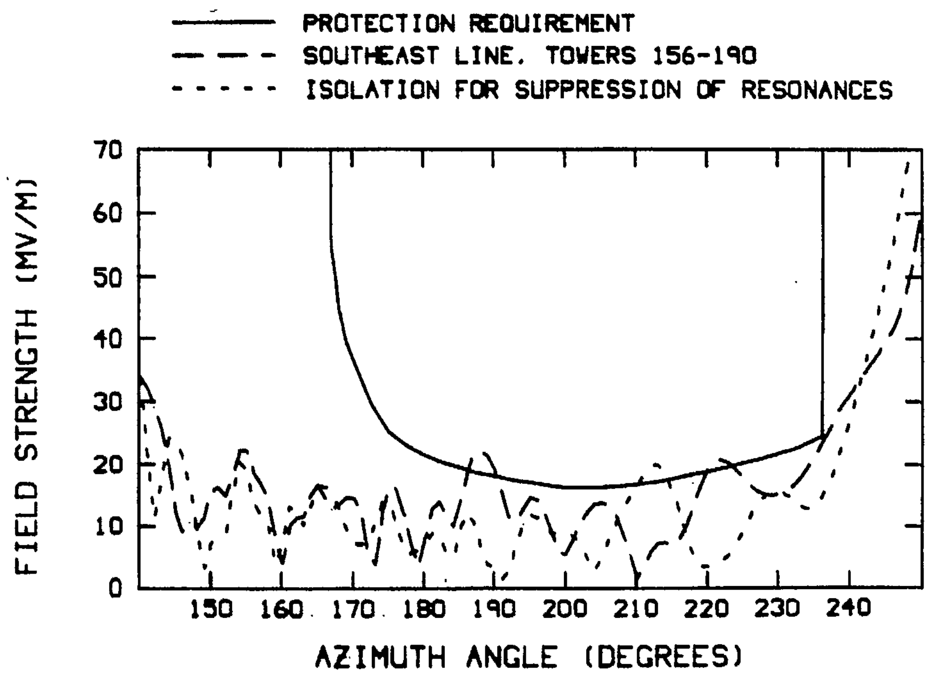


Fig. 5.7 (b) Field strength in the restricted arc for CHFA operating near the "southeast" power line with towers 158, 161, 166, 172, 174, 176, 179, 182 and 184 isolated from the skywire.

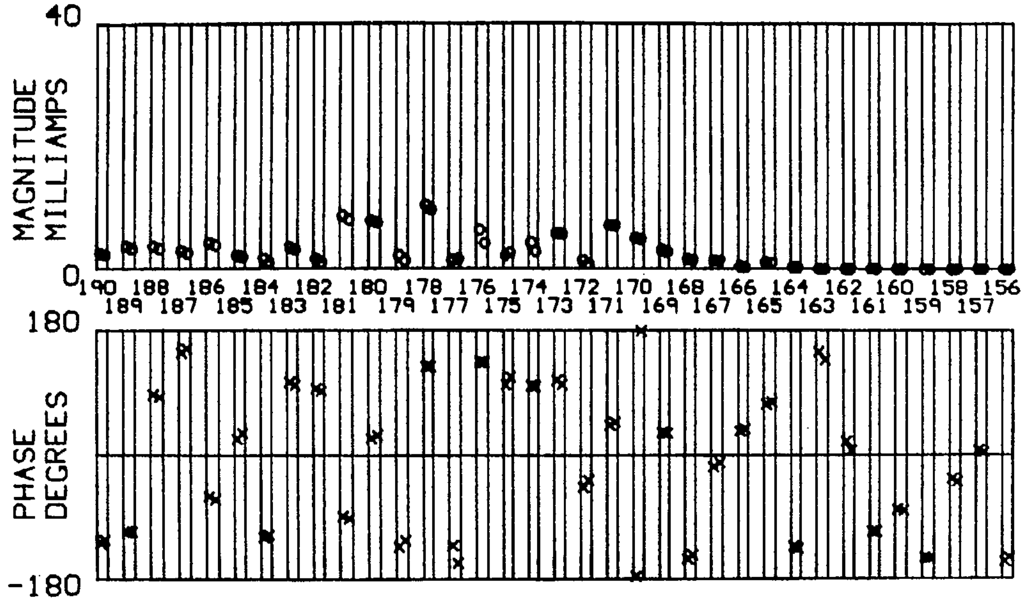


Fig. 5.7 (c) Tower base currents on the "southeast" power line with towers 158, 161, 166, 172, 174, 176, 179, 182 and 184 isolated from the skywire.

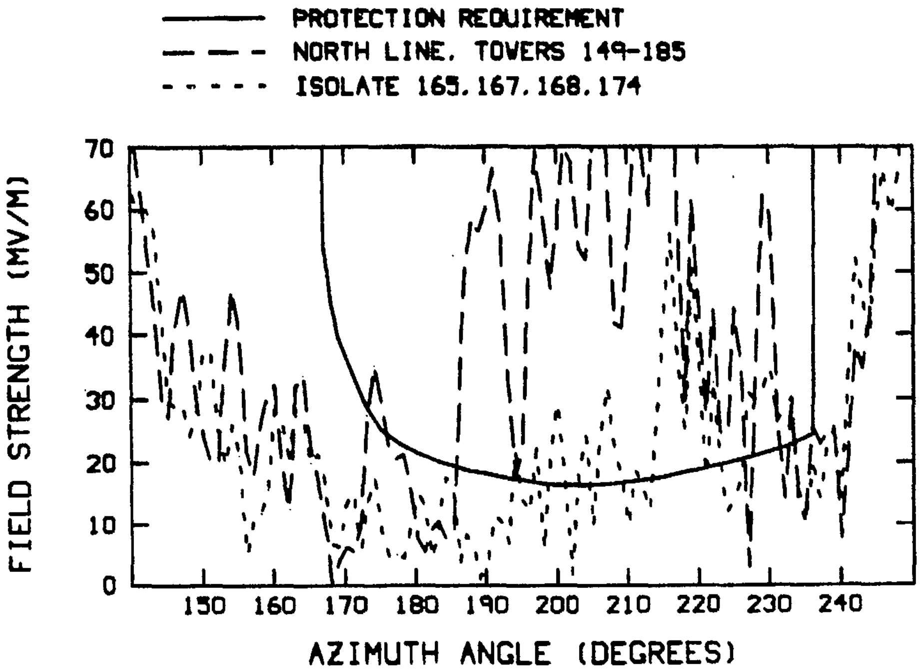


Fig. 5.8 (a) The field strength in the restricted arc for CHFA operating near the "north" line with towers 165, 167, 168 and 174 isolated from the skywire.

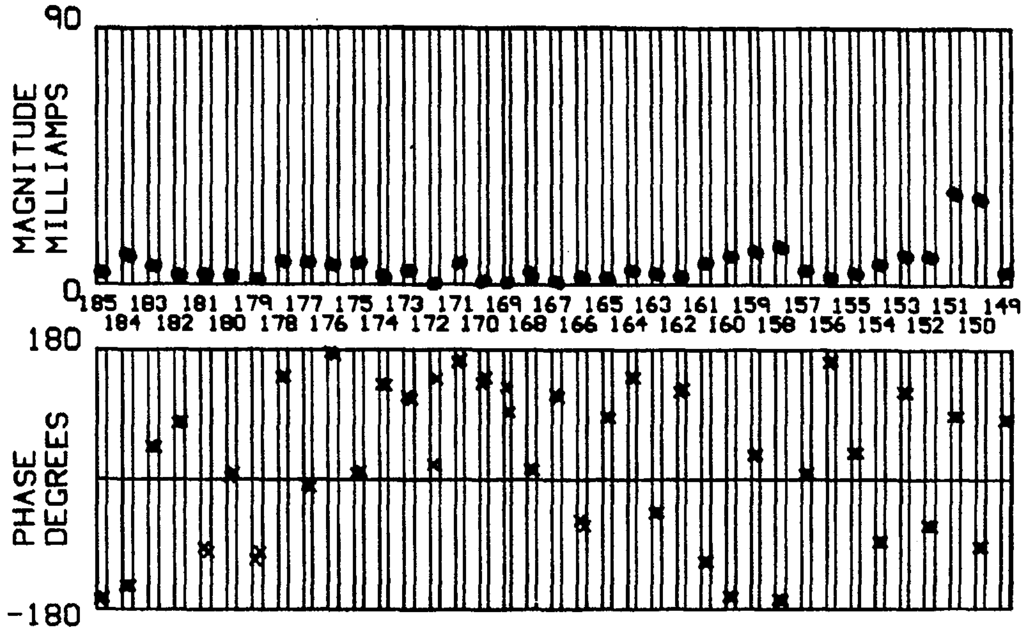


Fig. 5.8 (b) Tower base currents.

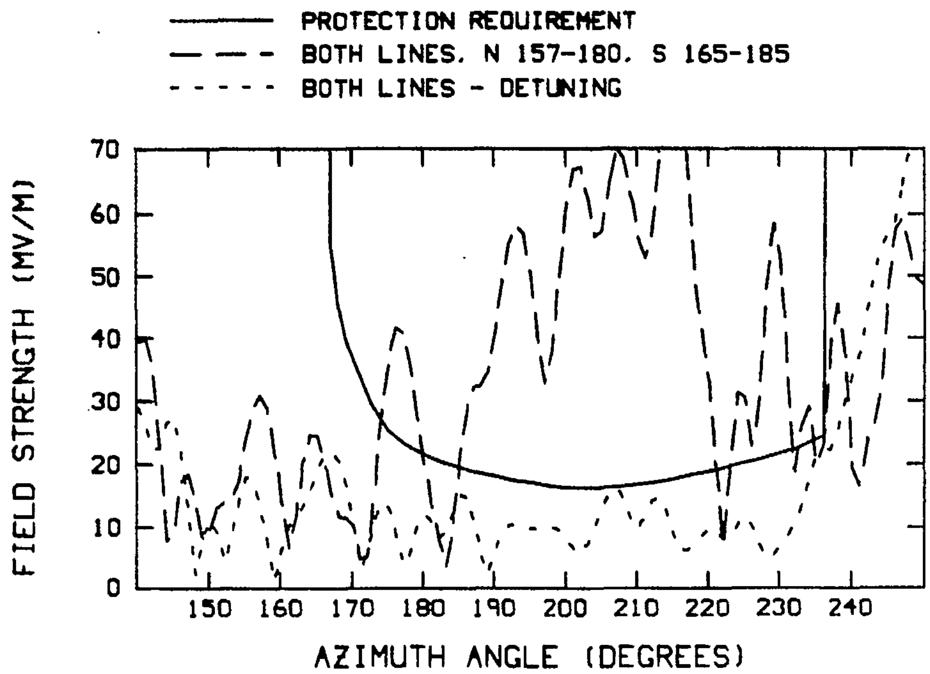


Fig. 5.9 The field strength in the restricted arc for CHFA operating near both power lines when the towers of Fig. 4.10 are included in the model, and when the towers of Table 5.4 are isolated from the skywire. The power lines are effectively detuned.

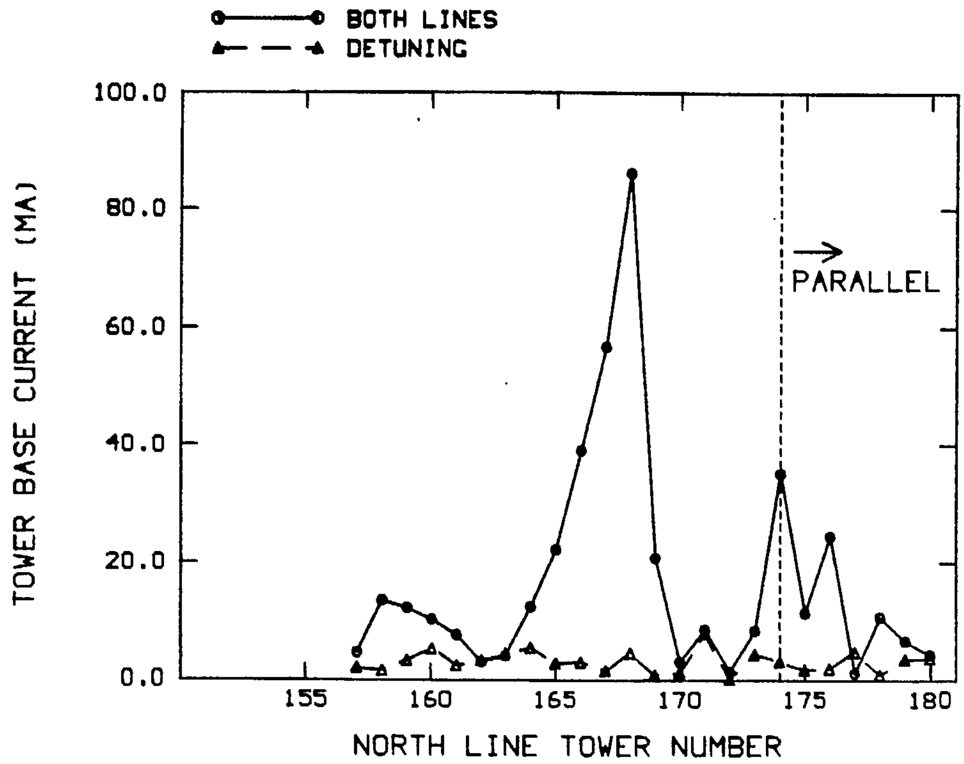


Fig. 5.10 (a) Comparison of the tower base currents on the "both lines" model before and after detuning for the "north" line.

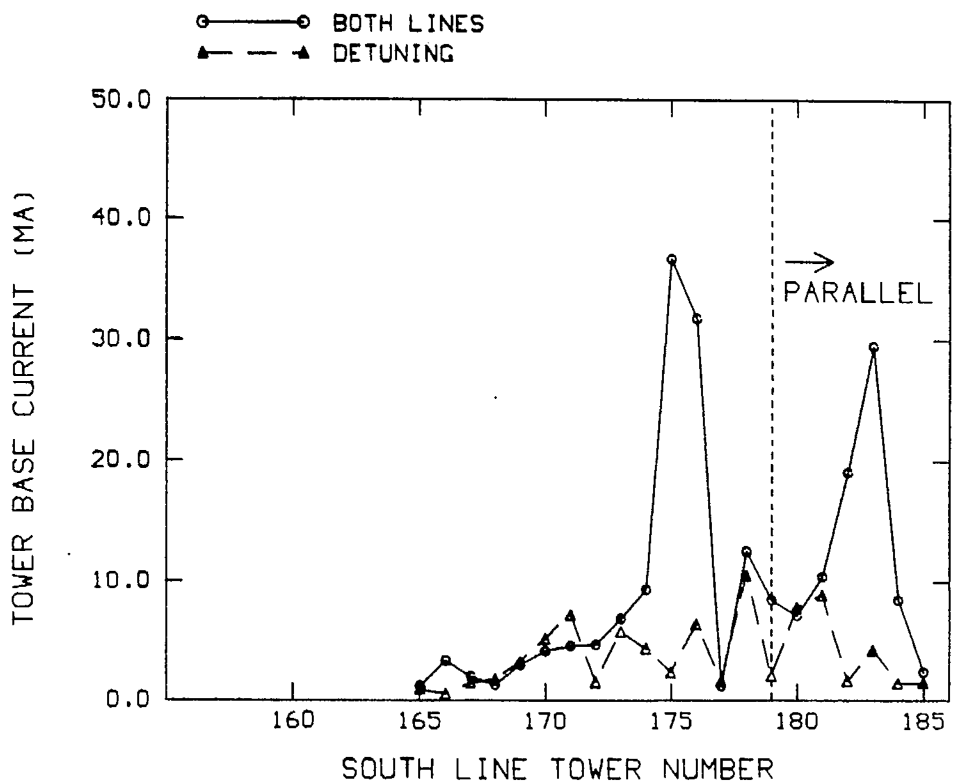


Fig. 5.10 (b) Comparison of the tower base currents on the "both lines" model before and after detuning for the "southeast" line.

APPENDIX I

TN-EMC-84-05

Technical Note No. TN-EMC-84-05

"Initial Assessment of Reradiation from the Lennox-Merivale Power Line into the Pattern of Station CBO, Ottawa"

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INITIAL ASSESSMENT OF RERADIATION
FROM THE LENNOX-MERIVALE POWER LINE
INTO THE PATTERN OF STATION CBO, OTTAWA

by C.W. Trueman
and S.J. Kubina

1. Introduction

Station CBO operates near Ottawa at a frequency of 920 kHz, and must maintain a directional pattern with a minimum field of about 16 mV/m at one mile in a pattern with a largest field value of about 2050 mV/m. Ontario Hydro proposes the construction of the Lennox (near Kingston) to Merivale (near Ottawa) power line, which will pass to the west of CBO within about 11 kilometres and to the north within about 15 kilometres. This report investigates the strength of the reradiation of CBO's signal from the towers of the power line. The resonant behaviour of the power line at AM broadcast frequencies will be discussed. A computer program will be used to model the CBO array and the power line, and will determine the net radiation pattern of CBO operating near segments of the power line. This will be repeated for various span lengths on the power line in order to discover which span lengths give the strongest reradiation, and to provide a quantitative idea of how strong that reradiation may be.

2. The CBO Array

The CBO array is described in Ref. (1) and has the design set out in Fig. 1. The "day pattern" is radiated by towers number 1, 3, 4 and 5 and is shown in Fig. 2. The pattern has a broad lobe oriented toward the northwest, with maximum field strength of about 2050 mV/m at one mile, at about 12 degrees azimuth, and again at 285 degrees azimuth. Thus the pattern maxima are oriented to the north and west and illuminate the power line strongly. The R.M.S. level of the pattern is 1290 mV/m at one mile. The field strength falls to only about 16 mV/m at about 120 degrees azimuth.

3. The Lennox-Merivale Power Line

Fig. 3 shows the route proposed for the Lennox-Merivale power line. The towers are of the "conventional lattice tower" type shown in Fig. 4, and carry a single circuit at 500 kV. The towers have a nominal height of 39.93 metres. The nominal spacing of the towers or "span length" of the power line is 300 metres, with a variability of 10 percent, and so spans of length 270 to 330 m must be considered. Two parallel lightning-protection "skywires" connect the top of each tower to the tops of the adjacent towers, and provide an electrical path for a lightning strike down the tower to the ground.

4. Loop Resonance Assessment

The electrical loop formed by a tower, the skywire to the next tower, that tower, and a return path on the images in ground can be electrically resonant at frequencies in the AM broadcast band. The length of this path is given by

$$\ell = 4h + 2s \qquad \ldots 1$$

where h is the tower height of 39.93 m and s is the span length, which varies from 270 to 330 m with a nominal value of 300 m. This electrical loop will be resonant at frequencies which can be estimated from

$$f = n\left(1.08\frac{c}{\ell}\right) \qquad \ldots 2$$

where c is the free-space speed of light, and n is an integer. The evaluation of this formula gives the resonant frequencies shown in Table 1. With the nominal span length of 300 m, the one-wavelength loop resonance frequency is estimated to be 426 kHz, too low to be of concern for CBO. The bandwidth of resonance has been very roughly estimated as about 100 kHz centered on the resonant frequency. The two-wavelength loop resonance frequency of 852 kHz is a bit above the bandwidth of two-wavelength loop resonance, but is close enough that CBO's pattern may be affected by reradiation. The three wavelength resonance frequency of 1278 kHz is too high to affect CBO's pattern. With a 270 m span length the two-wavelength loop resonant frequency is 926 kHz, very close to CBO's 920 kHz, and so spans of this length will be strongly resonant and so may be strong reradiators. The worst case is expected to be that of a power line with many spans of length 270 m.

Table 1 Estimated resonant frequencies of the spans of the Lennox-Merivale power line.

SPAN		RESONANT FREQUENCY	
LENGTH	One-wavelength loop resonance	Two-wavelength loop resonance	Three-wavelength loop resonance
270 m	463 kHz	926 kHz	1389 kHz
300	426	852	1278
330	395	790	1170

5. Computer Modelling Program

The antenna and power line will be analysed using the computer program called "AM Power Line" (AMPL) described by Tilston and Balmain in Ref. (2). This computer program models the broadcast array with a sinusoidal current distribution on each tower, of specified amplitude and phase at the base of each tower. The power line is modelled by specifying the location of each tower and its height, and specifying the radius of the equivalent cylinder used to represent the tower. The AMPL program evaluates the amplitude and phase of the broadcast antenna's field at each power line tower, which gives the driving voltage at each tower. The towers are coupled together by an ideal "transmission line" which models the skywires and their images in the ground. The wire radius of the skywire "transmission line" must be specified. The AMPL program computes the RF current flowing on each power line tower, accounting for the coupling via the skywire "transmission line." The details of the analysis of the power line tower at RF are given in Ref. (2). The amplitude and phase of the RF current on each power line tower is used to compute the strength of the field reradiated by the power line, which is added vectorially to the broadcast antenna's field to obtain the radiation pattern of the broadcast antenna operating near the power line. Results obtained using the AMPL program have been validated in Ref. (2) against the results of the more exact representation used in the Numerical

Electromagnetics Code(NEC), which is reviewed in Ref. (3). The AMPL model of the behaviour of the power line at RF frequencies is found to be a reasonable approximation up to about 1100 kHz, and can be used to analyse the behaviour of CBO near the Lennox-Merivale power line.

The AMPL code accounts for the actual conductivity of the ground by using an approximate method described in Ref. (2). The effect of ground conductivity on each power line tower is modelled as a lumped impedance connected in series with the base of the tower. The effect of ground conductivity on the skywire "transmission line" is modelled by including an attenuation factor for the travelling waves on the transmission line. These approximations could be verified against the Sommerfeld-Norton model of ground conductivity offered by the NEC computer program, but no such comparison has been reported. Thus the AMPL code includes some accounting for the ground conductivity in its results.

6. Computed Pattern for CBO

The CBO array was modelled by specifying tower # 1 in Fig. 1 as the origin of a coordinate system with the x-axis going north and the y-axis going west. The x,y coordinates of towers 3, 4 and 5 were calculated from the information of Fig. 1 to be (0,0) m for tower # 1, (-86.27,-49.81) m for tower # 3, (-172.53, -99.61) m for tower # 4, and (-266.27,-135.67) m for tower # 5. The towers were all modelled as 74.07 m tall, of radius 0.26 m. The amplitude and phase of the current at the base of each antenna tower given in Fig. 1 were input to the AMPL program. The result of running AMPL is the broadcast array pattern plotted in Fig. 5. The pattern is plotted on a linear scale from 0 to 1, and should be multiplied by 2050 mV/m to obtain field strengths at one mile. The circle at a level of about 0.63 is the R.M.S. level of 1290 mV/m at one mile. The discontinuities in the pattern at 90 and 195 degrees arise because the scale on the polar plot has been expanded in the pattern minimum by a factor of 20 when the field strength is less than 0.05. Thus in the pattern minimum the scale runs from 0 to 0.05, where a level of 0.05 represents a field strength of 0.05x2050 = 102.5 mV/m at one mile, and the pattern minimum is about 16.5 mV/m, in reasonable agreement with the polar plot of Fig. 2.

7. Modelling the Power Line

The towers of the power line must be modelled in AMPL as cylinders of a radius "equivalent" to the actual tower cross-section. The derivation of equivalent radius is discussed in Ref. (3). The cross-sectional size of the "conventional lattice tower" was estimated from Fig. 4 to be about 8.68 m square at the base and 2.35 m square at the waist. An equivalent radius of 2.71 m was obtained. The skywire "transmission line" must also have an equivalent radius specified. In this case, the pair of parallel, thin skywires which connect the top of each tower to the next is replaced by a single skywire of larger diameter, by the formula given in Ref. (3). A skywire equivalent radius of 0.2175 m was obtained.

Table 2 Points on the route of the Lennox-Merivale power line, expressed as distance from the CBO array, and angle west of north.

Point #	Angle	Distance
1	-26.1 deg	24.328 km
2	-20.1	21.241
3	-11.9	18.396
4	-4.2	16.431
5	5.4	14.875
6	29.2	13.903
7	33.2	13.869
8	37.8	13.417
9	41.7	13.072
10	50.0	13.036
11	56.6	13.382
12	66.6	12.749
13	84.2	11.136
14	101.3	10.936
15	115.8	11.986
16	126.2	13.937
17	132.9	16.379
18	137.5	19.095
19	140.3	21.977
20	143.3	25.842

The route of the power line given on the map of Fig. 3 must be specified to the computer in order that the coordinates of the bases of the power line towers can be obtained for various span lengths. Points were read from the map and are listed in Table 2. Since the route in Fig. 3 appears to have no sharp corners, the path of power line was represented as a smooth curve with a continuous derivative. This has the advantage that a power line with perfectly uniform span length can be constructed of any desired length, without having "corners" introducing uneven span lengths. A more precise model, representing corners in the power line accurately, would be required for a precise pattern prediction. Fig. 6 shows the computer model of the route of the power line.

To represent the power line of Fig. 6 with spans of length 300 m would require about 100 spans. The present implementation of the AMPL program on the Concordia University Electromagnetic Compatibility Laboratory's LSI-11 computer allows about 40 spans to be modelled. Thus the power line will be studied in two segments. Three span lengths will be considered for each power line segment, namely 270, 300 and 330 m.

8. Reradiation From the North Segment

The north segment of the power line is generated by starting at a point on the power line precisely north of the antenna, at x=15,633 m and y=0 m in the coordinate system described above. Then towers are added going west along the route of the power line, separated by the span length, until 40 spans have been generated. The length of the resulting power line segment is 40 spans times the span length. Fig. 7 shows the north segment with 300 m spans. Figs. 8 to 10 show the radiation pattern with spans of 270, 300 and 330 m length. With 270 m spans the power line is resonant at CBO's frequency. Fig. 8(a) shows that the "north segment", of length 10.8 km with 40 spans, adds a ripple to the field strength in CBO's minimum. Fig. 8(b) shows that the ripple rises about 10 mV/m at one mile above CBO's field strength in the minimum. Fig. 9(a) shows the radiation pattern with the nominal span length of 300 m, for a total line length of 12 km, and Fig. 9(b) shows a ripple of about 5 mV/m at one mile. With 330 m spans, for a total power line length of 13.2 km, Fig. 10 shows a ripple of about 2 mV/m at one mile on CBO's pattern. Thus in the worst case, the "north segment" causes reradiation which raises the field strength at certain specific angles in CBO's minimum by about 10 mV/m at one mile.

9. Reradiation From the West Segment

Fig. 11 shows the route of the "west segment" power line, with 40 spans for the case of 300 m span length. The "west segment" begins at a point on the power line 45 degrees west of north of the antenna, and extends southwest, then south. To specify tower locations, the first tower is positioned at (x=9154.34, y=9154.34) m, and then further towers are added going southwest along the route, separated by the span length, until 40 spans have been generated. The "west segment" is closer to the CBO antenna than the "north segment" and so a stronger reradiated field would generally be expected. With 270 m spans, the "west segment" is 10.8 km in length. Fig. 12(a) shows the radiation pattern with 270 m spans, which are resonant at CBO's frequency of 920 kHz. A large ripple is seen in the minimum. Fig. 12(b) shows that the strength of the ripple is about 21 mV/m at one mile. Fig. 13(a) shows the radiation pattern with a "west segment" with 300 m spans, for a total length of 12 km. Fig. 13(b) shows a ripple of about 10 mV/m at one mile. Fig. 14(a) shows the radiation pattern for a power line with 330 m spans, for a total length of 13.2 km, and Fig. 14(b) shows a ripple of about 3 mV/m at one mile. Thus the worst case occurs when all the spans are of length 270 m, and the strength of the ripple on CBO'S pattern is about 21 mV/m at one mile.

10. Conclusion

In this report, the radiation pattern of station CBO at 920 kHz operating near segments of the Lennox-Merivale power line was determined by computer modelling. The power line is resonant at CBO's frequency when the span length is 270 m, which is 10 percent less than the nominal value of 300 m. Reradiation from the power line was found to add a ripple to the field strength in the minimum of CBO's day pattern, from azimuth 90 to 180 degrees. Table 3 summarizes the results. The "north segment" power line, extending west along the Lennox-Merivale route for the length of 40 spans from a point due north of CBO, is about 15 km from the antenna array and gives rise to a ripple of 10 mV/m at one mile with 270 m spans, and 5 mV/m at one mile with 300 m spans. The "west segment" of the power line, extending southwest for the length of 40 spans along the Lennox-Merivale route from a point on the route which is 45 degrees west of the antenna array, is about 11 km from the antenna. The west segment, with 270 m spans, superimposes a ripple of amplitude 21 mV/m at one mile on CBO's pattern. With 300 m spans the ripple extends 10 mV/m above CBO's pattern. These tests use equally spaced towers to obtain a uniform span length for the power line, whereas the real power line will have a variable span length with a variation of 10 percent around the nominal value of 300 m for the span length. Thus it is unlikely that long runs of the power line will have uniform spans each 270 m long. Evidently, the strength of the ripple on CBO's pattern can be reduced by avoiding the shorter spans near 270 m length, and choosing as many spans as possible near 330 m length.

11. Further Investigations

At the time of this writing, a revision of the route for the Lennox-Merivale power line has become available, which moves a length of about 8 km of the "north segment" of the line about 1 km closer to the antenna array. Although the new route should be modelled and radiation patterns should be produced, it is not expected that the results presented here will be much changed.

It would be of interest to specify the protection limit that the pattern of CBO must meet. This would establish whether the 21 mV/m ripple at one mile is an acceptable figure, or is too large to be tolerated. If too large, then the question of how much reradiation is expected when only some of the spans of the power line are near 270 m in length becomes important. This could be investigated by modelling the span length as a "normally" distributed random variable of mean value 300 m, and standard deviation between 5 and 10 percent of the mean value. A set of span lengths with these statistics could be used to "build" a specific power line segment, which, when analysed by AMPL, gives rise to a ripple on CBO's pattern. If many such cases are examined, say 10 or 20, then a good indication is obtained of how much reradiation is expected when the span length is variable, as it will be on the real power line.

Table 3 Amplitude of the ripple induced on CBO's radiation pattern by reradiation from segments of the Lennox-Merivale power line.

Span Length	North Segment Power Line	West Segment Power Line
270 m	10 mV/m	21 mV/m
300	5	10
330	2	3

REFERENCES

1. Hoyles Niblock Associates Ltd., "Engineering Brief in Support of an Application for an Increase in Power to 50 kW and for a Change in Frequency for Standard Band Broadcast Station CBO, Ottawa, Ontario", Vancouver, B.C., May, 1973.

2. M.A. Tilston and K.G. Balmain, "A Microcomputer Program for Predicting AM Broadcast Re-Radiation from Steel Tower Power Lines", IEEE Trans. on Broadcasting, Vol. BC-30, No. 2, pp. 50-56, June, 1984.

3. C.W. Trueman and S.J. Kubina, "AM Reradiation Project," Technical Note No. TN-EMC-80-03, Dept. of Electrical Engineering, Concordia University, Montreal, March, 1980.

DESCRIPTION SHEET

Station: CBO

Main Studio: Ottawa, Ontario

Frequency: 920 kHz

Power: 50 kW

Time: Unlimited

Class: III

Notification List No.:

Date:

Geographic Location: 45° 11'09" N. Lat.
75° 44'53" W. Long

Antenna System: Mode of Operation: DA-2

Elements - seven guyed elements, 238' (80° electrical) high with overall height of 243', uniform cross-section, base insulated and series fed.

Tower Parameters:

Tower	Spacing Degrees	Spacing Feet	Orientation Degrees True	Ratio	Phase
				Night	
1	REF	REF	REF	1.0	0°
3	110	326.811	150	1.797	100.51°
4	220	653.623	150	0.94	-157.53°
6	227.408	675.632	187.573	0.846	-111.53°
7	155.442	461.82	213.137	1.617	146.51°
9	144.256	428.586	256	0.9	46°
				Day	
1	REF	REF	REF	1.0	0°
3	110	326.811	150	3.0	85.6°
4	220	653.623	150	3.0	169.4°
5	330	980.435	153	0.94	- 99°

Predicted Effective Field:

Day 1290 mV/m at one mile for 50 kW
(182 mV/m at one mile for 1 kW)

Night 1250 mV/m at one mile for 50 kW
(178 mV/m at one mile for 1 kW)

Fig. 1 The design of the CBO antenna array, reproduced from Ref. (1).

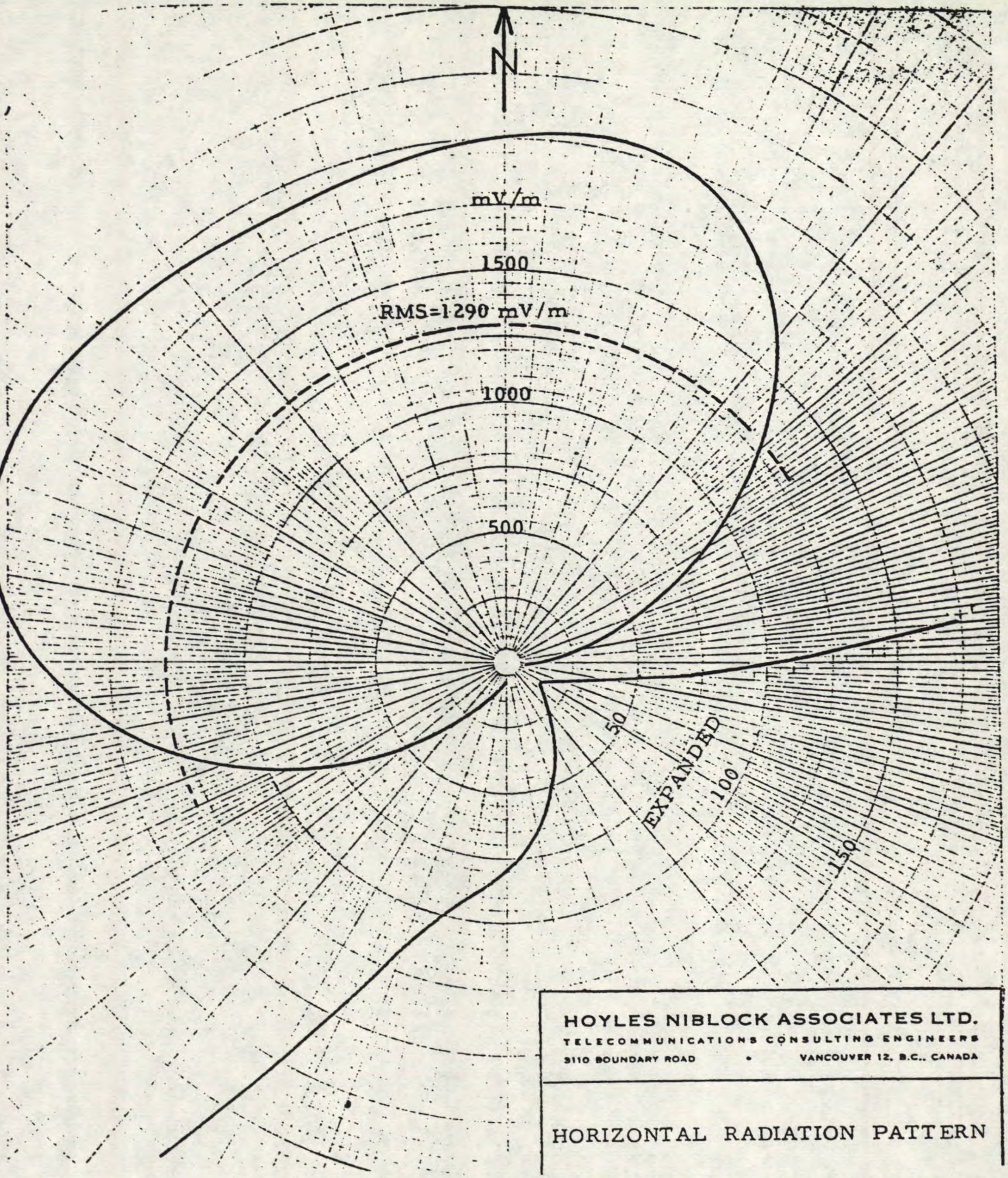

Fig. 2 The "day pattern" of station CBO, reproduced from Ref. (1).

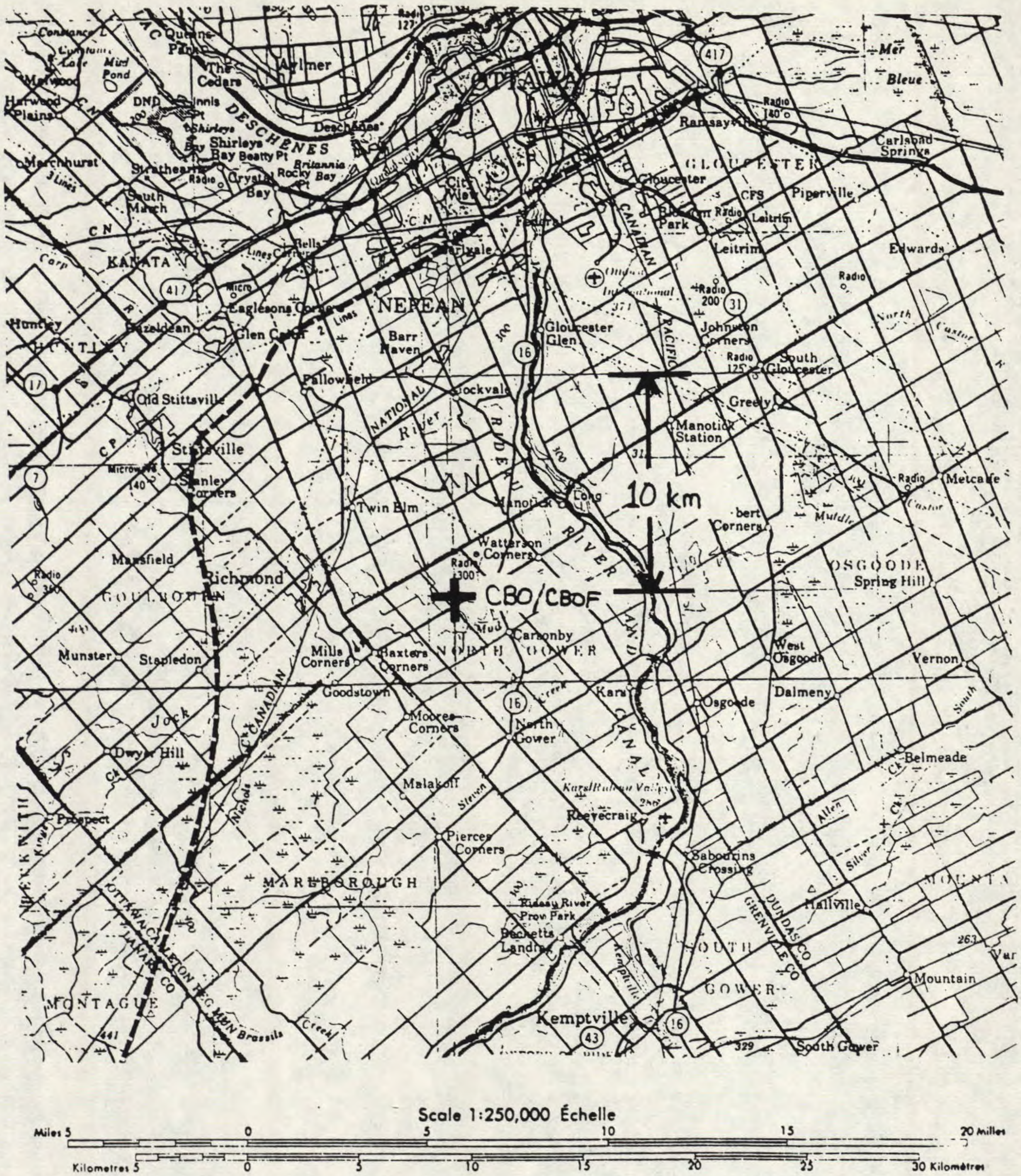

Fig. 3 The route proposed for the Lennox-Merivale power line.

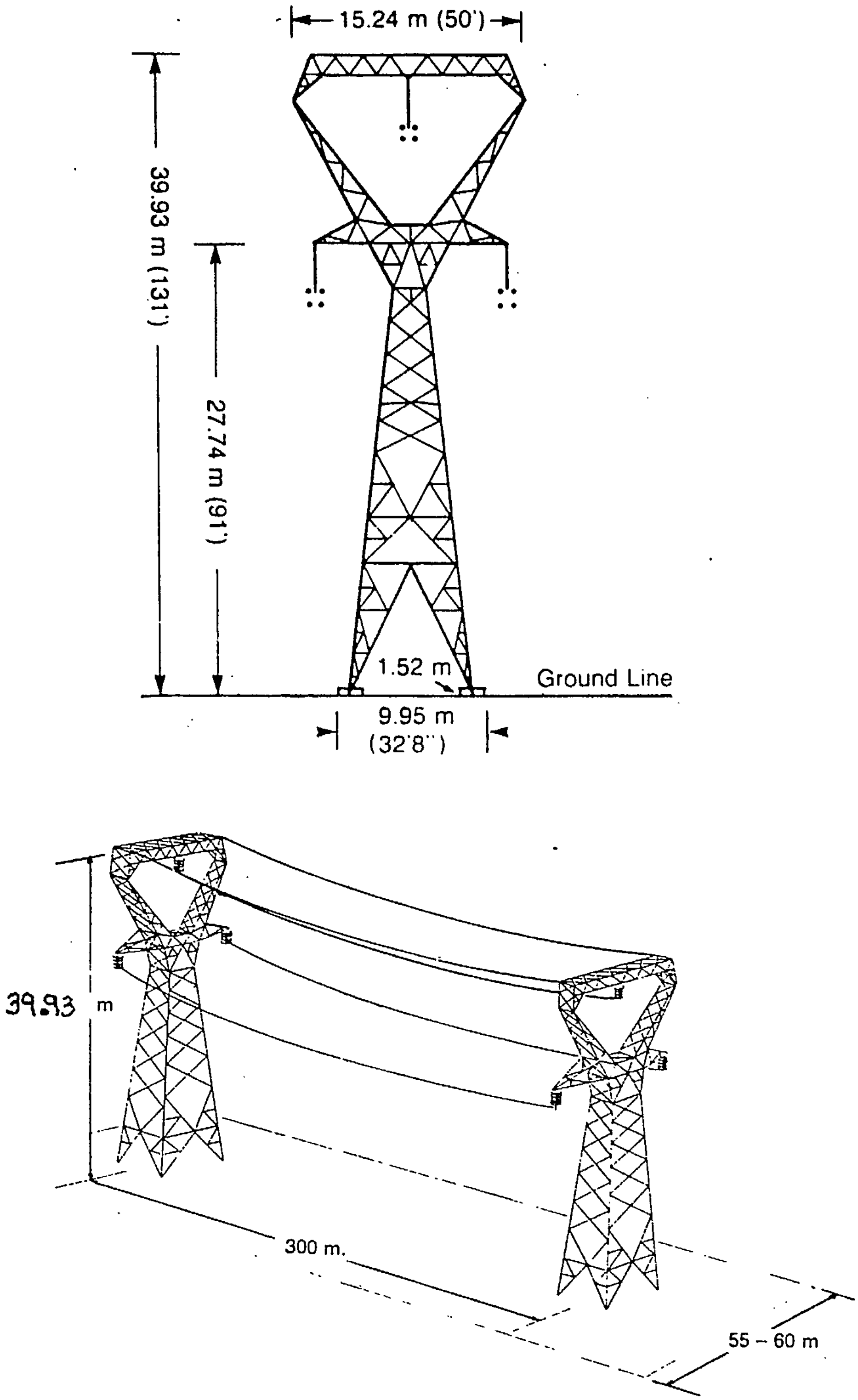

Fig. 4 "Conventional lattice towers" to be used on the Lennox-Merivale power line.

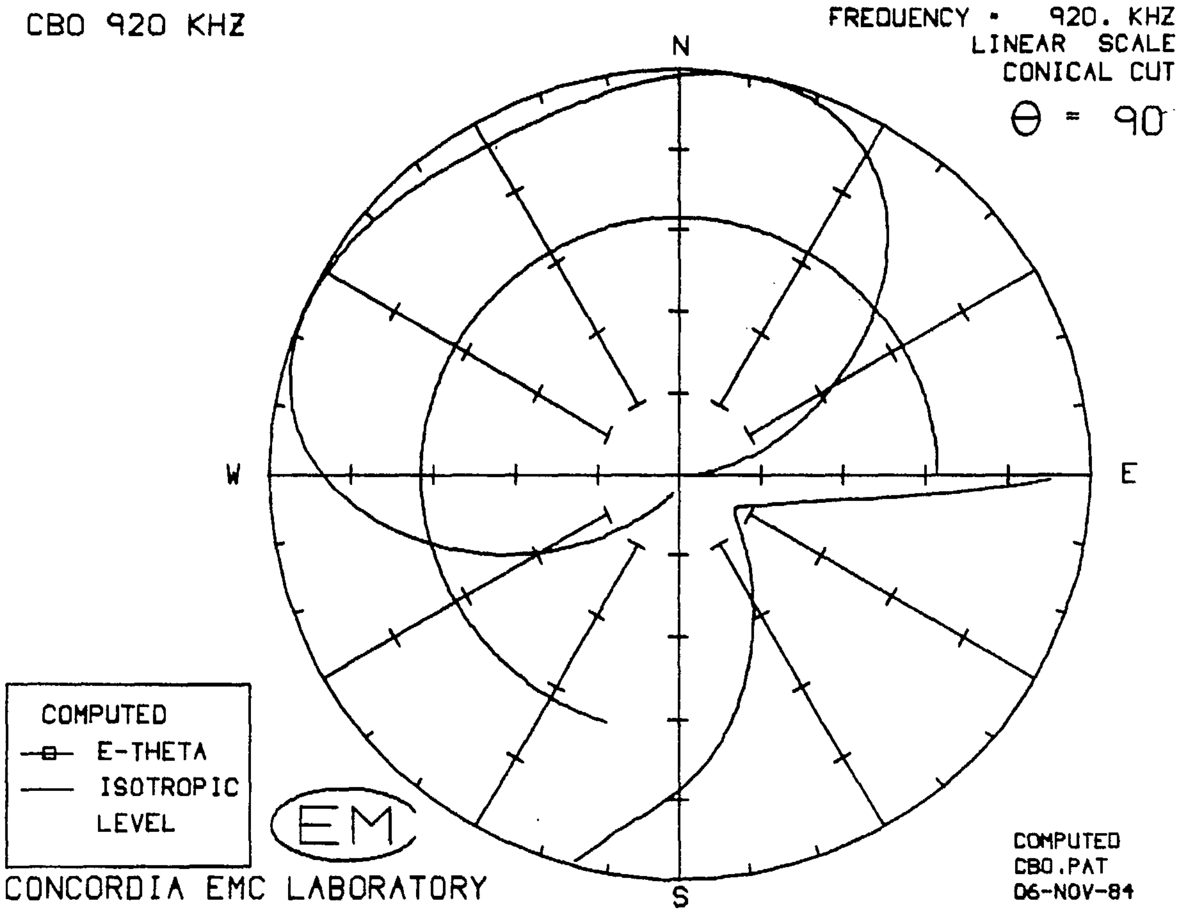

Fig. 5 The "day pattern" of the CBO array as computed by the AMPL program.

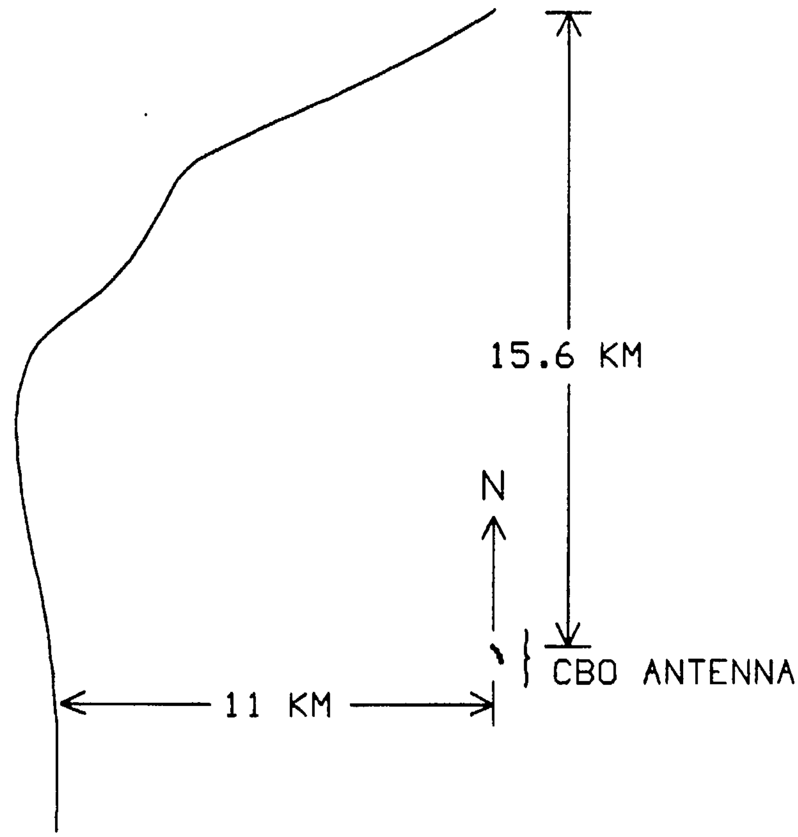

Fig. 6 Computer representation of the route of the Lennox-Merivale power line.

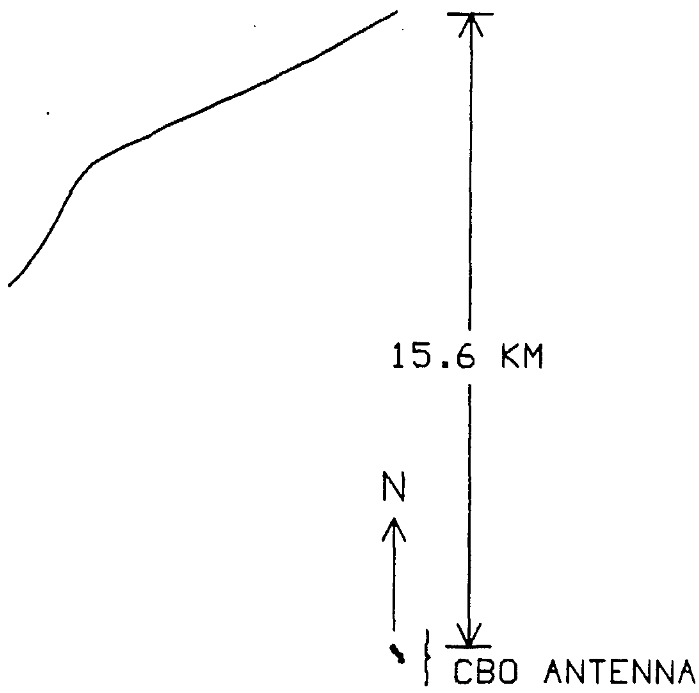

Fig. 7 The "north segment" of the Lennox-Merivale power line, with 40 spans of length 300 m.

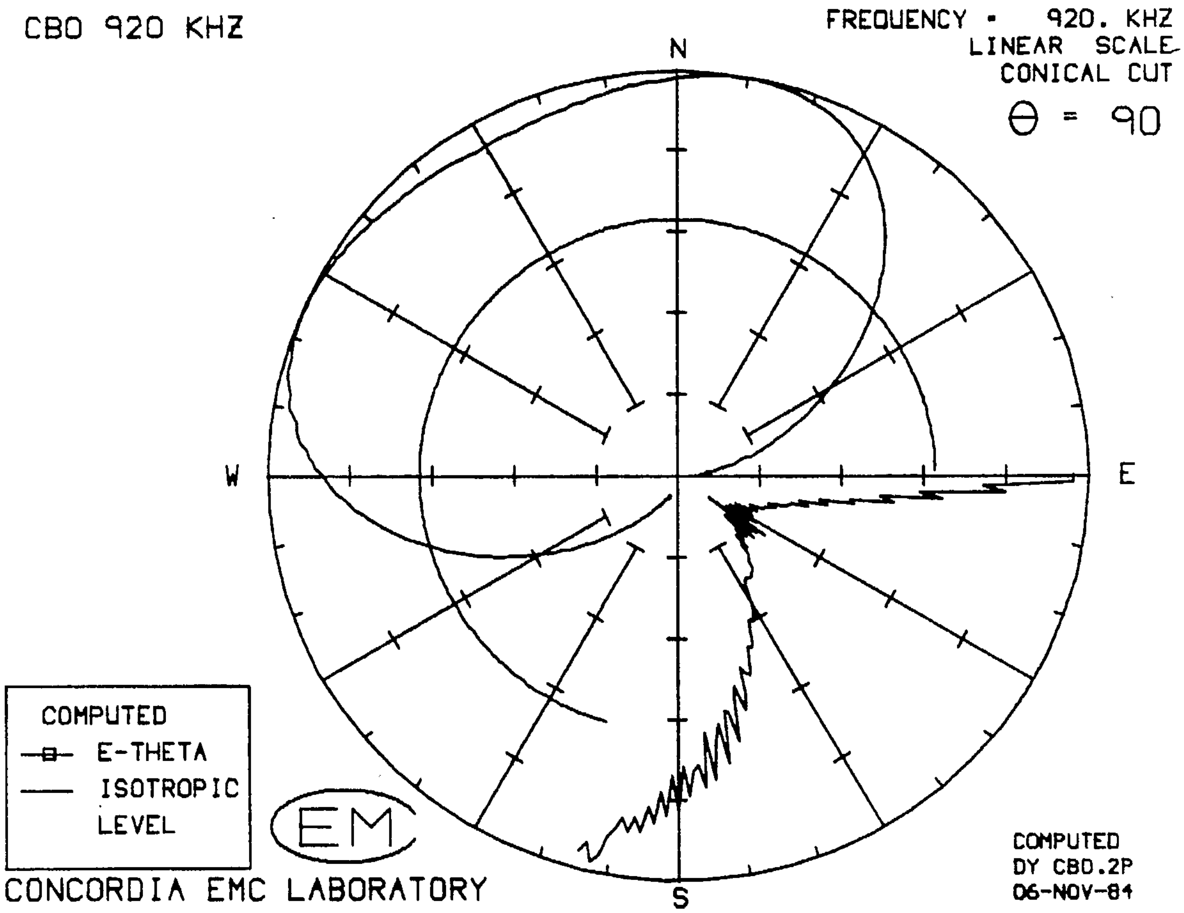

Fig. 8(a) Radiation pattern of CBO with the "north segment" power line, with 40 spans of length 270 m.

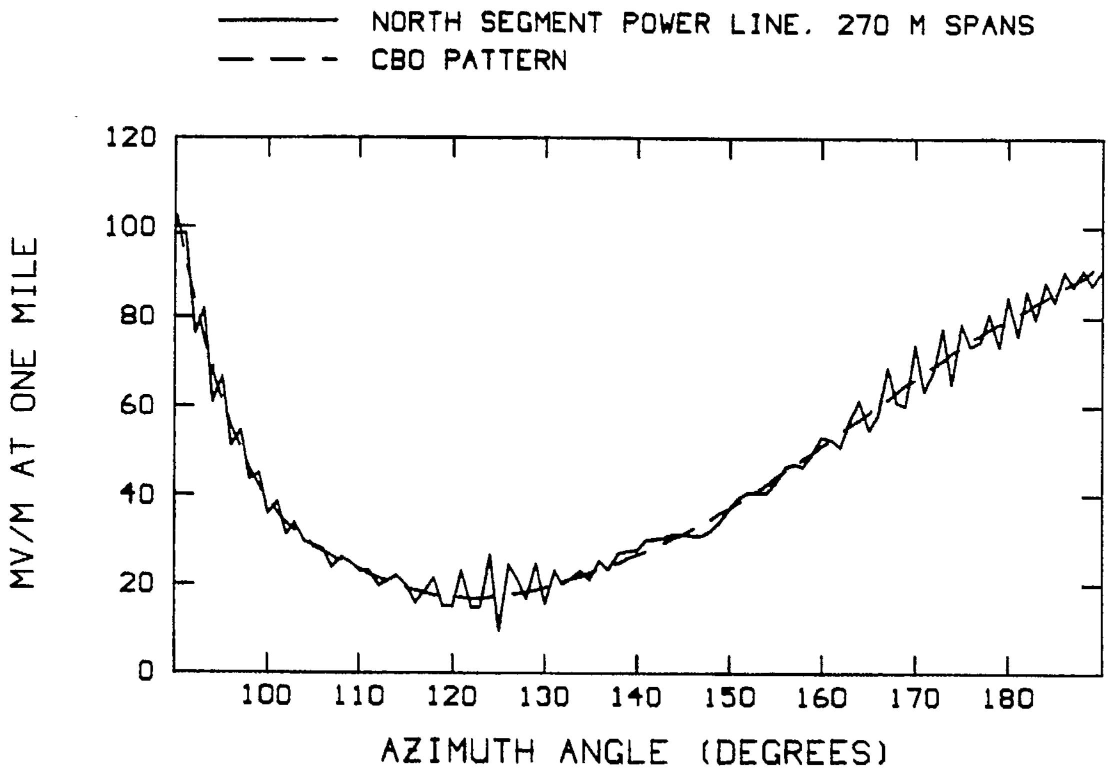

Fig. 8(b) Field strength in the minimum of CBO's pattern, with the "north segment" power line and span length 270 m.

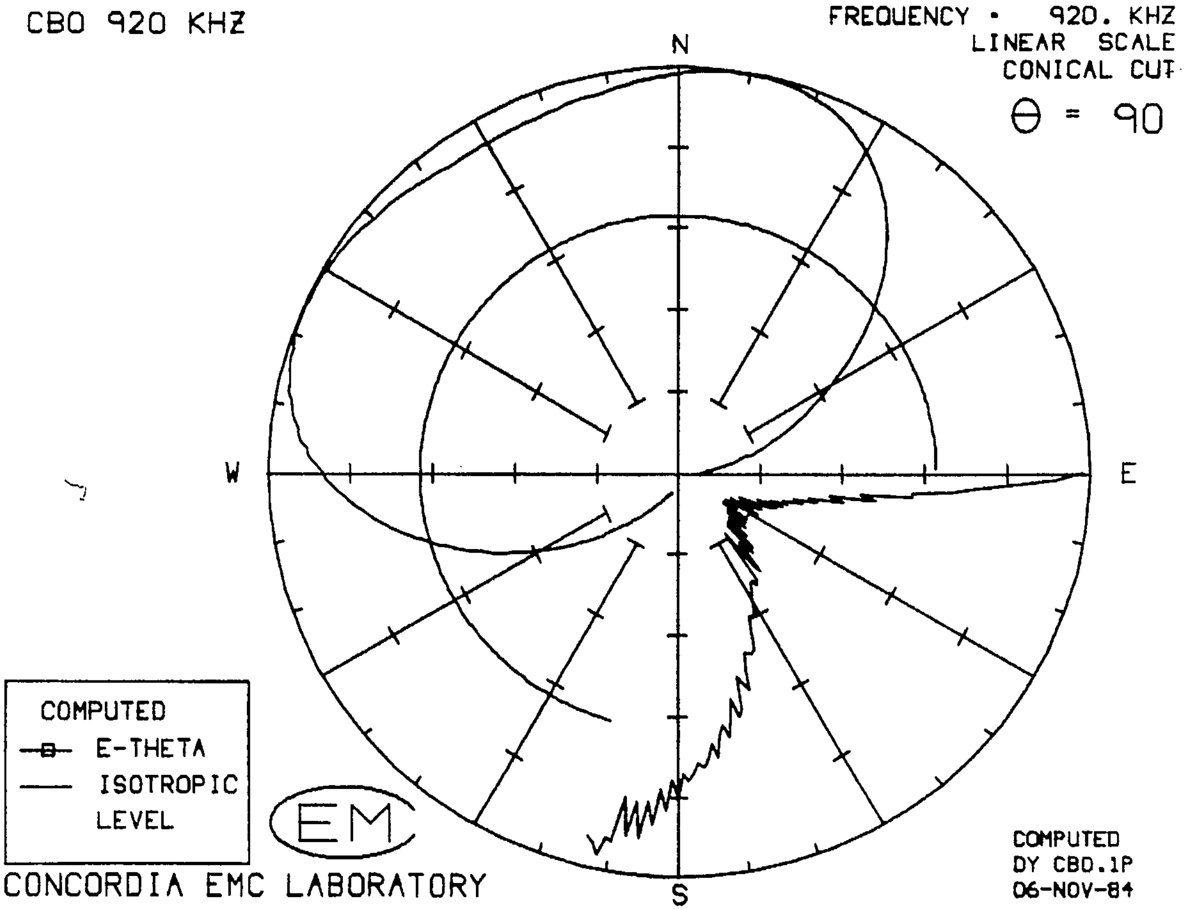

Fig. 9(a) Radiation pattern of CBO with the "north segment" power line, with 40 spans of length 300 m.

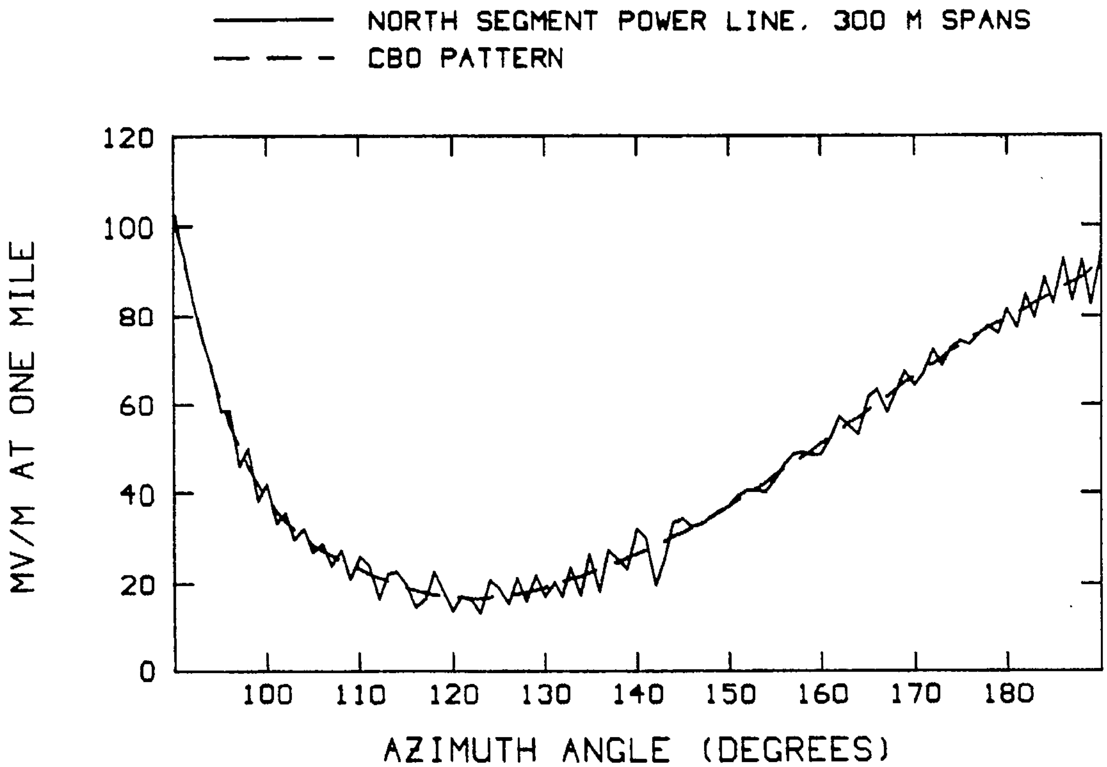

Fig. 9(b) Field strength in the minimum of CBO's pattern, with the "north segment" power line and span length 300 m.

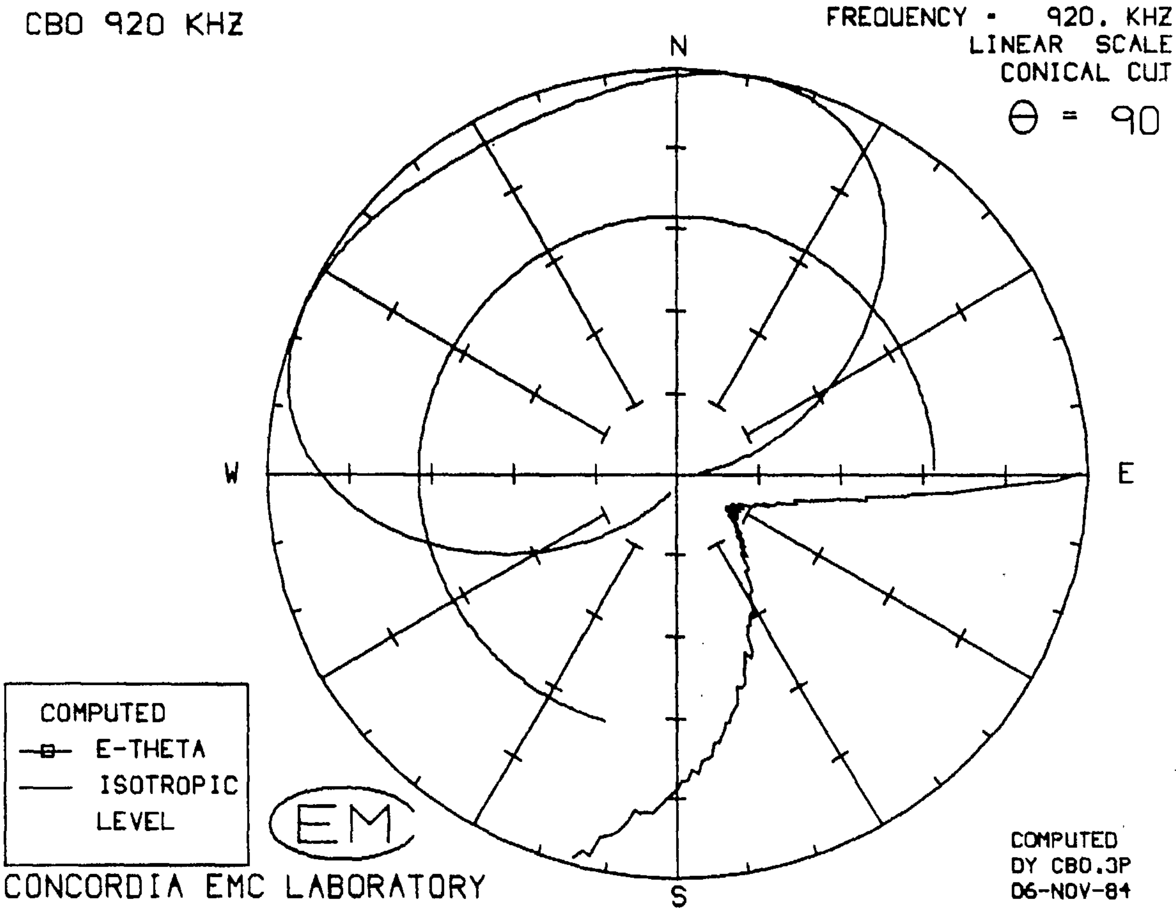

Fig. 10(a) Radiation pattern of CBO with the "north segment" power line, with 40 spans of length 330 m.

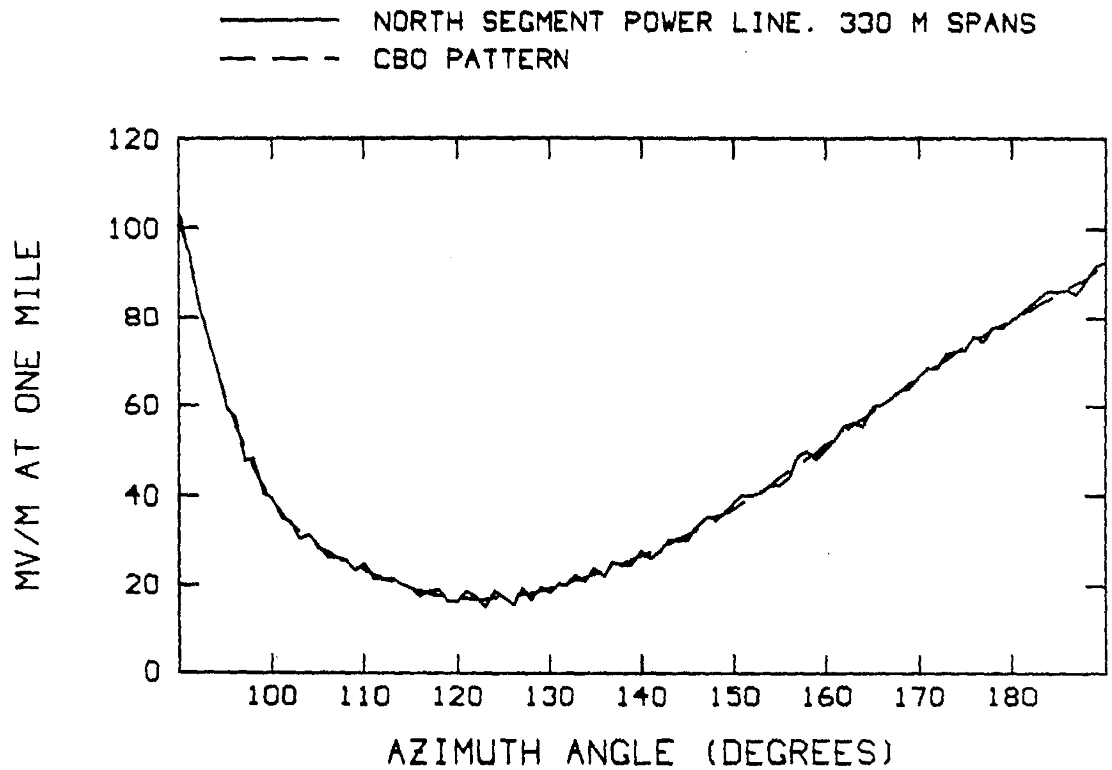

Fig. 10(b) Field strength in the minimum of CBO's pattern, with the "north segment" power line and span length 330 m.

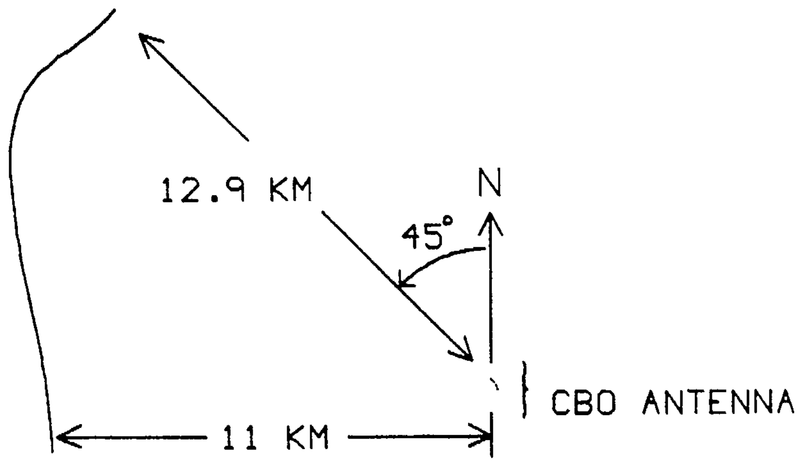

Fig. 11 The "west segment" of the Lennox-Merivale power line, with 40 spans of length 300 m.

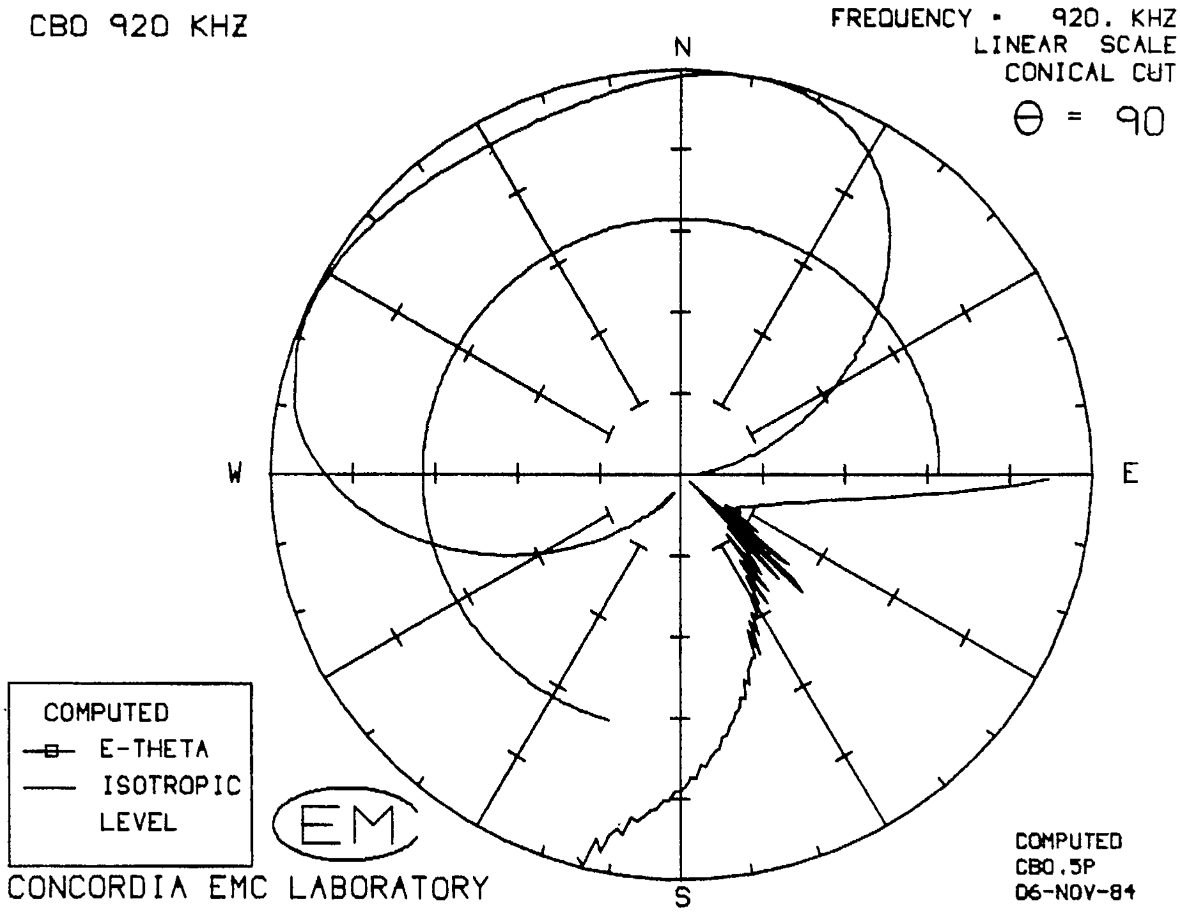

Fig. 12(a) Radiation pattern of CBO with the "west segment" power line, with 40 spans of length 270 m.

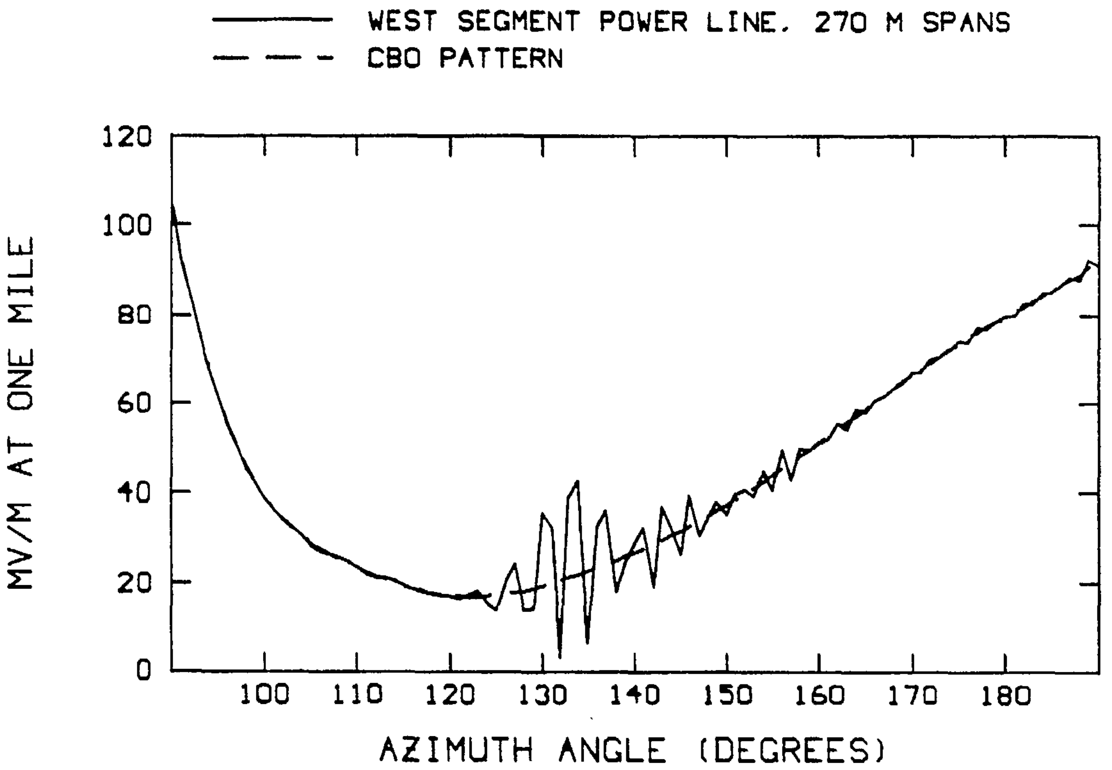

Fig. 12(b) Field strength in the minimum of CBO's pattern, with the "west segment" power line and span length 270 m.

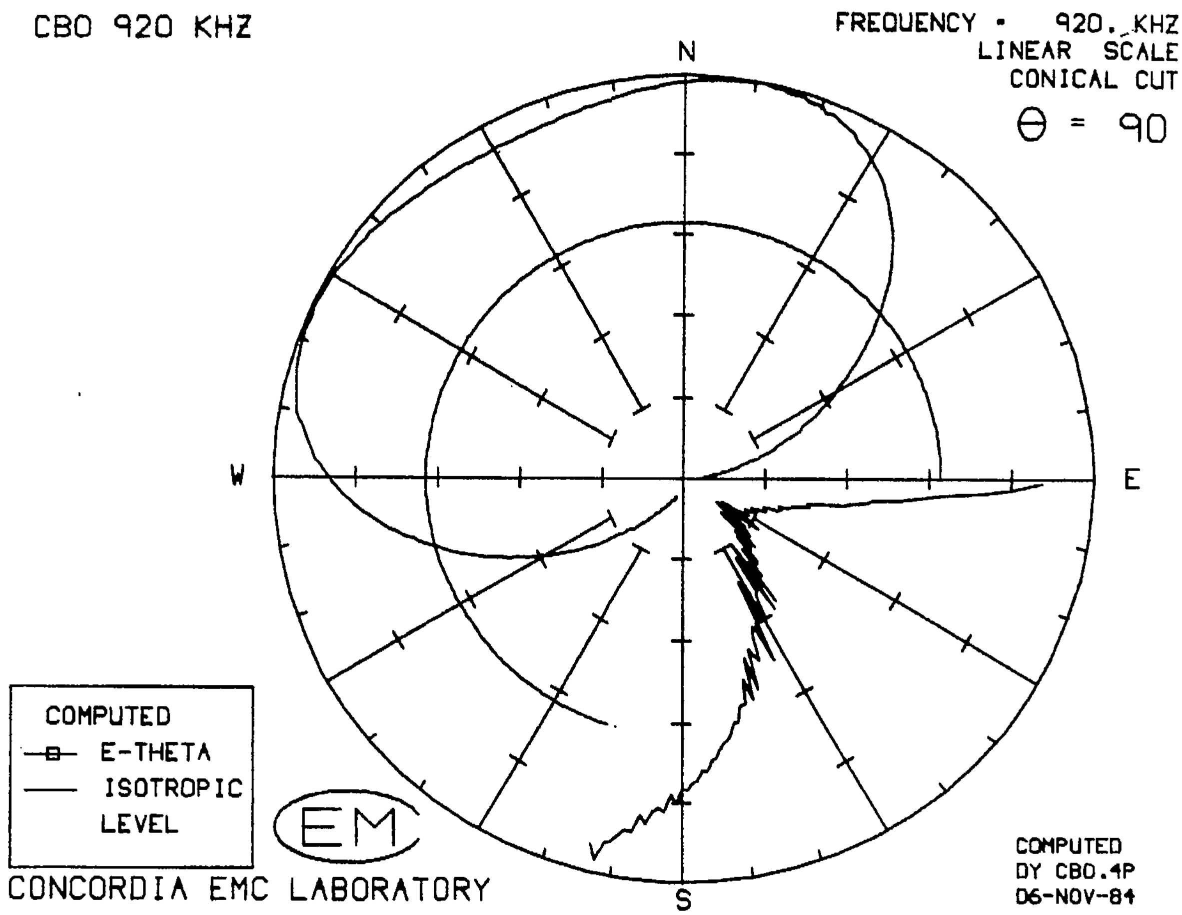

Fig. 13(a) Radiation pattern of CBO with the "west segment" power line, with 40 spans of length 300 m.

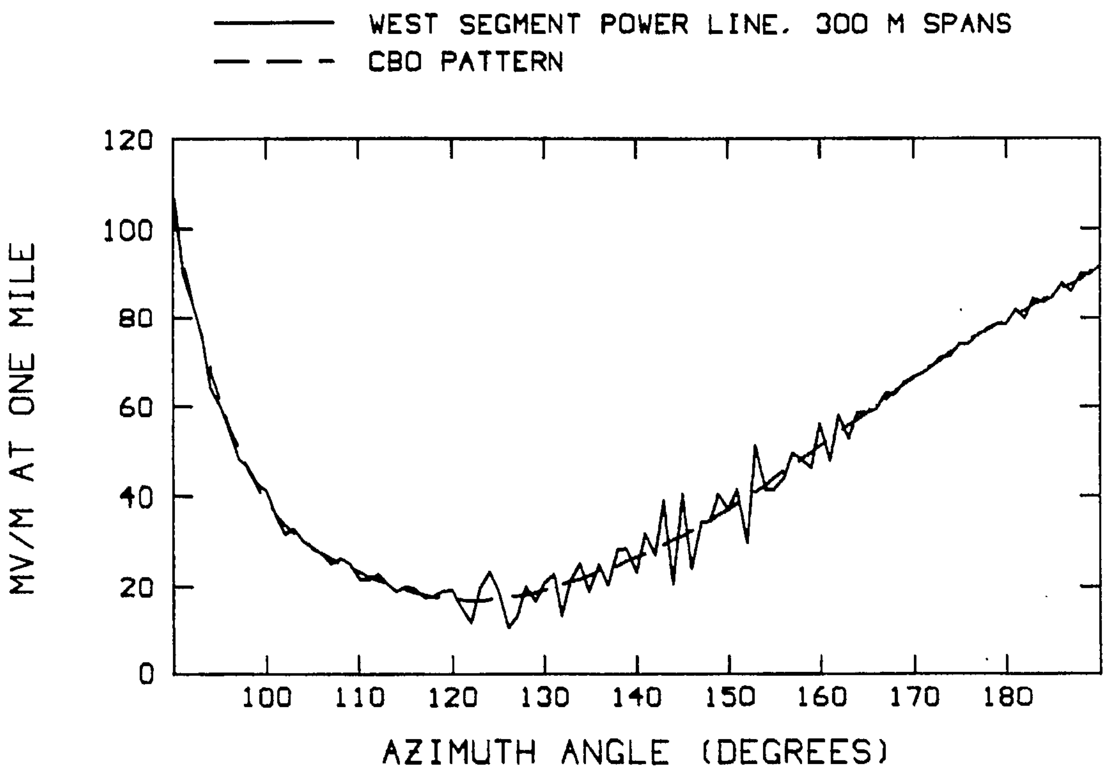

Fig. 13(b) Field strength in the minimum of CBO's pattern, with the "west segment" power line and span length 300 m.

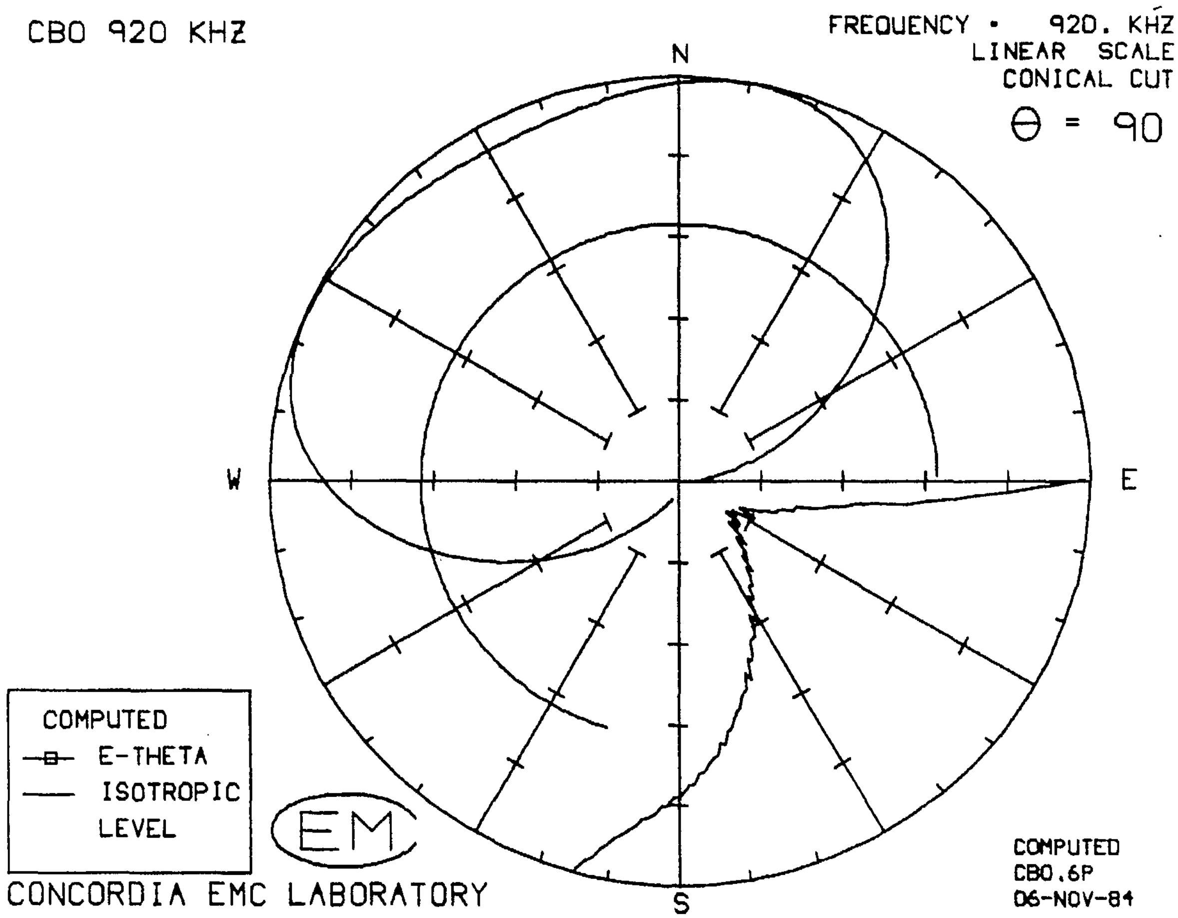

Fig. 14(a) Radiation pattern of CBO with the "west segment" power line, with 40 spans of length 330 m.

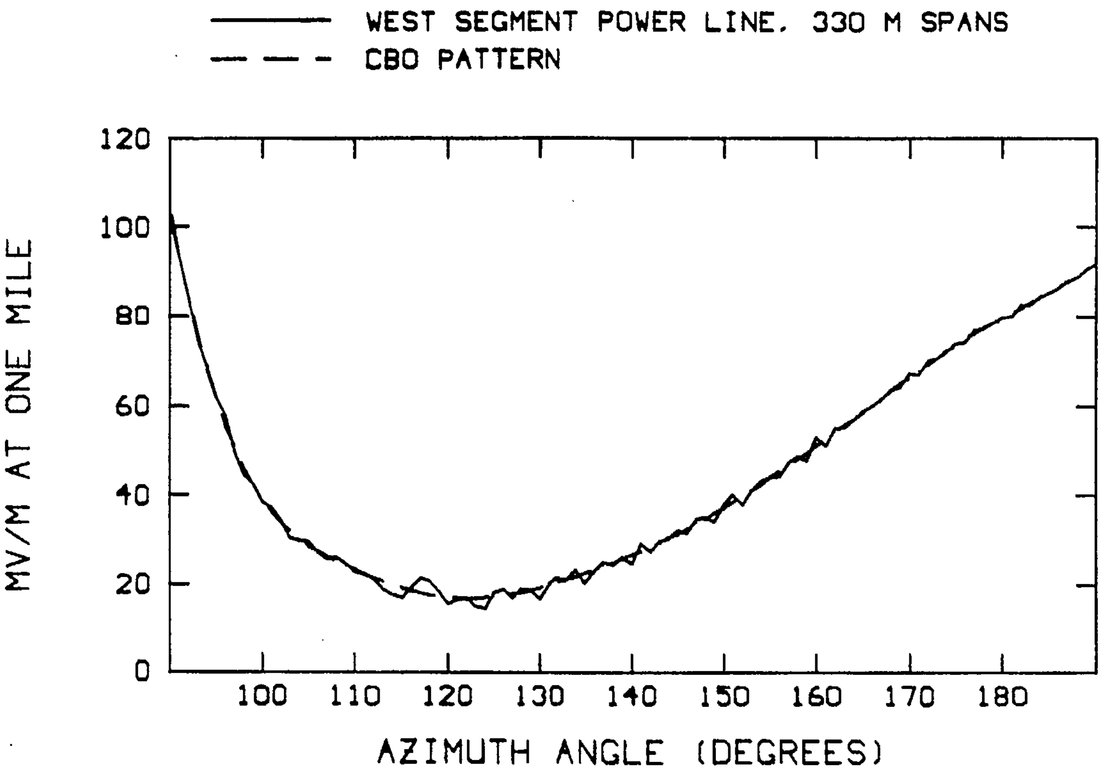

Fig. 14(b) Field strength in the minimum of CBO's pattern, with the "west segment" power line and span length 330 m.

APPENDIX II

TN-EMC-85-08

Technical Note No. TN-EMC-85-08

"Initial Assessment of Reradiation from the Lennox-Merivale Power Line into the Night Pattern of Station CBO, Ottawa"

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Prepared for:

Communications Research Centre, Ottawa
K2H 8S2

Contract No. 0ST83-00290

INITIAL ASSESSMENT OF RERADIATION FROM THE LENNOX-MERIVALE POWER LINE INTO THE NIGHT PATTERN OF STATION CBO, OTTAWA

by C.W. Trueman
and S.J. Kubina

1. Introduction

Station CBO operates near Ottawa at a frequency of 920 kHz, and must maintain a "night pattern" with a main lobe of field strength about 2900 mV/m at one mile, directed at about 3 degrees azimuth, as shown in Fig. 1(a). The pattern has a broad minimum extending from about 82 to about 246 degrees azimuth, in which the field strength is less than 120 mV/m, which is much less than the pattern's R.M.S. field strength of 1250 mV/m. Ontario Hydro proposes the construction of the Lennox (near Kingston) to Merivale (near Ottawa) power line, which will pass to the west of CBO within about 11 kilometres and to the north within about 16 kilometres. This report investigates the strength of the reradiation of CBO's signal from the towers of the power line, when the power line is illuminated by CBO's "night pattern". A previous report, "Initial Assessment of Radiation from the Lennox-Merivale Power Line into the Pattern of Station CBO, Ottawa", Ref. (1), investigated reradiation into the "day pattern" of station CBO. That report discussed the modelling of the power line and its analysis by the AMPL computer program, which is described in Ref. (2). The span length of the power line varies from 270 to 330 m, and Ref. (1) describes the resonant behaviour of such a power line. Spans of 270 m length are resonant at CBO's 920 kHz, while spans of 300 m are marginally resonant and 330 m spans are non-resonant. It was found that when segments of the power line are illuminated with CBO's "day pattern", the reradiation is largest for spans of 270 m length, and least for 330 m spans, at 920 kHz. In this report, a segment of 40 spans of the power line due north of the antenna is illuminated with CBO's night pattern, and the reradiation is investigated for spans in the same range of lengths.

2. The CBO Night Pattern

Ref. (3) specifies that towers 1, 3, 4, 5, 7 and 9 on the CBO/CBOF site are used to obtain the CBO "night pattern", and gives the set of tower base currents which are used to obtain Fig. 1(a), which was computed with the AMPL program. Fig. 1(b) compares the field strength in the minimum of from 80 to 250 degrees, computed using AMPL, with that reported by the consultants in Ref. (3). Points on the pattern given in Ref. (3) were read manually to obtain the curve labelled "Hoyles-Niblock". Fig. 1(b) shows that the AMPL pattern is close to that given in the consultant's report.

3. The "North Line" Segment

Fig. 3 of Ref. (1) is a plan of the route of the proposed Lennox-Merivale power line. The CBO night pattern of Fig. 1(a) is primarily directed northward, and so that part of the power line due north of the antenna is most strongly illuminated and is the segment most likely to reradiate. Consequently, 40 spans of power line along the portion of the route of the Lennox-Merivale power line due north of the antenna were included in the computer model, as shown in Fig. 2(a) for 270 m spans. Table 2 in Ref. (1) gives the set of points on the power line used to represent the line in the computer model. The section of the power line shown in Fig. 2(a) will be referred to as the "north line" segment, and begins at a point on the power line 13.9 degrees east of north of the CBO site, and extends southwest along the route of the power line for a distance of 40 spans. The point on the power line due north of the CBO cite is about 15.6 km distant. The angle of the starting point of the power line, east of north of the CBO antenna, will be adjusted as the span length is increased, to keep the segment of power line symmetric about a line extending northward from the antenna.

4. Reradiation From the "North Line" Segment

As discussed in Ref. (1), with power line towers of height 39.93 m, spans of length 270 m are resonant at 926 kHz, which nearly coincides with CBO's frequency of 920 kHz. Spans of 300 m length are resonant at 852 kHz, which is only a little more than 60 kHz different from 920 kHz, and so 300 m spans are "marginally resonant". The 60 kHz figure is one-half of the bandwidth of resonance, as discussed in Ref. (4). Spans of 330 m length, resonant at 790 kHz, are consequently non-resonant at 920 kHz, and should present no significant reradiation into CBO's pattern.

The level of reradiation from the "north line" was assessed by using the AMPL computer program, described in Ref. (2), to analyse the power line to determine the RF currents on the power line towers, and hence the radiation pattern of the CBO night pattern array operating in the presence of the "north line".

With 270 m spans, the "north line" segment shown in Fig. 2(a) was chosen to begin at 13.9 degrees east of north of the antenna, so that the 40 span, 10.8 km power line would be divided into two equal halves by a line extending north from the antenna. The night pattern of the CBO array operating near this power line segment is shown in Fig. 2(b). The field strength in the minimum is compared in Fig. 2(c) for CBO alone and CBO operating near the "north segment" power line. The figure shows some scalloping of the CBO pattern, particularly from 105 to 135 degrees, and from 175 to 210 degrees. At 106 degrees the the "net" field strength of the CBO array operating near the power line is 8.8 mV/m above the pattern of the CBO antenna alone. At 111 degrees the net field strength is 18.2 mV/m below CBO's night pattern. At 184 degrees the net field strength rises 21.9 mV/m above CBO's night pattern. Thus the reradiated field strength can be characterised as causing deviations as large as 22 mV/m.

With 300 m spans, the "north line" is 12 km in length and Fig. 3(a) shows the "north segment" power line with the angle of the starting point chosen at 15.2 degrees. Fig. 3(b) shows the radiation pattern of the CBO antenna operating near this power line. Fig. 3(c) compares the field strength of the antenna alone with the "net" field strength of the antenna operating near this power line. There is some scalloping of the CBO night pattern, particularly from 105 to 115 degrees azimuth, from 135 to 155 degrees azimuth, and from 170 to 230 degrees azimuth. At 107 degrees azimuth the net field strength rises 5.3 mV/m above that of the antenna alone. At 140 degrees azimuth the net field strength is 8.8 mV/m less than that of the antenna alone. At 194 degrees azimuth the net field strength is 4.4 mV/m above that of the antenna alone. At 216 degrees azimuth the net field strength is 7.8 mV/m above that of the antenna alone. The reradiated field can be characterized as causing deviations as large as 9 mV/m.

With 330 m spans, the "north line" segment is 13.2 km in length and Fig. 4(a) shows the configuration with the starting angle chosen as 16 degrees east of north of the antenna. Fig. 4(b) shows the the radiation pattern of the CBO night array operating near this power line. Fig. 4(c) shows the field strength in the minimum. The pattern shows only minor deviations from the CBO night pattern. The "net" field strength rises above the CBO night pattern by 3.2 mV/m near 107 degrees azimuth. The reradiated field can be characterized as causing deviations as large as 3 mV/m.

Table 1 summarizes these results. The strongest reradiated field is seen with spans of 270 m length, which are resonant at CBO's frequency of 920 kHz, and causes deviations as large as 22 mV/m at one mile, compared to CBO's R.M.S. field strength of 1250 mV/m at one mile. With "marginally resonant" spans of 300 m length, reradiation causes deviations of 9 mV/m. With non-resonant spans of 330 m length, the pattern including reradiation from the power line deviations from the pattern of the antenna alone by only about 3 mV/m.

TABLE 1
Amplitude of the deviations induced on CBO's night pattern by reradiation from the "north line" segment of the Lennox-Merivale power line.

Span Length	Deviation Amplitude
270 m	22 mV/m
300	9
330	3

5. Conclusions

This report has presented a study of the level of reradiation to be expected from the Lennox-Merivale power line, into the minimum of the "night pattern" of the CBO array, at 920 kHz. A length of 40 spans of the power line due north of the array, illuminated by the main lobe of the night pattern with a maximum value of 2900 mV/m at one mile, was represented in the computer model. In the worst case with resonant, 270 m spans, reradiation from the power line induces deviations of as large as 22 mV/m on CBO's "night pattern". With non-resonant spans of length 330 m, the reradiated field induces deviations of only 3 mV/m at one mile. These figures indicate the general level of reradiation to be expected from the power line.

6. Discussion

When the Lennox-Merivale power line is constructed, the actual lengths of the spans will not be the same, but instead will vary along the line according to local terrain and obstacles. The reradiation from a power line with a variable span length is inherently different from that of a power line with a perfectly uniform span length. In the uniform case, either all the spans are resonant, in which case all the spans reradiate strongly, or else all the spans are non-resonant, and there is little reradiation. However, on a real power line with non-uniform tower spacing, only those spans which are of resonant length will be strong reradiators, and "how much reradiation" is primarily determined by the number of resonant spans there are on the power line.

Because the actual power line will have a non-uniform span length, the evenly-spaced power line model is unrealistic. Thus the exact details of the radiation patterns in this report will not be duplicated. The usefulness of these patterns is to judge the general level of reradiation to be expected from a span of a given length. Thus, if the power line has a great many spans of resonant length, then deviations as large as 22 mV/m are expected between the radiation pattern of CBO operating after the power line is built compared to CBO operating with no power line. The span lengths of the proposed power line are expected to fall in the range 270 to 330 m, with a very few exceptionally short spans, and a very few exceptionally long spans. The spans which will be significant reradiators will be those whose lengths make them resonant within about 60 kHz of 920 kHz, which includes spans from 251 to 297 m. This encompasses half of the range of expected span lengths, and so half of the spans will be of resonant length, and this may be enough to cause reradiation at the level of 22 mV/m. To reduce the reradiation from the power line, those spans in this range can be "open-circuited" by disconnecting the skywire from one or the other of the towers terminating the span, provided that no resonant "double-spans" are created. The method to be used to determine which spans to treat is that described in Ref. (4).

REFERENCES

1. C.W. Trueman and S.J. Kubina, "Initial Assessment of Reradiation from the Lennox-Merivale Power Line into the Pattern of CBO, Ottawa," Technical Note No. TN-EMC-84-05, Dept. of Electrical Engineering, Concordia University, Montreal, Nov. 13, 1984.

2. M.A. Tilston and K.G. Balmain, "A Microcomputer Program for Predicting AM Broadcast Re-Radiation from Steel Tower Power Lines", IEEE Trans. on Broadcasting, Vol. BC-30, No. 2, pp. 50-56, June, 1984.

3. Hoyles Niblock Associates Ltd., "Engineering Brief in Support of an Application for an Increase in Power to 50 kW and for a Change in Frequency for Standard Band Broadcast Station CBO, Ottawa, Ontario", Vancouver, B.C., May, 1973.

4. C.W. Trueman and S.J. Kubina, "Analysis and Procedures for Detuning the Power Lines near CHFA, Edmonton, by Isolating Towers", Technical Note No. TN-EMC-84-03, Dept. of Electrical Engineering, Concordia University, Montreal, May 31, 1984.

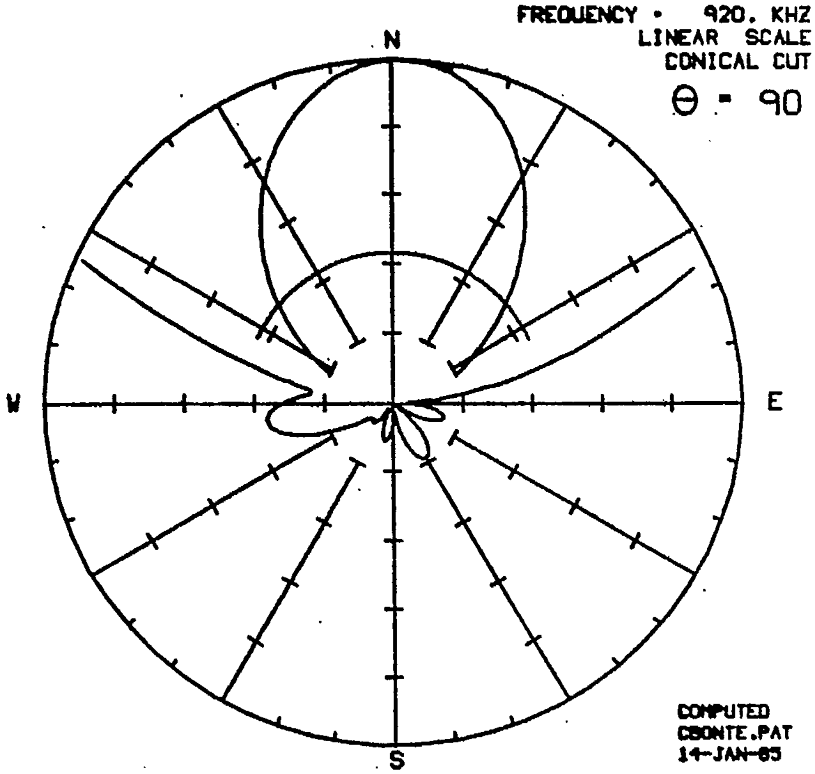

Fig. 1 (a) The "night pattern" of station CBO at 920 kHz, plotted on a linear scale from zero to 2900 mV/m at one mile. The scale is expanded by a factor of five from about 65 degrees to about 205 degrees azimuth.

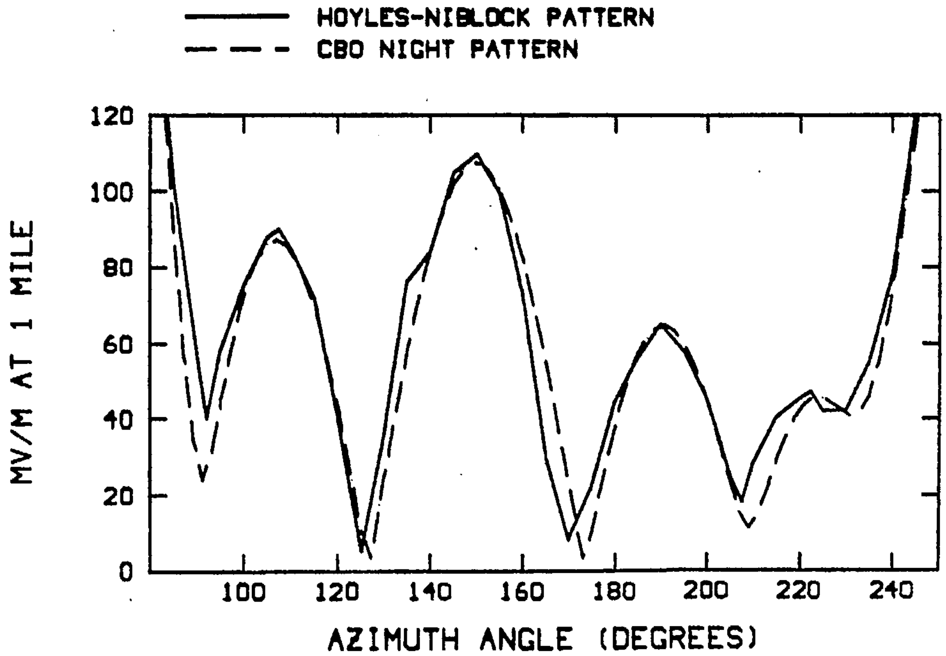

Fig. 1 (b) The field strength in the minimum of the CBO night pattern, from 80 to 250 degrees azimuth. The figure compares the Hoyles-Niblock pattern with that computed using AMPL.

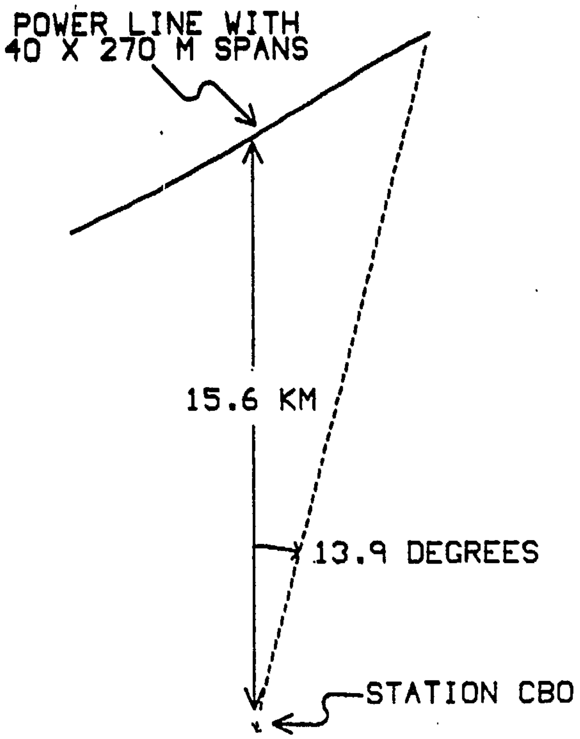

Fig. 2(a) The location of the "north line" segment of power line relative to the CBO antenna array. With 270 m spans, the line was set up to extend from a point at 13.9 degrees east of north of the antenna, southwest for a distance of 40 spans, which is 10.8 km.

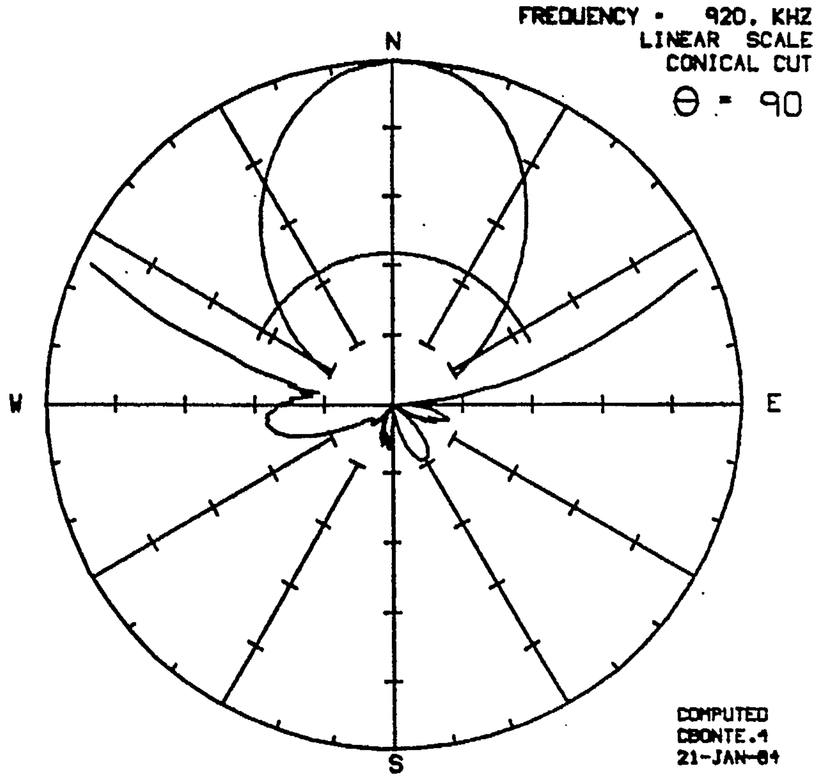

Fig. 2(b) The night pattern of CBO operating near the "north line" segment of power line with 40 spans, each 270 m in length.

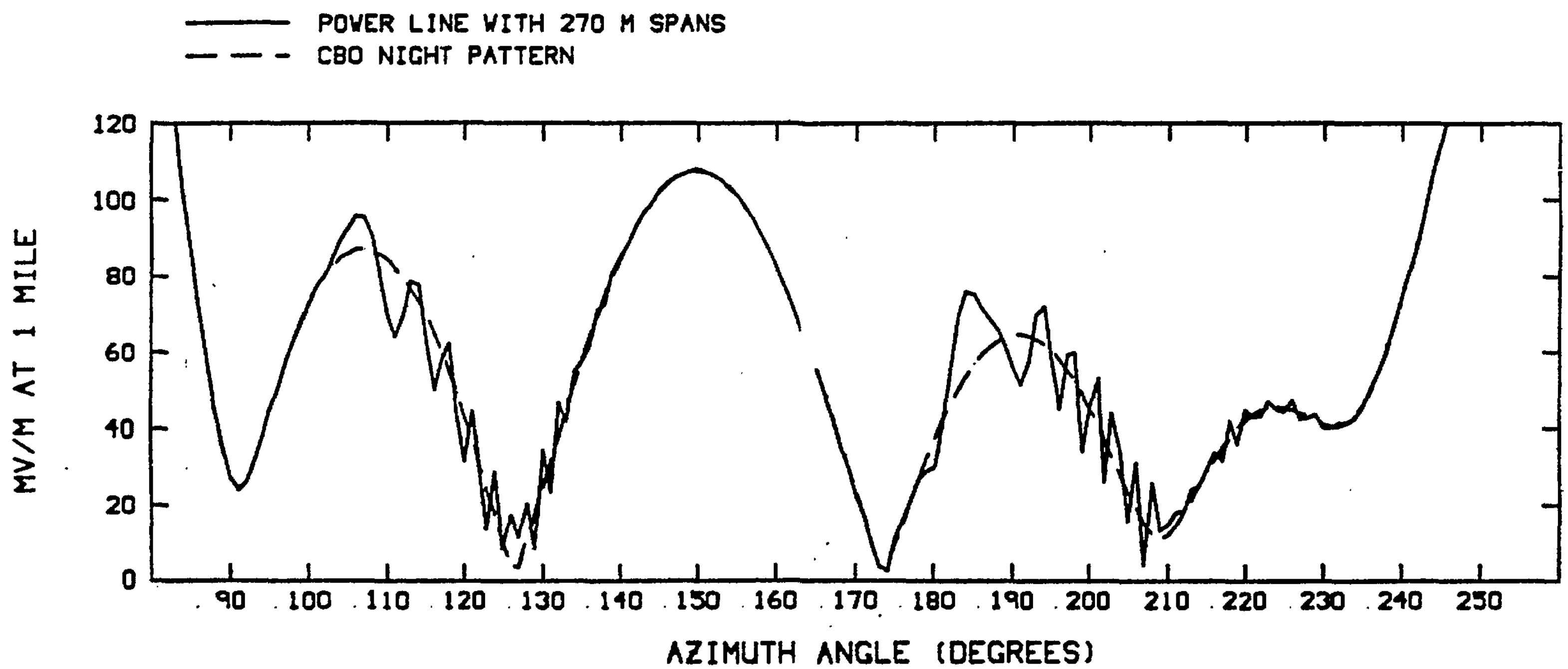

Fig. 2(c) The field strength in the minimum with 270 m spans on the power line. The maximum difference between the pattern of CBO alone and CBO operating near the "north line" segment is about 22 mV/m, at about 184 degrees.

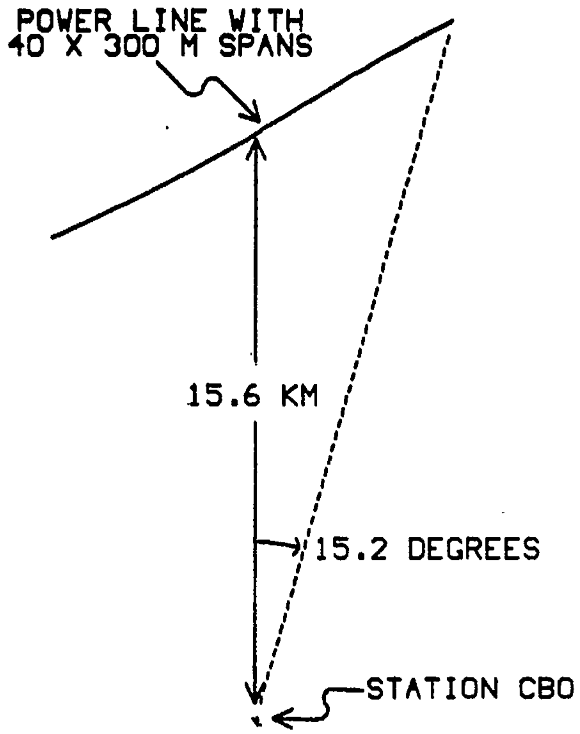

Fig. 3(a) The "north line" segment of power line with 300 m spans. The line extends from a point at 15.2 degrees east of north of the antenna, southwest for a distance of 40 spans, which is 12.0 km.

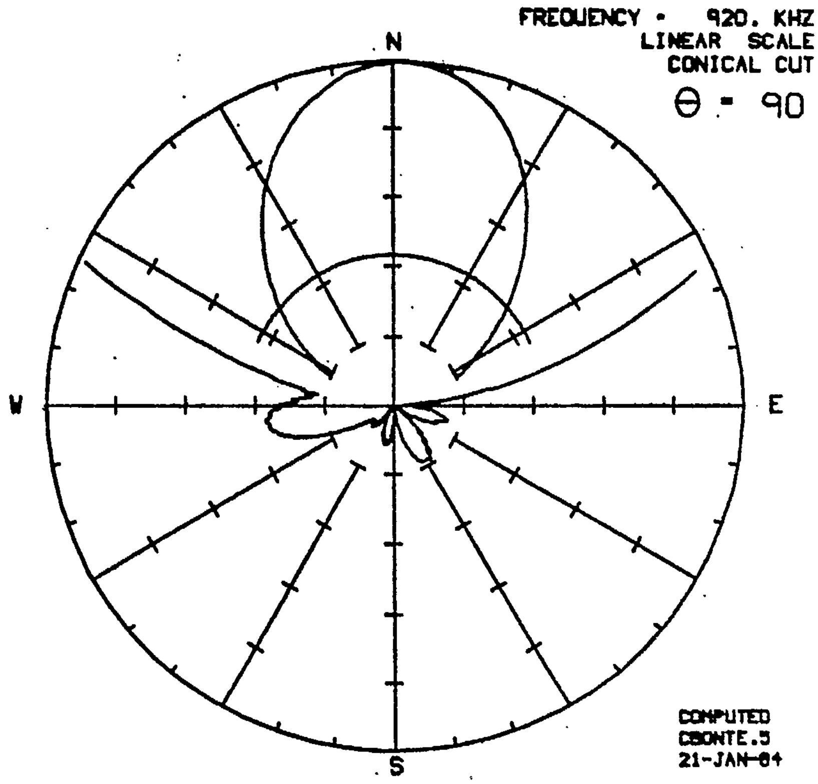

Fig. 3(b) The night pattern of CBO operating near the "north line" segment of power line with 40 spans, each 300 m in length.

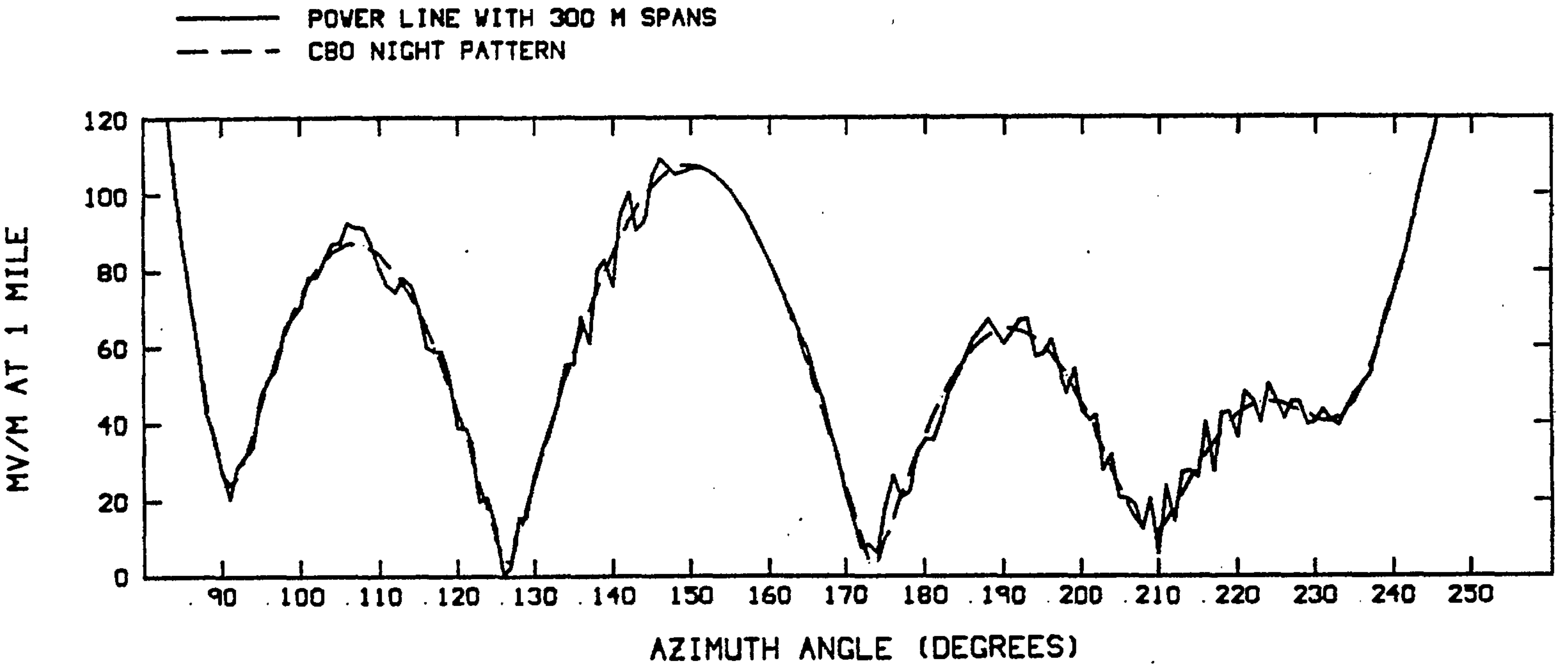

Fig. 3(c) The field strength in the minimum with 300 m spans on the power line. The maximum difference between the pattern of CBO alone and CBO operating near the "north line" segment is 8.8 mV/m, at about 140 degrees.

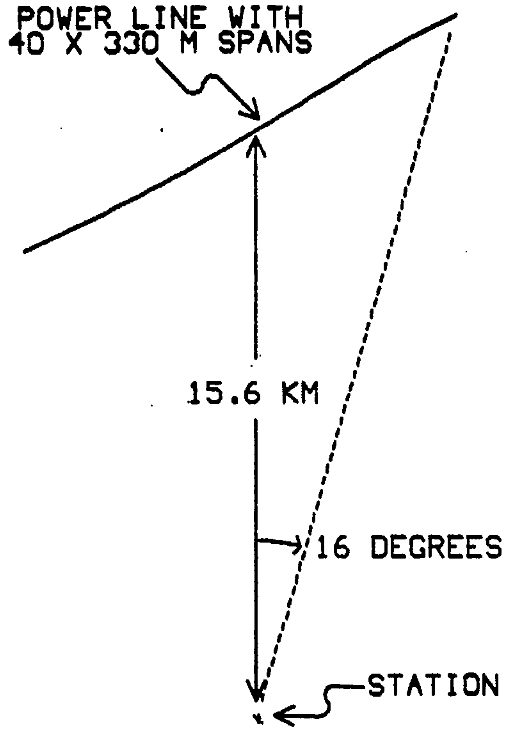

Fig. 4(a) The "north line" segment of power line with 330 m spans. The line extends from a point at 16 degrees east of north of the antenna, southwest for a distance of 40 spans, which is 13.2 km.

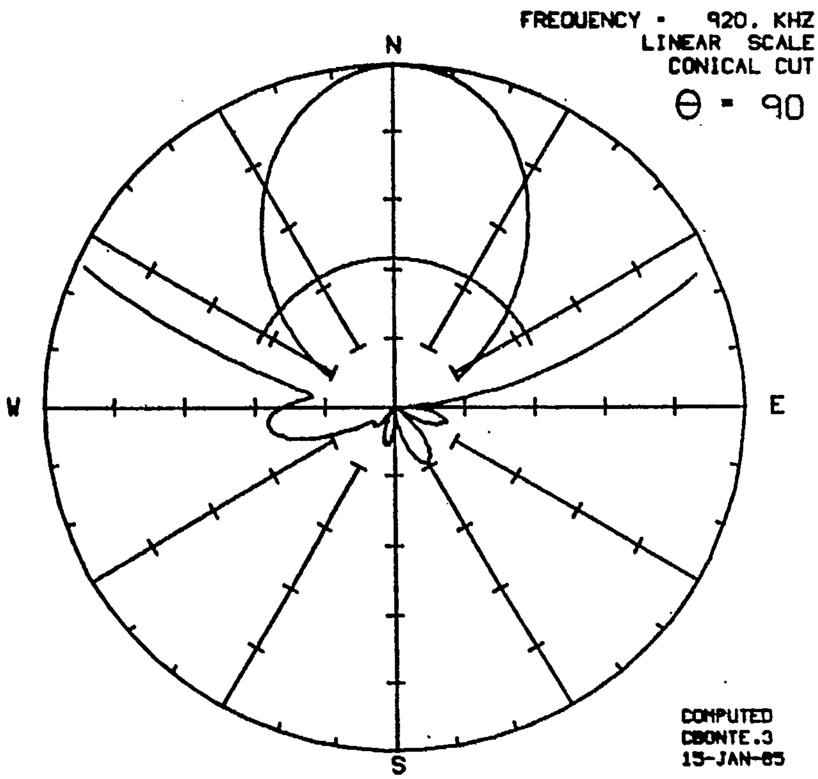

Fig. 4(b) The night pattern of CBO operating near the "north line" segment of power line with 40 spans, each 330 m in length.

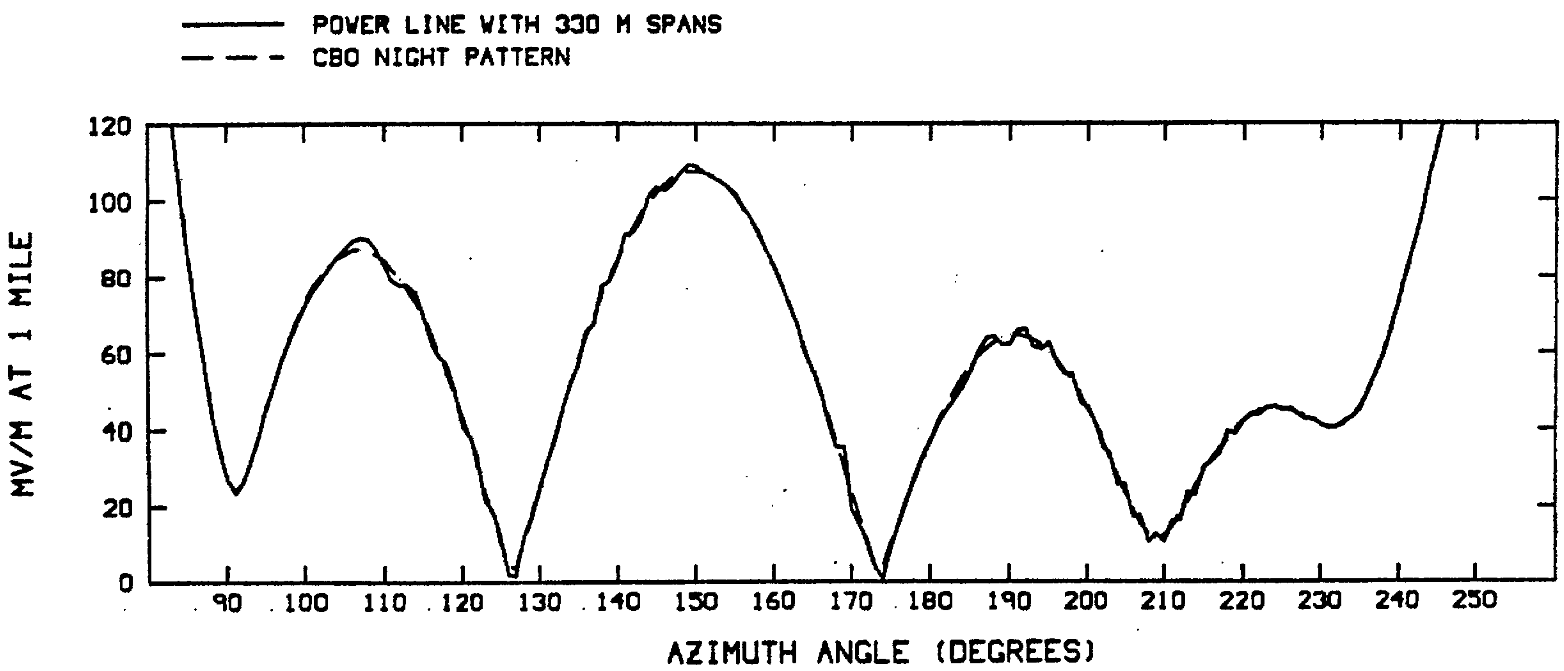

Fig. 4(c) The field strength in the minimum with 330 m spans on the power line. The maximum difference between the pattern of CBO alone and CBO operating near the "north line" segment is 3.2 mV/m, at about 107 degrees.

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--Initial assessment of reradiation from ...

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