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"Recent Advances in the Computer Modelling of Type V1S Power Line Towers at MF Frequencies"

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Recent Advances in the Computer Modelling of Type V1S Power Line Towers at MF Frequencies

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ABSTRACT

This report continues the work of previous reports on the reradiation of RF signals from high voltage power lines at MF frequencies. A survey of previous work is given, which concludes that the "single wire tower" computer model for type V1S towers is well established relative to scale model pattern measurements up to about 1000 kHz, that the effect of ground conductivity has been established as a damping of resonance effects but not a shift in resonant frequency, and that a variety of detuner designs have been proposed and explained. This report investigates the effect of phase wires on detuner performance and concludes that no degradation is expected. This report then extends the frequency range of the "single wire tower" model to 1400 kHz by developing a "tapered tower" model, top-loaded by a crossarm, which matches Belrose's measured loop impedance data for scale models of type V1S towers. The modelling of phase wires is addressed relative to loop impedance measurements, and a long, resistively terminated phase wire model is proposed, which represents the physics of the problem well. Loop impedance measurement is a promising new technique for the assessment of resonant behaviour of real power lines, and for the development of computer models of towers other than type V1S. The corroboration of the computer model's predictions relative to full scale measurements is then addressed in this report. It is shown that a tower representation similar to the "single wire tower" model generates an RF current distribution on the skywires which agrees well with Ontario Hydro's full scale measurements at Thornhill, at 825 kHz. However, at 1605 kHz, the agreement is not as good, and a modified model such as the tapered, top-loaded tower may be necessary. Thus further work on computer models of type-V1S towers is required at the high end of the AM broadcast frequency band, and suitable measured results are needed for reference. The procedure used for developing a computer model of the type V1S tower needs to be repeated for other typical tower types, relative to high-quality measured data, in order to provide a catalog of models for use by hydro utilities and broadcasters in assessing possible reradiation situations.

CHAPTER ONE

Introduction

1.1 Objectives

The principal goal of this work is the development of an accurate computer model for the RF behaviour of power line towers interconnected by skywires, so that it can be used to predict whether a particular power line will cause a reradiation problem when installed near an MF broadcast site. This development process subdivides into : the use of available measured results in adjusting a computer model so that those results are matched, and the use of the computer model to produce new results without further adjustment. A second goal of this project is the development of methods of "detuning" a power line, using the computer model as a guide to an understanding of the physics of each detuner (that is, "how it works") and how to design it for best performance. The ultimate goal of this project is to develop a comprehensive technique for the assessment of the amount of reradiation to be expected at a given frequency for a given broadcast array and power line configuration. This must span the whole AM frequency band, and include modelling expertise for various types of power line towers. After a site has been found to have a reradiation problem, a computer model could be used to test the effectiveness of a "design" for a configuration of detuners on the power line towers or skywires.

1.2 Review of Previous Work

This report describes the continuation of the work that was presented in references (1), (2), and (3). For continuity of outlook the reader should consult these references for the details of the past development and application of computer modelling techniques to high-voltage power lines at

MF frequencies.

In reference (1) the "single wire tower" model was developed. This model simplifies the lattice-like structure of a real power line tower to an equivalent cylindrical wire, and replaces the two parallel skywires of the type V1S tower by an equivalent single wire. Reference (1) establishes the usefulness of this model by comparing its predicted azimuth plane pattern with a measurement on a 600 scale factor model of a straight, evenly-spaced power line with 13 towers, illuminated by an omnidirectional broadcast antenna opposite the center tower, at 740 and 860 kHz. The model is a simplified representation of the CBC's transmitter at Hornby, Ontario. The tower spacing is 274 m, and the tower height is about 51 m, and these values have been used extensively as a typical case of power line geometry in this work. The power line was found to be resonant at the higher frequency, and the span length and tower height were such that two free-space wavelengths roughly equal the geometrical path length of a loop formed by two towers, the interconnecting skywire, and the images in ground. The comparison with measurements was then extended to a frequency range from about 830 to 900 kHz. The computer model was used to represent the actual tower locations of the two power lines near the Hornby broadcast antenna, and the resulting azimuth patterns were compared with scale model measurements on the 600 scale factor model. Reasonable agreement was found. A scheme for supressing the RF currents induced on the power line, that is to say "detuning" the power line, was examined. Large resistors were introduced in series with the skywire at a point where the current flow is large, namely at the center of the span, and it was found that at 860 kHz the current is effectively suppressed, and the resulting azimuth pattern is smooth. Thus reference (1) developed a model and checked it against measurements at 740 and 860 kHz.

Reference (2) extended this work. Thus resonant behaviour in which the geometrical path length is about one wavelength was investigated. The "single wire tower" computer model was established in this frequency range by comparing its predicted azimuth pattern with a scale model measurement at 515 kHz, for the same 13 tower evenly-spaced power line configuration. The behaviour of the evenly-spaced power line from 200 to 1100 kHz was then investigated by computation, and the bandwidth of the resonant effect was thus found. Azimuth patterns were plotted for both one- and two-wavelength resonance, and the RF-current distribution was plotted throughout the resonance frequency ranges. An enigmatic problem was addressed, namely the comparison of computed azimuth patterns with full-scale meeasured "ratio patterns". Ratio patterns were available for stations CBL at 740 kHz, and CJBC at 860 kHz at Hornby, and these were compared with the computer model's prediction, using the best available representation of the complex, two parallel power line site. Detailed agreement could not be established, but the dB range of variation of the measured ratio pattern and the computed pattern corresponded well at both frequencies, and was interpreted to mean that the real power line is not resonant at 740 kHz, but is strongly resonant at 860 kHz. Reliable full scale measured patterns are difficult to obtain, and are subject to variability due to changing ground conductivity as the moisture content and snow cover of the ground change, and to changing environment as new construction proceeds. These results will be reviewed in Chapter 3 of the present report. Reference (2) also looked briefly at the prediction of null-filling, using a two-tower broadcast array with a figure-eight pattern. It was found that useful results could be obtained, but detailed agreement with a scale model measurement in the nulls was difficult to establish. Several detuning methods were investigated in reference (2). Isolating towers from the skywire was found to have limited effectiveness, because an isolated tower reradiates as a free-standing tower, capacitively coupled to the skywire. Detuning with stubs parallel to the skywire was found to be highly effective, provided the stubs were designed according to the RF current distribution associated with the resonance mode to be detuned. A short, capacitively terminated stub on each tower was investigated as a detuning method, and found to be effective but also to be high-Q, with a very narrow bandwidth. Reference (2) looked at the error incurred by using perfect ground in the computer model to represent real ground of conductivity in the range of 20 millimhos per meter. Using that value, the Sommerfeld-Norton ground model(6) was used in conjunction with the SOMNEC computer code(7) to find the azimuth pattern of a three tower power line at 860 kHz, and this was found to be very similar to the pattern over perfect ground.

Reference (3) continued this investigation by computing azimuth patterns over ground of realistic conductivity, for a five tower, evenly-spaced power line of the Hornby geometry over ground of conductivity 5, 10 and 20 millimhos per meter, throughout the one- and two-wavelength resonance frequency ranges. It was found that the frequency of resonance is only slightly dependent on ground conductivity, but the magnitude of the resonance effect decreases as the conductivity is reduced. Thus computations over perfect ground are useful in predicting the frequency of resonance of a power line over real ground with conductivity in the range of 15 millimhos per meter. Such computations tend to overestimate the strength of reradiation effects. Reference (3) continued the practice of comparing with measured results where possible, by comparing measured behaviour for the 13 tower evenly-spaced power line with computer predictions throughout the one-wavelength resonance frequency range. The behaviour of various detuners was documented in Reference (3) over a wide frequency range from 300 to 1000 kHz, and it was found that detuners often introduce new resonances of their own, which might cause a problem if two broadcast antennas at different frequencies are close together, and the power line is detuned for one of the stations. The behaviour of various detuner designs was compared. The performance of tower stubs over ground of realistic conductivity was found to be the same as over perfect ground. Thus References (1), (2) and (3) have provided a well established computer model, the "single wire tower" model, for type V1S towers, and an extensive documentation of the behaviour of straight, evenly-spaced power lines up to 1000 kHz. Also, an understanding of the behaviour and frequency dependence of various detuning devices has been provided, and of the effect of the conductivity of the ground.

1.3 New Results

Appendix (1) of this report presents an update of the detuning methods reported in references (2) and (3), in the form of a paper published in the IEEE Transactions on Electromagnetic Compatibility(4). The new material deals with an initial assessment of the effect of the phase wires on the performance of various detuning devices. This raises the question of the best design for a computer model for the phase wires, which is followed up in Chapter 2.

Chapter 2 of this report advances the primary project goal, by developing a computer model which can match the "loop impedances" measured by Belrose(5). The measurement of "loop impedances" shows promise as a practical method of identifying the dominant RF characteristics of power lines and possibly as a method of establishing an experimental impedance data base against which computer models might be tested over a large range of frequencies. Since loop impedance is readily measured on a full scale power line, it may provide hydro utilities and broadcasters with a simple, direct method of assessing the resonant frequencies of a given power line. In Chapter 2, Belrose's scale model measurements(5) of loop impedance for a straight, evenly spaced power line of the Hornby dimensions, are matched by evolving a "tapered tower" model from the "single wire tower" model. It is found that the frequency range of the model can be extended to at least 1400 kHz by adding a top crossarm, which "top-loads" the tower. The new model is then used to test two proposals for modelling the phase wire, a problem for which no measured results are available. The better of the two models represents the physics well, and no great change in the predicted loop impedances is found in the presence of the phase wire. Thus the loop impedance measurements have been used to refine the computer model and extend its frequency range, and to investigate the phase wire models.

Chapter 3 compares the RF currents predicted by a computer model with RF currents measured by Ontario Hydro Research Division on a five tower line at Thornhill, Ontario. The agreement between the computer model, using highly conductive ground, and the full-scale measurements, is excellent at 825 kHz, but poorer at 1605 kHz, and suggests that the computer model needs modification in order to extend its range of validity to the top end of the AM radio frequency band. Thus crossarms may be necessary to top-load the tower. Other ground representations are then used to seek improved agreement. The Sommerfeld-Norton ground model(6), with a ground conductivity of 10 millimhos per meter, is a small improvement over highly conductive or "perfect" ground. The "footing impedance" model of ground, based on Monteath's work(18), gives slightly better agreement at 825 kHz, but slightly worse at 1605 kHz. Overall, the effect of ground conductivity is very small in the two cases tested, and "perfect" ground is a surprisingly good model.

1.4 Paper on Detuning Methods

Appendix 1 contains a recently published paper entitled "Corrective Measures for Minimizing the Interaction of Power Lines with MF Broadcast Antennas"(4), which summarizes the work reported in references (2) and (3). The general reader is encouraged to look into Appendix 1 for a discussion of detuning methods, which will not be repeated here. The following summarizes the new work contained in Appendix 1, for those already familiar with references (2) and (3).

Concerning uneven tower spacing, the paper comments upon the statistics of the tower spacing using Hornby, Ontario as a typical site. It is suggested that if the tower spacing does not deviate too greatly from a mean value, then a computer model using evenly spaced towers with the mean spacing is expected to be useful in approximating the resonant behaviour of the power line. Thus at Hornby, the actual tower spacings vary from 213 to 293 m, with a standard deviation of 21 m. Also, the shortest spans tend to fall at bends, and if four short spans are excluded, then the shortest span is 258 m, and the standard deviation is 10 m. The mean is about 274 m, and so the power line is very nearly evenly spaced. A standard deviation of 10 m in the span length corresponds to roughly a standard deviation of 20 kHz in the two-wavelength resonant frequency of the spans.

The difference between the behaviour of an evenly-spaced power line and one with a 10 m standard deviation in the tower spacing would be, on the average, that the resonance curve would show a broader but less tall resonance peak. Thus resonance would be expected over a broader frequency range, but would not be as strong an effect as for a power line of perfectly uniform spacing. It is suggested that a statistical study could be undertaken to make this result quantitative, by computing the pattern perturbation spectrum for a large number of unevenly-spaced power lines, with known mean and standard deviation of the tower spacing, and relating the Q-factor of the resonance curve to the standard deviation. Also, it is expected that for sites where the standard deviation of the power line tower spacing is too large, the spans no longer act together, but instead are individually resonant at various frequencies, and so the evenly-spaced power line model must be used to assess the resonant behaviour of the individual span lengths. Thus the evenly-spaced model is a useful guide to the behaviour of power lines in general, but must be applied with an understanding of its limitations.

Appendix 1 contains new computations for the skywire insulator detuner and for the skywire stub detuner operating in the presence of an "equivalent" phase wire. If the phase wire were to provide a path by which the RF current could bypass an "open circuit" detuning device in series with the skywire, then the detuning stub or insulator would be rendered ineffective by the phase wire. A proven computer model for the phase wire was not available, and so a "first approximation" model was designed to exaggerate any effects that might be present. The phase wire was represented as a wire of the same radius as the skywire, parallel to the skywire, but shifted in a horizontal plane by 10.7 m away from the skywire, and also shifted in a vertical plane downward from the skywire by 15.7 m, so that the phase wire is 19.0 m from the skywire, and 35.2 m above the ground. These dimensions were derived from the type V1S tower, and put the phase wire at the location of the tip of the highest crossarm carrying a phase wire. The phase wire is expected to couple to the skywire and in the full scale is expected to carry RF energy away from the system to be dissipated elsewhere. In Chapter 2, a phase wire model is designed which represents this behaviour. In Appendix 1, the phase wire was terminated with an open circuit at either end, and made the same length as the skywire. As a result, energy coupled to the phase wire can only be radiated away at its ends, and so the RF current on the phase wire in this model can be quite large. The phase wire can be strongly resonant, when its length is a multiple of the half-wavelength. The frequencies of such resonance in the present model do not coincide with the bandwidths of either one- or two-wavelength loop resonance, and so are of little importance here. In spite of the large RF currents induced on the phase wire, the detuners remain fully effective. Fig. 7 of Appendix 1 tests the performance of the skywire insulator detuner in the presence of the phase wire. It was thought that RF energy could couple to the phase wire and then back to the skywire and so "bypass" the insulator. Fig. 7 of Appendix 1 shows that the insulator retains its effectiveness. A small peak is seen at about 820 kHz, which becomes larger as the phase wire is moved closer to the skywire. Thus such coupling exists, but is negligible at the separation distances, skywire to phase wire, which are actually found on the real power line. Fig. 12 shows that the phase wire has very little effect on the performance of the skywire stub detuner. Thus when the phase wire was included in the model for testing skywire stub detuners or skywire insulator detuners, no significant change in detuner performance was found. If the better phase wire model developed in Chapter 2 were applied to this problem, then it would be expected that the same result would hold.

1.5 Summary

The following chapters present an important new method for developing computer models of various tower geometries, namely comparison with loop impedance measurements over a wide frequency range, and present the best confirmation of the reliability of the computer predictions obtained thus far, namely comparison with full-scale measured RF current distributions.

CHAPTER TWO

Development of a Computer Model for the Prediction of Loop Impedance

by C. W. Trueman

2.1 Introduction

In this report a computer model is developed which can reproduce the loop impedance measured by Belrose(5) for a one span "power line". If an RF generator is placed in series with the skywire near a tower, then the "loop impedance" measured at the terminals of this generator has resonances at the frequencies expected for one- and two-wavelength loop resonance discussed in references (1) and (2). Belrose's measurements of loop impedance were carried out using a 1:200 scale factor model with type V1S towers, over the frequency range 200 to 1500 kHz. The measurements used here are for one span, and data is also available for two, three and four spans of a power line. The tower separation was 274.32 m, and so the power line dimensions are the same as those used in previous work reported in references (1), (2) and (3). Belrose uses two parallel skywires, connected to each tower at the tips of the top crossarm. The generator is adjacent to one tower, and the skywires are insulated from the crossarm at this tower. The two skywires are connected together by a jumper. The system is fed by a coaxial cable, with the shield attached to the top of the tower and the center conductor connected to the center of the jumper.

Belrose's loop impedance measurement for one span is used in this report to develop a computer model capable of "predicting" loop impedance from 300 to 1000 kHz. The RF current distributions on the computer model at the resonant frequencies of the loop impedance, are shown to be the same as those found in reference (2) for one- and two-wavelength loop resonance on a power line excited by a nearby broadcast antenna. Thus the loop impedance clearly indicates the frequencies at which the power line would be excited into resonance by a broadcast antenna. Since the loop impedance is readily measured on a full-scale power line, it may be a useful guide to the line's resonant behaviour.

The measured loop impedance is used in this report to study a refinement of the computer model. It is shown that a top crossarm added to the computer model extends the frequency range of the simple computer model to 1400 kHz, and the tower-with-crossarm model may be useful in studying three- and four-wavelength loop resonance phenomena.

The computer model is used to examine the changes in the power line's behaviour which come about due to the presence of the power-carrying "phase wires". Two computer models are studied, and the better of the two may also be useful in scale model measurement studies of the changes in behaviour brought about by including the phase wires in the model. It is shown that the phase wires do not significantly alter the power line's resonant behaviour.

2.2 Straight Tower Model

The starting point in the development of a suitable tower model for computing the "loop impedance" is the "single wire" tower model developed in reference (1). The model represents a type V1S tower by an equivalent "fat" wire of radius 3.51 m and height 51 m. (It was subsequently remarked that 53 m better represents the height of Belrose's 1:200 scale factor model towers. However, 51 m has been used throughout the present work. By "running" the computer model with 53 m towers, it was found that this discrepancy introduces less than one-half a percent change in the resonant frequencies.) The span length in the computer model is 274 m. The two parallel thin skywires are replaced in the computer model by a single skywire of radius 0.71 m, and the resulting geometry is shown in Fig. 2.1. Previous experience with the computation of impedance indicated that short segments must be used near the generator, and that unsatisfactory behaviour of the computer model can be expected if the generator is too near a wire junction, especially if there is a large change in the wire radius at the junction. Thus the generator was put on the third segment from the tower, and the length of the two segments forming the link from the tower to the generator was shortened until the impedance showed signs of instability. The result is that the generator was located 17.9 m from the tower. Note that the number of segments on the towers and skywires is increased with increasing frequency, so that the segments are maintained shorter than 0.05 wavelengths. The "extended kernel"(7) is used to obtain greater accuracy in evaluating the interactions between segments which are close together.

The model of Fig. 2.1 differs from Belrose's measurement model in several ways. The crossarms of the tower are not represented, except possibly as a gross effect lumped into the large radius of 3.51 m chosen for the tower wire, by the method described in reference (1). The measurement model has two skywires, while the computer model uses one, with a radius of 0.71 m chosen to make the skywires-plus-images transmission line characteristic impedance the same for both models, as described in reference (1). More important, the details of the feed region are quite different. No attempt has been made to represent the "jumper" that connects the feed cable to the skywires. Hence, the electrical environment near the feed is dissimilar. Also, the physical location of the feed point in the scale model is much closer to the tower than is possible to represent in the computer model.

The "loop impedance" is computed by driving the generator segment with one volt at its center, and calculating the RF current distribution on the whole structure, using the NEC computer program, which is described in reference (1). The loop impedance is

$$Z = \frac{1 \text{ volt}}{I \text{ amps}}$$

where I is the current flowing on the generator segment. Fig. 2.2 shows the value of the loop impedance for the straight tower model of Fig. 2.1, from 300 to 1000 kHz, in comparison with Belrose's measurements for one span. The "resonant frequencies" are the positive-going zero crossings of the phase, and agree very well with the measurement. The anti-resonant frequency of 740 kHz is about 70 kHz higher than that of the measurement. The magnitude of the loop impedance is too large in the frequency range of two-wavelength loop resonance, between 800 and 900 kHz.

Fig. 2.3 shows the current distribution on the "straight tower" model at 860 kHz. The top portion of the figure is a schematic representation of the power line span, showing the magnitude of the RF current at the center of each segment of the computer model in Fig. 2.1. The arrowheads give the direction of the current flow for zero phase angle. The lower portion of the figure plots, on rectangular axes, the magnitude and the phase angle of the RF current as functions of the distance on the path indicated by the arrowheads. The phase reference is the one-volt, zero-phase-angle generator. Thus it is seen that the RF current distribution at 860 kHz is very similar to that reported for "two-wavelength loop resonance" in reference (2). The current has nulls on the skywire near the towers where the phase changes by 180 degrees. The current is a maximum at the center of the skywire. The phase of the current on both towers is nearly zero degrees, and so in reference to the arrowheads in the top portion of the figure, the current flows "up" the tower near the generator, and "down" the "far" tower .

The RF current distribution of Fig. 2.3 explains why the magnitude of the loop impedance plotted in Fig. 2.2 is too large near 860 kHz. Evidently, the RF current decreases rapidly with increasing distance from the tower. The current distribution is substantially independent of the position of the generator. Thus if the generator is too far from the tower, the resulting current on the generator segment is too small, and so the impedance is too large.

The model of Fig. 2.1 is a first approximation, and it is expected that moving the generator closer to the tower will give improved agreement with the measurement. To avoid having the generator too close to a large change in wire radius at a wire junction, a tapered tower model is developed in the following section.

2.3 Tapered Tower Models

An improved tower model is the "tapered tower" of Fig. 2.4. This section describes its derivation from the straight tower, and serves to demonstrate that better agreement with Belrose's measurement of the loop impedance can be obtained with a tapered tower model. A refined tapered tower model is then developed to overcome some imperfections in the behaviour of the simple tapered tower.

2.3.1 Simple Tapered Tower Model

In comparison to the straight tower of Fig. 2.1, the tapered tower model of Fig. 2.4 has the generator closer to the top of the tower. The wire "link" between the tower top and the segment driven with the generator has been shortened. The NEC computer program requires that the "match point" at the center of any segment be outside the volume of any other wire. At the "match point" at the center of each segment, a linear equation is formulated which forces the tangential electric field to be zero. By enforcing this "boundary condition" at the center of each segment, a set of linear equations is obtained which is solved for the RF current on each segment. Poor results may be found when a segment near a junction is so short that the match point at its center lies inside another wire. Thus the center of the "link" must be outside the radius of the tower wire, and this requires that the tower be "tapered" to a small radius at its top. The "isoperimetric inequalities" discussed in reference (1) were used to determine radii of 4.73, 80 and 0.90 m for the base, mid-section, and top portions of the tower of Fig. 2.4. The length of the "link" was then chosen to be 1.83 m, so that the match point at 1.83/2=0.915 m satisfies the NEC requirement, being further from the tower top than the top wire's 0.90 m radius. This shortened link then puts the voltage generator, which is at the center of the source segment, 5.70 m from the top of the tower, which is considerably closer than the 17.9 m of the straight tower model. The voltage generator was surrounded with short segments, but the usual 0.05 wavelength segments were used elsewhere on the model.

Fig. 2.5 shows the "loop impedance" for this simple tapered tower in comparison with Belrose's measurement. The resonant frequencies correspond precisely. The magnitude of the impedance is quite close to Belrose's curve. The anti-resonant frequency is 40 kHz too high, but this is an improvement of 30 kHz over the straight tower model. The behaviour of the "tapered tower" computer model is somewhat unsatisfactory because the magnitude curves are not smooth. This gave incentive to the development of a refined tapered model.

2.3.2 Refined Tapered Tower Model

The small instability seen with the simple tapered tower was attributed to the segmentation near the voltage generator. The generator is too close to a corner in the structure, and the lengths of the segments are quite dissimilar on either side of the generator. To correct these deficiencies, a more refined tapered tower model was developed, and is shown in Fig. 2.6. The radii were chosen to be the same as those given above, except that the two segments at the very top of the tower use a radius of 0.71 m. The latter was chosen to avoid any radius change at the junction near the generator. To alleviate the segmentation problems near the generator, the feed segment was moved to a distance of 6.5 m from the tower top, and the driven wire was subdivided into three very short segments. It was intended to drive the center segment of the three, but better results were obtained by driving that nearest the tower. The length-to-diameter ratio for these three segments is nearly unity, so that shorter segments could not be used without violating the length-to-diameter criterion for the NEC program. The link segment in Fig. 2.6, which connects the tower top to the generator, was represented with one segment at low frequencies, but with two in the two-wavelength resonance range. For greater accuracy, the extended kernel(7) was used in computing the interaction between these short, colinear segments.

Fig. 2.7 compares the loop impedance "predicted" by the refined tapered tower model with Belrose's measurement. The magnitude and phase curves are smooth, and so the model has achieved its objective. The resonant frequencies agree well with the measurement. The magnitude of the loop impedance is almost exactly in agreement throughout the one-wavelength loop resonance frequency range. The anti-resonant frequency is about 25 kHz too high in the computer model, and this makes the magnitude of the loop impedance too high at the low end of the two-wavelength resonance frequency range. The magnitude agrees well from about 830 to 960 kHz, but evidently both magnitude and phase differ in behaviour as 1000 kHz is approached. These differences may be attributable to omissions from the computer model. Thus the crossarms are not represented, and their effect is explored in the next section. The difference in anti-resonant frequency may be associated with additional capacitance near the feed point in the measurement model, as discussed below.

Figs. 2.8, 2.9, and 2.10 show the RF current distributions on the tapered tower model at 440, 860 and 700 kHz. The number of segments on each wire of the computer model is increased as the frequency increases, in order to maintain the accuracy of the NEC solution. The figures plot the current at the center of each segment. Thus the number of points plotted can be counted to determine the number of segments. Since there are 3 segments on the generator wire of Fig. 2.6, there are in total 14 segments on the skywire at 440 kHz, 22 segments at 700 kHz and 24 segments at 860 kHz. At the one- and two-wavelength loop resonance frequencies of 440 and 860 kHz, the current distributions in Figs. 2.8 and 2.9 are exactly those expected from previous work(2). At 440 kHz, the current for one-wavelength loop resonance has maxima on the towers, and a null at the skywire center. The phase demonstrates that the current is a standing wave on the skywire, changing by 180 degrees across the null. As shown in Fig. 2.9, at 860 kHz the current for two-wavelength loop resonance has minima near the towers and a maximum at the skywire center. Note also in these figures that the reference direction for phase is "upward" on the tower near the generator, but "downward" on the far tower, as given by the arrowheads in the top portion of the figure. If the phase reference on the far tower is reversed so that it is "upward" as well, then at one-wavelength loop resonance the current is "upward" on adjacent towers, but at two-wavelength loop resonance, the current is 180 degrees out of phase on adjacent towers, being "upward" on one and "downward" on the next.

Fig. 2.10 shows the current distribution at the computer model's anti-resonant frequency of 700 kHz. At anti-resonance, the current at the generator terminals is in-phase with the applied voltage, and in Fig. 2.10 the phase is seen to be about -70 degrees on the tower near the generator, to rise sharply to zero degrees at the generator, and then return to a value approaching -90 degrees over most of the skywire. The phase has a sharp 180 degree reversal about two-thirds of the way along the skywire. The current distribution at anti-resonance at first seems similar to that for two-wavelength loop resonance. Comparing Figs. 2.9 and 2.10, at resonance the current is in-phase on adjacent towers, and so flows "up" the tower near the generator, and "down" the far tower. But at anti-resonance, the current is 180 degrees out of phase on the two towers and flows "up" on both towers. The generator in Fig. 2.10 is about one-half a wavelength at 700 kHz from the null in the skywire current. The current on the tower and this portion of the skywire is like that on a monopole of similar length with the excitation displaced from the base. Similarly, the far tower and its adjacent portion of skywire behave as a top-loaded short monopole, and carry a quarter-wavelength of standing-wave current. As the frequency is increased approaching anti-resonance, the wavelength gets shorter and the far tower, with its quarter-wave of current, uses up a smaller and smaller portion of the skywire. The remainder of the skywire and part of the tower near the generator, are taken up with a half-wavelength of standing wave current, with the null falling on the tower for frequencies below anti-resonance. As the frequency is increased, this null moves up the tower, and then onto the skywire and approaches the generator. At anti-resonance, the null coincides with the generator.

The feed used by Belrose to excite the 1:200 scale model is quite different from that used on the computer model, and the difference may account for the discrepancy in anti-resonant frequency. Belrose's feed uses a jumper parallel to the top crossarm to feed the signal from the center conductor of the coaxial cable to the pair of skywires on the V1S tower. There exists parasitic capacitance between the jumper and the top crossarm. This capacitance combines in parallel with the loop impedance computed using the tapered tower model. Fig. 2.11 shows how the loop impedance changes when it is "corrected" with 117 picofarads in parallel. This value makes the anti-resonant frequency agree with the measured value. The magnitude of the impedance is little affected at frequencies near the resonant frequencies, because the capacitor's impedance is large compared to the loop impedance. The magnitude of the loop impedance is reduced near anti-resonance and this gives better agreement with the measurement as two-wavelength loop resonance is approached.

However, the resonant frequencies are slightly raised. Also, as 1000 kHz is approached, the "corrected" curve for the phase follows the measured curve much better.

In summary, the tapered tower model of Fig. 2.6 is able to reproduce the one-wavelength loop resonance behaviour of the power line quite precisely, and finds the two-wavelength resonance frequency precisely. If the loop impedance is corrected by combining it with a parallel capacitance which models the parasitic capacitance of the feed arrangement of the measurement model, then the anti-resonant frequency is "predicted" well. The magnitude behaviour is somewhat different in the computer model compared to the measured values as 1000 kHz is approached, and this may be due to tower crossarms, as discussed in the next section.

2.4 Tower Model with Crossarms

The tapered tower model "predicts" the measured frequencies of loop resonance very well, matches the measured loop impedance in both magnitude and phase reasonably well, and a satisfactory explanation for the disparity in anti-resonant frequency has been suggested. However, the magnitude shows the wrong trend as 1000 kHz is approached. An explanation is given in this section in terms of the top loading effect of the tower crossarms. It is shown that the frequency range over which the "tapered" computer model of the V1S tower is valid can be extended by adding an "equivalent" crossarm.

The crossarms top-load the tower. Free-standing, top-loaded towers have been studied by Balmain(8). The top-loading makes a free-standing tower resonant at the frequency where the tower height plus the top-load length is about a quarter of the wavelength. The effect of crossarms on the "loop resonance" behaviour found with towers interconnected by skywires is not studied. It is clear that Balmain's "pole model" would not be satisfactory in the context of loop resonance, for it lengthens the resonant path length. In the following, it is shown that a crossarm top-loading the tower has little effect below the two-wavelength loop resonance frequency range. Above that frequency, the top-load changes the loop impedance considerably.

Fig. 2.12 shows the "tapered tower" model with an "equivalent" crossarm added to the top of each tower, to represent the top-loading effect of the six crossarms for the phase wires and the two skywire-carrying crossarms of the type V1S tower. The crossarm is of the same radius as the skywire, and extends perpendicular to the tower and skywire. The length of the crossarm is to be chosen so that the loop impedance agrees with the Belrose measurement that established the desired equivalence. Since the top crossarm of the V1S tower extends about 10 m on either side of the tower, a length comparable to 10 m would be considered reasonable. A single unsymmetrical crossarm was used here because one segment could be assigned for ecomony of computation at low frequencies. At higher frequencies where a resonance of the tower itself is possible, the resonant frequency is determined by the path length from the base of the tower to the tip of the crossarm, and where such a resonance is important, two symmetical wires on either side of the tower top should be used to provide a realistic top arm. Such a resonance mode is important for free-standing towers, but for towers with the ends of the top arm connected to skywires, no such resonance for the top crossarm is expected, but such resonances exist for the arms carrying the phase wires.

Fig. 2.13 shows the loop impedance of the tapered tower model given in Fig. 2.7 over a frequency range that has been extended to 1400 kHz. The parallel capacitance described above has not been included in the values of Fig. 2.13. Note that the measured values show no three-wavelength loop resonance, which is expected at about 1300 kHz. The loop impedance for the tapered tower with no crossarms is shown, and behaves differently from the measurement. The magnitude takes on much larger values above 950 kHz, and the phase angle attains larger positive values between 900 and 1100 kHz, and "crosses over" at an anti-resonant frequcency which is 100 kHz higher than that found in the measurement.

The effect of adding the top crossarm is shown in Fig. 2.13, for lengths of 10, 20 and 30 m for the top-load wire in Fig. 2.12. The top-load "crossarm" wire has very little effect over the one-wavelength resonance frequency range up to 600 kHz. There is a small upward shift in the resonant frequency for long top-loads. The crossarm has no effect on the 690 kHz anti-resonant frequency, and little effect on the 860 kHz resonant frequency for lengths of 10 and 20 m. Long crossarms tend to raise the value of the loop impedance in the two-wavelength loop resonance frequency range, because the RF current distribution tends to shift somewhat, bringing the null in the RF current closer to the tower and so raising the impedance seen by the generator. The primary effect of the crossarm is seen above 900 kHz. The crossarm greatly reduces the magnitude of the loop impedance, and brings the phase down in value, so that with a 10 m crossarm, the computer model's phase behaviour matches the measurement quite reasonably.

The long 30 m crossarm introduces another effect which may be important for shorter top-loads at higher frequencies. The electrical path from the ground, up the tower and along to the end of the crossarm is one-quarter of the (free space) wavelength at 824 kHz. Thus the tower-crossarm system is itself in resonance near the two-wavelength loop resonance of the power line span. No zero-crossing of the phase can be seen near 860 kHz in Fig. 2.13. Indeed, the long crossarm is exactly the same as a "straight stub" connected to the tower top, and so effectively detunes the two-wavelength resonance mode. The "self-resonance" of a tower with a top-load crossarm of length comparable to 10 m falls in the frequency range expected for three and four wavelength loop resonance, and so will complicate the resonant behaviour of the towers-with-skywires system.

Fig. 2.14 shows the loop impedance with a 10 m crossarm, but "corrected" by combining it in parallel with a 117 pF capacitance. The anit-resonant frequency at 670 kHz now agrees well with the measurement. The magnitude of the loop impedance matches the measurement better above 900 kHz, but the phase takes on too-small values and the anti-resonant crossover falls at too low a frequency. Evidently both a crossarm and the parallel capacitance represents too much of a correction, and perhaps less of each would be a good compromise. The problem of modelling the tower to predict loop impedance above 900 kHz has thus not been fully solved.

Thus a reasonable choice of "equivalent" crossarm length such as 10 m has little effect on the loop impedance below two-wavelength loop resonance, and greatly improves the agreement of the computer model with the measurement above that frequency. The top-load crossarm is a useful device for extending the frequency range over which the simple tapered tower is a valid representation of the type V1S power line tower.

2.5 Effect of Phase Wires

This section explores the effect of adding a phase wire on the resonant bahaviour of the one-span "power line". While it is shown that a phase wire does not much change the resonant frequencies of the span, it can change the loop impedance of the power line span in certain frequency ranges, where the specific structure used to model the phase wire is itself in resonance.

2.5.1 The Long Phase Wire

Fig. 2.15 shows one possible representation for the phase wire. The power line span is modelled using the tapered tower of Fig. 2.6. The phase wire in this model is of the same radius as the skywire, is at the same height above the ground, and is 10 m from the skywire. The geometry was obtained by arguing that only "common mode" RF currents would be present on the six phase wires of the V1S tower, and so the six act together as one wire and form a two wire transmission line with their images in ground. The "center" of the bundle of six is expected to be closer to the ground than the top of the tower, and the equivalent radius for a single wire representing the six may be quite large. It was intended that the present model exaggerate any qualitative changes in behaviour that phase wires may give rise to, and so a precise model was not attempted. Instead, the "equivalent" phase wire was positioned quite close to the skywire to induce large coupling and increase any effects that might be found.

Balmain(9) has stated that the phase wires are expected to carry RF energy away from the system, and so some mechanism should be provided on the phase wire to dissipate energy coupled to it. In the model of Fig. 2.15, a long phase wire has been provided, so that energy transferred from the power line span to the phase wire can be conducted by the phase wire away from the span. The phase wire extends 548 m or two span lengths on either side of the power line span. In order to dissipate the energy coupled to the phase wire, a length of 274 m at each end of the phase wire was "loaded" with distributed resistance. The total resistance distributed over the 274 m length at each end should be chosen so that the input impedance of this open-circuited, 274 m lossy transmission line "matches" the characteristic impedance of the lossless phase wire transmission line. Then any wave which is induced on the phase wire is fully absorbed by the resistive load and not reflected. In practice, a 274 m length is not long enough to obtain a very good match. To determine how well a 274 m, resistively loaded, open-circuited section does match the phase wire's characteristic impedance, its input impedance was calculated. An approximate method was used which divided the section into 17 segments, each loaded at its center with a discrete resistor. The reflection coefficient was computed from the input impedance, and then the SWR on the center of the phase wire was found. Plotting the SWR as a function of frequency shows the quality of the match achieved across the band, and is shown for various values of loading resistance in Fig. 2.16. Evidently, a low value such as 150 ohms achieves a poor match with the SWR greater than two over the whole band. Conversely, too large a value of loading resistance presents a large SWR across the band as well. A value of 600 to 1200 ohms makes the SWR less than 2 over the band, and calls for loading of roughly 2 to 4 ohms per meter.

Fig. 2.17 shows the loop impedance computed without the phase wire, and in the presence of the phase wire, for two values of load resistance. The phase wire causes a small upward shift of the resonant frequency, but the effect is almost negligible. The anti-resonant frequency is little changed. The magnitude of the loop impedance is not affected very much. The phase of the loop impedance shows a change between 700 and 800 kHz, which is readily associated with a resonance of the phase wire transmission line, as discussed below.

Figs. 2.18, 2.19 and 2.20 show the RF current distribution at the resonant frequencies and at 740 kHz, where the phase wire is in resonance. In these figures, a load of 150 ohms was distributed over a 274 m length at each end of the phase wire. At 440 and 860 kHz, as shown in Figs. 2.18 and 2.19, the RF current distribution on the skywire is little changed from that without the phase wire as shown in Figs. 2.8 and 2.9. Comparing Figs. 2.8 and 2.18, at 440 kHz, it is evident that the largest value of the RF current is decreased from about 50 mA with no phase wire to about 15 mA in its presence. This decrease reflects the increase in the loop impedance in Fig. 2.17, which does not have nearly as small a value exactly at 440 kHz in the presence of the phase wire. A slight shift in the phase of the skywire current can be noted at both frequencies. Fig. 2.20 shows the RF current on the skywire and phase wire at 740 kHz, where the phase of the loop impedance of Fig. 2.17 shows different behaviour with the phase wire in place. The magnitude of the RF current on the phase wire is now about 80 percent of that on the skywire, compared to about 40 percent in Figs. 2.18 and 2.19. The RF current on the phase wire shows five half-wave cycles spread over the 1370 m between the open-circuited ends of the phase wire, for resonance at about 770 kHz using the free-space wavelength. Since the wavelength is actually shorter on the 548 m of phase wire which is lossy, longer waves are needed on the lossless portion to achieve resonance, so a somewhat lower resonant frequency is expected, and this is consistent with the phase wire being in resonance at 740 kHz.

The SWR data of Fig. 2.16 were checked against the NEC program by determining the SWR from the RF current distributions such as Figs. 2.18, 2.19 and 2.20, and these values are plotted on Fig. 16. The NEC data generally underestimates SWR because in general none of the points at which NEC computes the current will exactly coincide with the minimum in the standing wave pattern. Hence, using the smallest current value near the minimum gives too small a value for the SWR, and so the estimate from NEC data is low. For the poor "match" with 150 ohm loading in Fig. 2.16, the NEC estimates are indeed low, but for the reasonable "match" using 300 ohm loading, the NEC estimates fall quite close to the theoretical curve.

The long phase wire provides a useful model for the phase wires of a real power line. The phase wire itself displays resonance, and should be designed in the model so that its resonant fequencies do not coincide with those of the power line. The phase wire's resonances can be made less evident by using a longer phase wire which is resistively loaded over a much longer distance at the ends. This could achieve a much lower SWR over the frequency band of interest than has been done in Fig. 2.16. The simple computer program used to generate Fig. 2.16 could aid in the choice of overall length, length of resistively loaded end sections, and value of load resistance to achieve a specified SWR over a given frequency range. This phase wire model could be used in measurement by using resistive wire, or by soldering individual resistors in series with the phase wires at evenly spaced intervals over the loaded section.

2.5.2 Phase Wire Terminated to the Tower

Balmain(9) studied scattering from a five tower and a nine tower power line by measurement. The scattering as a function of frequency and angle with no phase wires is compared to the behaviour with the phase wires in place. The problem of how the phase wire is to be terminated is resolved by connecting each end of the phase wire to the end tower through a resistor equal to the characteristic impedance. The resistor is intended to provide a "matched load" for travelling waves on the phase wire, whose power is to be absorbed by the resistor. This section tests this terminated phase wire representation on the one span "power line".

Fig. 2.21 shows the one span "power line" with a skywire terminated to the towers through a resistor at each end. As above, the phase wire is 10 m from the skywire, of the same radius, and height above the ground as the skywire. The phase wire is connected to the tower through a short link wire, in which is inserted a series resistor of 150 ohms. Fig. 2.22 shows the loop impedance from 300 to 1000 kHz in comparison to the case of no phase wire. It is seen that up to the one-wavelength loop resonance frequency, the loop impedance is about the same with the phase wire as it was without, but above that frequency, the "terminated" phase wire changes the loop impedance completely. The anti-resonant frequency is raised, and no two wavelength resonant frequency is seen. It appears that if the curve were extended, there would be a resonance around 1100 kHz.

Fig. 2.23 compares the RF current on the skywire with that on the phase wire at 440 kHz. The lower part of the figure shows the skywire's current at left and the phase wire's current at right. The current distribution is about 135 degrees out of phase at adjacent points on the skywire and the phase wire. The skywire, phase wire and the two resistively-loaded links form a closed loop, and the current distribution in Fig. 2.23 is close to that expected for one-wavelength loop resonance for the structure, which would be geometrically one wavelength long at about 530 kHz. The resistive loads heavily damp out the resonance near that frequency, because they are placed at the maxima of the RF current distribution. A two-wavelength loop resonance is expected near 1060 kHz, and the trend in the curves of Fig. 2.22 indicates this may be present. That there is no two-wavelength resonance due to the tower-skywire loop, expected at 860 kHz, is at first puzzling. The RF current distribution at 860 kHz, shown in Fig. 2.24, suggests that the phase-wire-plus-links to the towers actually behaves as a pair of open-circuited stubs, which are connected one to each tower, and which "detune" the loop resonance at 860 kHz. Thus in Fig. 2.24 the phase wire may be thought of as divided into two sections, with the boundary between them coinciding with the current null nearest the far tower. The right-hand portion is seen to carry a quarter-wave of standing-wave current, and the length can be measured from Fig. 2.24 as about 82 m, which with the 10 m link added, makes about a quarter-wavelength at 860 kHz. This 82 m length of the phase wire is thus an open-circuited, quarter-wave stub connected to the "far" tower, and is exactly what is required to "detune" the two-wavelength resonance mode on the tower-skywire loop. The remaining 192 m of the phase wire is nearly a half-wave stub, and so presents a high impedance at its connection point to the tower near the generator. Thus in Fig. 2.24 the current on the phase wire near the generator is small. Such a stub has little effect on the tower to which it is connected.

Because the loop resonance is inadvertently detuned, a wire terminated to the tower is not a useful representation of the phase wires for a one span "power line". For multiple spans, the span at each end of the power line may be "detuned" by its connection to the phase wire through a resistor. Thus the magnitude of resonant effects on the power line would be reduced by the contribution of two spans. The results of the use of such a model must be interpreted with caution.

Of the two phase wire representations considered, the better is the long, open circuited phase wire, with a distributed series resistive load near each end. A reasonable "match" can be achieved so that waves induced on the center of the phase wire travel to the ends and are absorbed by the resistive loading. This may be a useful model for direct measurement.

2.6 Summary

In this chapter, a computer model of the type V1S tower was developed capable of reproducing Belrose's measurement of loop impedance for one span. The starting point was the "single wire tower" model of reference (1), which was refined by introducing taper in order to better match the real tower's profile, and by careful handling of the segmentation of the computer model near the generator. The resulting "tapered tower" model has the same resonant frequencies as Belrose's measurement model. The magnitude and phase of the loop impedance agree very well with the measurement throughout the one-wavelength loop resonance frequency range, and correspond reasonably for frequencies near two-wavelength loop resonance. The computer model has an anti-resonant frequency which is 30 kHz higher than the measurement model. There is a parasitic capacitance in the measurement model between the top crossarm and the jumper which feeds the signal from a coaxial cable to the pair of skywires. When this capacitive impedance was included in parallel with the generator in the computer model, it brought the anti-resonant frequency down to agree with the measurement. Thus, the "tapered tower" reproduces Belrose's measured loop impedance very well from 300 to about 900 kHz. The next step was the extension of the model to higher frequencies. As 1000 kHz was approached, the trend in the measured data was different from that in the computation. It was shown that above 900 kHz, top-loading of the towers by their crossarms becomes a significant effect, and to extend the frequency range of the "tapered tower" model it was necessary to include a "crossarm" which provides equivalent top-loading. Thus it was shown that a single crossarm of length 10 m significantly improves the agreement with the measurement. Once again, when the capacitive impedance of the feed arrangement was included in the computed data, even better agreement was obtained. However, the model is not nearly as satisfactory at frequencies above 1000 kHz as it is in the one-wavelength loop resonance frequency range.

The modelling of phase wires was also considered. A model was proposed which allows energy to couple from the skywire to a "long" phase wire, which then carries the energy away from the single span "power line", and dissipates this energy in resistive loading distributed on the phase wire near its ends. Although both ends of the phase wire are open circuited, it was shown that a suitable choice of resistance distributed over 274 m at each end of the phase wire can provide a reasonable "match" to the characteristic impedance of the lossless phase-wire-plus-image transmission line. Thus waves induced at the center of the phase wire by coupling from the skywire are largely absorbed by the resistive loading and not reflected back from the open-circuited ends. The presence of the phase wire was shown to have only a minimal effect on the computed loop impedance, even though the geometry was designed to exaggerate any effects present, by putting the phase wire unrealistically close to the skywire thereby increasing coupling. This phase wire model could be built and tested by measurement, but at present no such measured results are available to test the computer model.

A second model of the phase wire was considered, in which the phase wire is terminated to the tower through a resistor. This model was unsuccessful because the phase wire can act as a pair of "stubs" connected one to each tower, and so can "detune" the power line's resonances. Thus if the phase wire is represented on a multiple-span power line by terminating it to the towers at each end through a resistor, it is expected that the two end loops may be detuned by the phase wire, and so resonant effects may be reduced in magnitude.

2.7 Conclusion

This chapter contributes to the development of the computer model, the extension of its frequency range and and its proof by comparison with scale model measurements.

The extension of the computer model to frequencies higher than 1000 kHz has been systematically addressed in this chapter. It has been shown that the crossarms of the type V1S tower have little effect below 900 kHz, but above that frequency they make an important difference. Thus crossarms have little effect on the one- and two-wavelength resonant behaviour for the 274 m span length. The computer model is useful to at least 1400 kHz if an "equivalent" crossarm is added to the top of the tower as a top-load. The crossarm is thus expected to be of importance in determining the three- and four-wavelength resonant frequencies of the power line, and indeed the tower-plus-crossarm structure is itself quarter-wave resonant in this frequency range. Precise measurements of the radiation pattern of a 9 or 13 tower line at many frequencies from 1000 to 1600 kHz, or even 2200 kHz, may be useful in establishing a tower model for the full AM band.

The computer model has been used in this report to propose a useful design for a model of the phase wires. These wires are expected to couple RF energy from the skywire, and carry it away from the system, and the "long" phase wire achieves this goal. The "long" phase wire representation is used to show that phase wires are expected to have only a minor effect on the resonant behaviour of the power line. It is also shown that if the phase wire is modelled by terminating it to the end towers of the power line with a resistive load, then the resonant behaviour of the end spans of the power line will be altered and care must be used in interpreting the results of any measurements or calculations. Balmain(9) has suggested that the phase wires might cause a degradation in the results achieved by isolating towers from the skywire, or otherwise "detuning" the power line. It may be useful to determine whether this is so using the long phase wire model, either by computation or by direct measurement.

Allen(10) has measured the loop impedance on one span of a real power line near Winnipeg, Manitoba. This data could be used to test the computer model against the full scale. The loop impedance of the tapered tower model over both perfect ground and over a ground of finite conductivity would be compared with the measured data. The comparison would indicate the degree of approximation associated with the perfect ground model. Also, it may be possible to estimate the "footing impedance" due to the concrete base of each power line tower, from the difference between the computed and measured loop impedance.

Loop impedance is readily measured on a full-scale power line, as opposed to radiation pattern, which is a costly and uncertain measurement. The direct measurement of the loop impedance on an actual power line could provide a useful guide to its resonant frequencies. It may be possible to use loop impedance to assess the effectiveness of devices installed to "detune" a power line. This chapter has shown that loop impedance is also readily calculated, and such computations could be a guide to the design and installation of detuners based on loop impedance measurements. Loop impedance provides a promising laboratory tool, for it is readily measured on a scale model, and could be the basis of the study of power line resonance for power lines with bends, non-uniform spacing, and uneven tower height, and for power lines over ground which is not flat. Thus loop impedance provides a straightforward measurement which may be the key to further understanding of power line resonance phenomena.

CHAPTER THREE

Comparison of Computer Models of Power Lines with Full Scale Measurements

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3.1 Introduction

A high-voltage power line which passes near an MF broadcast antenna can cause a significant change in the radiation pattern of the antenna. The use of a computer model to predict the RF currents which the antenna induces on the power line, and hence the radiation pattern of the antenna operating in the presence of the power line, promises to provide both an assessment of the potential changes to the antenna's pattern due to the construction of a proposed power line, and also a guide to the design of "detuning" devices which could be used to suppress RF current flow on an existing line. These benefits accrue only after the computer model has been proven to be an accurate representation of the physical reality, and this chapter examines comparisons of the computer predictions with full scale measurements of radiation pattern, and particularly of the RF current distribution.

The "single wire tower" computer model of references (1), (2) and (3) is a simplification in many ways. The complex lattice geometry of the power line is simplified to a circular cylinder. The ground is represented as a perfectly flat plane. Two models of the ground conductivity have been used. In the Sommerfeld-Norton model(6), the actual ground conductivity and permittivity are used explicitly in a rigorous solution, at a considerable expense in computer time. In the perfect ground model, the conductivity of the ground is assumed to be high enough that the ground can be modelled as an image-plane. The two models do not give rise to greatly different results, as discussed in reference (3). Also, neither represents the reinforced concrete pedestal or "tower footing" upon which each power line tower is built. It has been proposed in reference (11) that a lumped impedance can be used to take this into account, in conjunction with the perfect ground model. The results obtained with the computer model over perfect ground have been compared extensively in reference (3) with scale model measurements of radiation patterns over a metal ground plane of high conductivity, and it has been shown that the computer model predicts the scale model's azimuth pattern closely, and also that the behaviour of the computer model with changing frequency exhibits the same resonances as does the scale model. But this does not establish the usefulness of the computer model over perfect ground in predicting the behaviour of real power lines, which are, of course, operated over ground of finite conductivity. The scale model cannot easily be made to represent ground of finite conductivity and so the computer model of the power line above a Sommerfeld-Norton ground cannot be checked against scale model measurements. Thus this computer model must be assessed in comparison with measurements on a real power line. The usefulness of these computer models can only be judged against results taken on real power lines.

Thus the problem of the "proof" of the "single wire tower" computer model has been dealt with in references (1), (2) and (3) by comparison with scale model measurements of radiation patterns. In particular, the computer model was designed to agree with Lavrench and Dunn's measurements of the radiation pattern of a 13 tower line, modelled with a scale factor of 1:600, as a function of frequency over the one- and two-wavelength loop resonance frequency ranges for type V1S towers. The model represents type V1S towers, and matches radiation patterns for a straight, evenly spaced power line. This chapter serves to summarize the comparisons with full scale measurements which have been carried out to-date. These measurements consist of the CBC's "ratio patterns" for the CBL/CJBC antenna at Hornby, Ontario, reported in references (12) and (13), Ontario Hydro's measured base currents for many of the power line towers at the Hornby site, reported in reference (14), and Ontario Hydro's detailed measurements of the skywire currents on a power line with five towers at Thornhill, Ontario, reported in references (15), (16) and (20). The best proof of the computer model is the comparison of its predicted RF current distribution with these measured current distributions on an actual power line. In this chapter, a computer model is set up to "predict" these current distributions. At 825 kHz, the agreement between the computer model and the full scale measured values is good, but at 1605 kHz the comparison suggests that a more complex computer model may be required to precisely match the behaviour of the full scale measurement. The measured data will be used to assess the improvement obtained by modelling the conductivity of the ground, and by including a correction for the impedance of the tower footing, relative to the case of the simple "perfect" ground model.

3.2 Comparison with Full Scale Pattern Measurements

Full scale measurements of the radiation pattern of a broadcast antenna before and after the construction of a power line offer a means for assessing whether the power line changes the antenna's radiation pattern. The accuracy of such "field measurements" of radiation patterns has been the subject of considerable dispute(17). The azimuth pattern is obtained by measuring the electric field strength at about eighty individual points around a circle of large radius. It has been noted that the field strengths obtained in two measurements of the same antenna, separated in time by some months, can be different by significant amounts. Aside from errors in individual measurement points due to a change in the precise location, or to new local construction, a systematic change in a group of field values can sometimes be seen. It has been proposed that the ground conductivity changes with changing moisture content of the ground and with heavy snowfall, and that this change in conductivity is directional and so distorts the pattern by introducing a variable attenuation of the ground wave with direction. This effect serves to obscure the changes in a radiation pattern which are seen by measuring the pattern before and after the construction of a power line. Ground conductivity can be measured by taking a set of points along a radial line and comparing the field strength as a function of distance with standard curves. However, the available measurements do not include enough "radials" to assess conductivity variations with direction. The "ratio pattern" is a plot of the ratio of the field strength "after" the construction of the power line to that "before" construction. Regrettably, the changes due to measurement error and changing ground conductivity apparently can be of the same order of magnitude as the distortions due to reradiation from a power line.

The ratio pattern for the CBC's antenna near Hornby, Ontario resulting from measurements before and after the construction of a pair of parallel transmission lines was reported by the CBC in references (12) and (13). The antenna is a single tower radiating an "omnidirectional" pattern and carrying two stations, CBL at 740 kHz and CJBC at 860 kHz. Fig. 3.1 shows the geometry of the site. The power line uses type V1S towers, each carrying two three-phase circuits, protected from lightning by two parallel skywires. Reference (2) describes a computer model of the site which represents tower numbers 13 to 26 of the north line and numbers 13 to 27 of the south line. The computer model assumes a perfectly conducting ground, and uses a "single wire tower" model similar to that of Fig. 2.1, with tower radius 3.51 m and skywire radius 0.71 m. The azimuth pattern predicted by the computer model shows that the power line is strongly resonant at frequencies near 860 kHz, and much stronger reradiation from the power line is present at that frequency than at 740 kHz. This is borne out in the CBC's measured ratio patterns, shown in Fig. 3.2, in comparison to the computer model's radiation patterns. The comparison of the computer model's pattern with the measured ratio pattern at the two frequencies is unsatisfactory in the detailed sense. What is quite evident is that the max-to-min ratio of the measured and computed patterns is quite similar at 740 kHz, and also at 860 kHz. In particular, at the frequency where the computer model predicts that the full scale power line is in resonance and will have a strong effect on the radiation pattern, the measured ratio pattern shows a strong effect. This lends confidence to the use of the computer model in predicting the resonant frequencies of real power lines, although not to the detailed radiation pattern so obtained. The computer model used to obtain these patterns represents a limited number of towers, and the pattern is sensitive to the addition of towers to the computer model. The patterns of Fig. 3.2 may not model enough towers. Also, the pattern may change somewhat if the Sommerfeld-Norton ground model were used, but this was not done because of cost. What is seen in these patterns is that the size of the deviations from isotropic in the measured pattern is comparable to that in the computed pattern at each frequency. In particular, both the measurement and the computation agree that there is considerably more reradiation at 860 kHz than at 740 kHz.

This comparison with full scale measured patterns tends to be unsatisfactory because of the variability associated with the measurement. Precise agreement has not been obtained. A direct measurement of the RF current on the power line removes the change in conductivity with azimuth direction as an unknown factor, and provides a better means of validating the computer model.

3.3 Comparison with Tower Base Currents

Ontario Hydro Research Division has undertaken the measurement of the RF current flowing on the towers and skywires of full scale power lines using a large toroidal coil as a measurement probe. In reference (14), the current flowing at the base of each tower of the power lines of the site at Hornby of Fig. 3.1 is reported at 740 and 860 kHz, and the data is shown in Fig. 3.3. The measurement shows twice as much current on some towers at 860 kHz than at 740 kHz, supporting the idea that the power line is resonant at the upper frequency. The currents on the towers "predicted" by the computer model are also shown in Fig. 3.3. There is general agreement between the computation and the measurement as to which groups of towers carry the strongest currents. Thus at 740 kHz on the north line, Fig. 3.3(a), there is strong current on towers numbered 16 to 20, but weaker currents on towers 22 to 26. On the south line, Fig. 3.3(b), there are strong currents on towers numbered 16 to 21, and weaker currents on towers 22 to 26. Similarly, at 860 kHz the computations and measurements agree that on the north line, Fig. 3.3(c), a group of towers near tower number 18 carry very strong currents, and that towers 20 to 26 carry much weaker currents. On the south line, the current is weakest at the center of the line near the antenna, and stronger toward the ends of the line.

Fig. 3.3 demonstrates a clear correspondence between full scale measured tower base currents and those predicted by the computer model. The agreement might be improved by repeating the calculation using the Sommerfeld-Norton model(6) of the conductivity of the ground, but this was not done because of cost. The trends in the measured and computed currents are the same, and where the measurement shows a group of towers carrying strong RF currents, then a corresponding group in the computer model also carries strong RF currents. However, precise agreement is not found. Thus the proof of the computer model by comparison with full scale measurements has not been satisfactory in a detailed point-by-point sense.

The following presents a comparison of Ontario Hydro's full scale current distribution measurements on the skywires of the two center spans of a five-tower line at Thornhill, Ontario with a computer model's predictions at 825 and 1605 kHz. It will be shown that a good correlation exists between the full scale measurement and the computation.

3.4 Comparison with Measured Skywire Currents

Ontario Hydro Research Division has reported in references (15), (16) and (20) measurements of the RF current distribution on the skywires of a power line with five towers at Thornhill, Ontario, shown in Fig. 3.4. For this series of measurements, only the five towers were erected and strung with skywires. The site uses type V1S towers, each about 50 m tall, with the skywires at the top separated by about 21 m. Ontario Hydro reports the current measured on the spans from tower 107 to 106, and from tower 106 to 105, at 825 and at 1605 kHz. These measurements are used here to test the computer model.

The Thornhill site was modelled using a tower which represents the top crossarm and both skywires explicitly, as shown in Fig. 3.5. The tower stem was 3.51 m in radius, the crossarm radius was 1.00 m, and the crossarm length, 21.3 m. The skywire radius was 0.025 m. The towers were located according to the plan of Fig. 3.4, and the tower heights were obtained from the data supplied by Ontario Hydro, given in Table 1. The computer model is set up for a perfectly flat ground, and a major extension of the method would be required to represent an undulating surface. The ground at Thornhill drops off to the west and the towers are of varying height to maintain an acceptable distance of the phase wires above the ground. The transmitter was represented as a 30 m tall monopole at the position given in Fig. 3.4.

TABLE 1 Dimensional Data for the Thornhill Site

Tower #	Base Coordinates X	Base Coordinates Y	Height
104	492.8 m	-349.8 m	52.4 m
105	264.4	-301.9	50.9
106	0.	-254.4	52.4
107	-241.5	-207.1	58.5
108	-514.9	-225.3	60.0

The tower of Fig. 3.5 represents the top crossarm and both of the skywires of the type V1S tower explicitly. It is worth noting that a frequency sweep computation with a model similar to this has revealed a discrepancy between the NEC program's predictions and scale model measurements. Thus a five tower, evenly spaced power line using this two-skywire model is found by the NEC program to have resonant frequencies which are low compared to those measured on a scale model. In particular, the two-skywire computer model resonates at about 815 kHz, while the measured data with two skywires indicates resonance at 860 kHz. The behaviour of the NEC results is apparently explained by the additional path length due to the crossarm. Thus the longer path is resonant at a lower frequency. Yet this is inconsistent with the scale model measurement, and as a consequence leads to a questioning of the available measured data. A new measurement with one skywire at the center of the crossarm, with one skywire at the crossarm tip, and with two skywires would provide a basis for resolving the problem. A fuller tower model with all crossarms and a realistic tapered profile also has low resonant frequencies. Thus models such as that of Fig. 3.5 which explicitly represent both skywires cannot be regarded as better than the "single wire tower" or the "tapered tower" of Chapter 2 until this difficulty has been resolved.

3.4.1 Comparison of RF Currents at 825 kHz

Using a perfectly conducting ground, the RF current distribution on the towers and skywires was computed at 825 kHz and is shown in Fig. 3.6. The RF current is typical of that described in reference (2) for a power line near its "two wavelength" resonant frequency. The current on each span has two sharp minima, falling near the towers, and a maximum near the center of the span. The current distribution on the north skywire is about the same as that on the south skywire of each span, at 825 kHz. The current distribution is compared with Ontario Hydro's measured current distribution for span 107 to 106, in Fig.3.7 parts (a) and (b), and for span 106 to 105 in parts (c) and (d). The measured data of part (c) may be in error, as discussed below. The current was scaled or "normalized" by dividing the current on each individual skywire by its maximum value. Thus the current cannot be compared in value from one graph to the next. This normalization allows the position of maxima and minima and the overall shape of the curves to be compared readily, but not the relative level of the current between one skywire and another. Comparing the perfect ground curve (long dashes) with the measured curve (solid line), it is seen that there is good agreement overall. In Fig. 3.7 parts (a) and (b), the computed curve for span 107 to 106 appears to be shifted to the left relative to the measured curve. No measurement was available for the south skywire of span 106 to 105 in Fig. 3.7(d). The calculation was repeated using the Sommerfeld-Norton ground model(6) with a ground conductivity of 10 mmho/m and a relative permittivity of 15. The actual ground conductivity was not measured by Ontario Hydro. Comparing the computation over a ground of 10 mmho/m conductivity (short dashes) with the two other curves, it is seen in Fig. 3.7(a) and (b) that including the ground conductivity shifts the computed curve to the right and so improves the agreement with the measurement. A lower conductivity value would result in even better agreement. However, in Fig. 3.7(c) there is little difference between the perfect ground case and that using finite conductivity ground. Overall, Fig. 3.7 shows a good correlation between computation and a full scale measurement, and shows that fractionally better agreement is obtained using the Sommerfeld-Norton ground model.

Evidently, a misinterpretation of the Ontario Hydro data of reference (15) is present in Fig. 3.7 (c). Thus the measured curve used to obtain the data has discontinuities of 10 dB, such that the center of the curve is shifted down by 10 dB. This was "restored" to obtain the smooth measured curve reported in Fig. 3.7(c). Evidently this is not a correct interpretation(19). Fig. 3.8 plots the current as reported, to the same scale as the original figure. This ambiguity or inconsistency in the measurement makes it unrewarding to attempt a better normalization of the data of Fig. 3.7. In a recent publication prepared for the CEA(20), Ontario Hydro reports the data of Fig. 3.7 parts (a) and (b), but not part (c).

3.4.2 Comparison of RF Current at 1605 kHz

The computation with perfect ground and with ground conductivity 10 mmho/m was repeated at 1605 kHz. Previous work reported in references (1) (2), and (3) has not explored computation at this high a frequency, and so this must be looked upon as an extension of the computer model. The power line is expected to display "four wavelength" resonance near this frequency. The computer model requires about twice as many "segments" at 1605 kHz than at 825 kHz, increasing CPU time consumed to 879 CPU seconds at 1605 kHz compared to 338 seconds at 825 kHz, both over Sommerfeld-Norton ground. Over perfect ground, the CPU times are shorter, being 563 seconds at 1605 kHz, and 163 seconds at 825 kHz. The current distribution over perfect ground is shown in Fig. 3.9. On each span, three minima and two maxima can be seen. There is a significant difference between the current distribution on the north and on the south skywire at this frequency.

Fig. 3.10 compares the computed skywire current distribution with perfect ground and with ground conductivity 10 mmho/m with Ontario Hydro's measured current distribution at

1605 kHz. The curves were individually "normalized" by dividing the current on each span by its maximum value. The inclusion of the actual conductivity of the ground in the computation does not change the current very much compared with the perfect ground curve. In fact, only in Fig. 3.10(d) is any appreciable difference seen. In comparison to the computations, the measured current distribution behaves in a similar manner, but "agreement" cannot be claimed. There is a shift to the right of the computed data relative to the measured data, on both the tower 107 to 106 span, and on the 106 to 105 span. The precise locations of the peaks and nulls in the current distribution at 1605 kHz are strongly dependent on the geometry of the model. A small error in the position of the broadcast antenna may account for the shift of the curves. Or, as discussed in Chapter 2, a more detailed tower model may be necessary. Thus perhaps taper and top-loading crossarms should be included.

A better normalization for Fig. 3.10 would use the same scale factor for all three parts of the figure, so that the magnitude of the current could be compared from one skywire to another. Thus the total area under the square of the current, summed over all three parts of the figure, was calculated for both the measured and the computed data, and then the curves were scaled to make this squared-area the same for both. At 1605 kHz, Fig. 3.11 is the result. If the large values taken on by the measured data near 25 m in Fig. 3.11(a) are ignored, then it is seen that the measured current is somewhat larger in part (a) on the north wire of span 107 to 106, than it is in parts (b) or (c). The calculated current has a very similar level to the measured current in parts (a) and (c), but is larger in part (b) than is the measured current. The change in the strength of the measured current from part (a) to part (c) of the figure is nicely matched by the change in the level of the calculated current. But the conclusion is not changed by the new normalization. The systematic shift in the position of the calculated curves relative to the measured curves indicates a deficiency in the computer model at 1605 kHz.

Figs. 3.7 and 3.10 show that the skywire current predicted by the computer model is similar in behaviour to that obtained by full scale measurement on a real power line. Good agreement was obtained at 825 kHz in Fig. 3.7. Factors that were not included in the model may have a significant effect. For example, the conductivity of the steel towers and wires making up the power line is high and is assumed to be infinite in the model. This is not expected to introduce significant error. The impedance of the tower footing was not included, and is discussed in the next section. The flatness of the ground is not readily included in the present computer model, although this may have a significant effect. The comparison at 1605 kHz indicates that a more complex computer model needs to be developed for the higher frequencies in the AM band.

3.5 Inclusion of the Tower Footing Impedance

Each tower of the power line is installed on a reinforced concrete "tower footing" buried in the ground. It has been suggested by Balmain in reference (11) that the tower footing can be modelled as a lumped impedance at the base of each tower in the perfectly conducting ground model. The value of the footing impedance is computed by considering the tower footing to be a highly conductive cylindrical post buried in a ground of a given conductivity. Monteath's formula in reference (18) is aimed at the replacement of a ground of finite conductivity with an equivalent problem in which the ground is perfectly conducting, and to do this an impedance is included in series at the base of each of the power line towers. Thus this "footing impedance" does not model a local footing effect near the tower base, but instead is a global replacement of ground of finite conductivity by perfectly conducting ground. In Monteath's method the tower footing is a perfectly conducting cylinder extending very deep into a ground of a specified, finite conductivity. That ground is then replaced by a perfect ground and the "footing impedance" is inserted at the base of each tower, with a value chosen to give the same RF current on the tower for both problems. Monteath's formula is used to obtain the series impedance required to model ground of finite conductivity, and this series impedance is then included as a lumped "tower footing impedance" at the base of each power line tower in the model over perfectly conducting ground. Accordingly, a computer program was written to evaluate the tower footing impedance and was checked by recomputing the footing impedance values quoted in reference (11). Subsequently, the tower footing impedance for the Thornhill site was computed using a ground conductivity of 10 mmho/m and a ground cylinder radius of 0.144 m. The values obtained were (20.0+13.9j) ohms at 825 kHz and (25.6+15.9j) ohms at 1605 kHz. These values are considered to be for each of the four legs of the tower. The legs are taken to act in parallel, so the net impedance to be included at the base of each power line tower is one-quarter of the value quoted above.

Fig. 3.12 compares the skywire current computed using the footing impedance over perfect ground (short dashes), to that computed with perfect ground but no footing impedance, and to Ontario Hydro's measured current distribution, all at 825 kHz. The inclusion of the footing impedance makes little difference to the current distribution. The slight shift seen on span 107 to 106 in Fig. 3.12(a) and (b) is in the correct sense, giving slightly improved coincidence with the measurement. Fig. 3.13 repeats the comparison at 1605 kHz. Again, little change is seen due to the small series impedance inserted to model the tower footing. The small change is in the wrong sense.

Fig. 3.14(a) and (b) compare the azimuth radiation patterns at 825 and 1605 kHz with and without tower footing impedance. The small changes seen when the footing impedance is modelled do not seem to justify the additional complexity introduced into the modelling procedure.

3.6 Conclusion

This chapter has presented comparisons of the full scale measured behaviour with that predicted by various computer models of a power line which is excited at RF frequencies by an MF broadcast antenna. The objective has been to validate the computer model and to choose among various representations of the ground.

Full scale measured radiation patterns for a site near Hornby, Ontario were compared with patterns predicted by a computer model above perfect ground, at 740 and 860 kHz. The measured patterns show much larger deviations from isotropic at 860 kHz than at 740 kHz, suggesting that the computer model's prediction of resonance near that frequency is correct. The measured patterns do not, however, correspond closely in detail with the computed patterns. This may be due to the uncertainty inherent in the measurement procedure, to variations in ground conductivity with direction near the Hornby site, or to shortcomings in the computer model. Of these, it may be that too few towers of the actual power line were included in the computer model, or that factors not modelled, such as the deviation from perfect flatness of the ground, have a significant effect. Comparison with full scale pattern measurements may not be the best validation procedure for the computer model.

The RF current distribution on power lines has been measured by Ontario Hydro Research Division, using a large toroidal coil. For the site at Hornby, the current flowing at the base of each power line tower was measured. This report presented a comparison with the tower base currents of the computer model at 740 and 860 kHz. The result is a clear correlation between the measured and computed data, although precise agreement is not obtained. In general, on groups of towers where a strong RF current is measured, the computer model shows a strong RF current. Similarly, where the RF current is measured as weak, the computer model is in agreement. Both the computation and the measurement show a much stronger current at 860 kHz than at 740 kHz.

Ontario Hydro Research carried out a detailed measurement of the RF current distribution on the skywires of two spans of a five tower test site near Thornhill, Ontario, at 825 kHz and 1605 kHz. A computer model was constructed incorporating the proper tower locations and heights. A tower model was used which explicitly represents the top crossarm and both skywires. It was shown in this report that the computed RF current distribution on the skywires is very similar to the measurement, especially at 825 kHz. The close correspondence allows several computer models to be compared. Thus it was shown that the computer model using the Sommerfeld-Norton model of ground of finite conductivity(6) generates somewhat better results than the perfect ground model but at much greater cost. The difference between the results using the two models is not great. The actual ground conductivity at Thornhill was not known and was assumed to be 10 mmho/m. Even closer agreement with the measurement would be obtained with a lower value. Also, the inclusion of a lumped impedance at the base of each tower to model the tower footing was tested. The perfect ground model with no footing impedance was compared to the same model including the footing impedance. Because the value for the footing impedance is so small, little difference was seen in the two cases, and so in this instance the inclusion of the footing impedance appears to be an unnecessary complication.

The most accurate computer model appears to be that using the Sommerfeld-Norton model of the ground(6), provided the ground conductivity is known. The perfect ground model is not greatly different, exhibiting the same resonant behaviour but somewhat less damping. In most cases, the perfect ground model is adequate. The computer model agrees well with the measurement of the RF current distribution at 825 kHz. The comparison at 1605 kHz suggests a more complete tower representation may be necessary at the higher frequencies in the AM band.

CHAPTER FOUR

Conclusion and Recommendations

4.1 Conclusion

In this report various computer models have been tested against full scale measured RF current distributions, and against scale model measurements of the loop impedance. In general, excellent agreement up to about 900 kHz is obtained. The "straight tower" version of the "single wire tower" model has been validated against measured radiation patterns up to that frequency. For computing loop impedance, the "single wire tower" model must be modified to a "tapered tower" model, and then excellent agreement with measured impedance is obtained to 900 kHz. For comparison with the measured RF current distributions on each individual skywire, a two-skywire variation of the "single wire tower" model was used, and good agreement with the measurement was obtained at 825 kHz. The comparison with the measured skywire current at 1605 kHz suggests that a more detailed tower model is necessary at the higher frequencies in the AM band. Indeed, it was found in Chapter 2 that the simple "straight tower" or "tapered tower" model with a single skywire must be modified for higher frequency work. Evidently a top-loading crossarm extends the useful frequency range to 1400 kHz or higher. A fuller representation of the crossarms may be needed at higher frequencies.

The performance of skywire stub and skywire insulator detuners in the presence of a phase wire was investigated. On a power line of four spans, the phase wire was represented as a wire running the length of the power line, and terminated in an open-circuit adjacent to each of the end towers. The detuning devices worked just as well in the presence of the phase wire as without the phase wire. The representation of the phase wire was not considered satisfactory for general use, because the open-circuited phase wire has no mechanism to dissipate energy coupled to it, and exhibits strong resonances. A more satisfactory phase wire model was developed in the context of loop impedance calculations, and consists of a "long" wire extending well beyond either end of the the span of the "power line", and "loaded" with distributed resistance over a considerable distance near each open-circuited end. This models the physics well by providing a path along the phase wire for energy coupled to it from the skywire to be conducted away from the "power line", and then provides resistance to dissipate the energy. It was found that the phase wire has little effect on resonant behaviour. This "long" phase wire could be constructed with resistive wire or with discrete resistors, and may be a useful phase wire representation for scale model measurements.

The modelling of the ground has been considered by comparing computations with "perfect" ground, with the Sommerfeld-Norton model of finite conductivity ground, and with the inclusion of footing impedance to model the ground conductivity. The computed RF current distribution in each case was compared with Ontario Hydro's full-scale measured current distribution. The result is that "perfect" ground is a surprisingly good representation, and other ground models do not predict very different behaviour. For the cases examined, the footing impedance did not significantly improve the agreement with the measurement.

The concept of loop impedance promises to provide a useful tool for the understanding of resonance phenomena on power lines, and for the development of accurate computer models. Loop impedance is readily measured, both full-scale and using scale models. Measurement of loop impedance by a hydro utility could provide a simple means of assessing the resonant behaviour of a power line. This report has used loop impedance measurements to develop a better computer model of the type V1S tower, which generates agreement with the measurement to 1400 kHz. Measured loop impedance data could provide a means for developing computer models of other tower types over the whole frequency band.

4.2 Recommendations for Further Work

A comparison of the loop impedance "predicted" by the best computer model available with Belrose's measured data for a full scale power line would provide further "proof" of the computer model. The actual ground conductivity could be included in the model using the Sommerfeld-Norton ground model, and the conductivity of the skywire and tower could also be included, so that all losses would be represented, and then the difference between the computed results and the measured values may be attributable to the "footing impedance" of the concrete base of each power line tower. Various footing impedances might be included in the computer model to seek better agreement. By exploiting the full-scale measured data in this way, it may be possible to establish the magnitude of the effect that the footing impedance has on the resonant behaviour of the power line.

It may be of interest to test the "long" phase wire model by measurement. Thus a direct measurement may serve to allay fears about whether the phase wire causes changes in the resonant behaviour. Loop impedance or pattern measurements could be used and must be taken over a wide frequency range. In Appendix 1, little change was found in the performance of detuners using a short, open-circuited phase wire representation. It may be of interest to investigate whether the effectiveness of detuning devices is degraded in the presence of the phase wire using the "long" phase wire model, either by computation or by direct measurement.

It is evident that the "tapered tower" model must be further developed for calculations at frequencies as high as 2200 kHz. A top-loading crossarm appears to extend the frequency range of the model to 1400 kHz. All numerical models must be expected to have a limited bandwidth over which their accuracy is acceptable. Should it be prudent or necessary to have models that can be applied up to the proposed AM band extension to 2200 kHz, then computer models should be developed to have the necessary degree of accuracy up to that frequency. Essential to such a computer model development is a coordinated measurement program. The work above shows that loop impedance measurements would be useful over the whole range, as they appear to be good for "fine tuning" the resonant behaviour of the tower model. A catalog of measured radiation patterns in the three- four- and five-wavelength loop resonance frequency ranges would allow confirmation of the performance of the computer model for pattern prediction. It is expected that the radiation pattern will change rapidly with frequency in this range, and will exhibit complex behaviour. Measured patterns on the 600 scale factor model at closely spaced frequencies are invaluable. Top-loading by the crossarms may introduce new resonance modes, and this needs to be investigated both by computation and by scale model measurement.

It has been suggested above that the question of the effect of uneven tower spacing on the behaviour of the power line near resonance be investigated by computation using random tower spacings. A thorough evaluation using many spacing sets would be expensive in computer time and cumbersome to carry out. It may be practical and of interest to produce a few specific results that would indicate the nature of the changes to be anticipated. This is a step toward the generalization of the methodology. The more exhaustive and systematic investigation can be considered by the CRC using in-house computer resources.

At the present stage of model development, computations can be used with confidence in the lower half of the AM band, and with reservations at higher frequencies. Type V1S towers have been modelled extensively, and the model well validated up to 900 kHz, but no other tower type has been proven. Evidently the specific type of tower will make a difference, especially at higher AM frequencies, where top-loading by the crossarms has a significant effect. Thus it is suggested that another representative tower type be chosen, and loop impedance measurements be made with 1:200 scale factor models. The results could be used to test the computer modelling guidelines for a new tower type. Then pattern measurements could be made at frequencies where the tower geometry or crossarms should have a significant effect. Eventually, a catalog of computer models of various tower types, each validated by comparison with measurements, can and should be developed for use by the hydro utilities and by the Canadian Association of Broadcasters and their consultants to assess the seriousness of a potential reradiation problem, and to test schemes for detuning the power lines involved.

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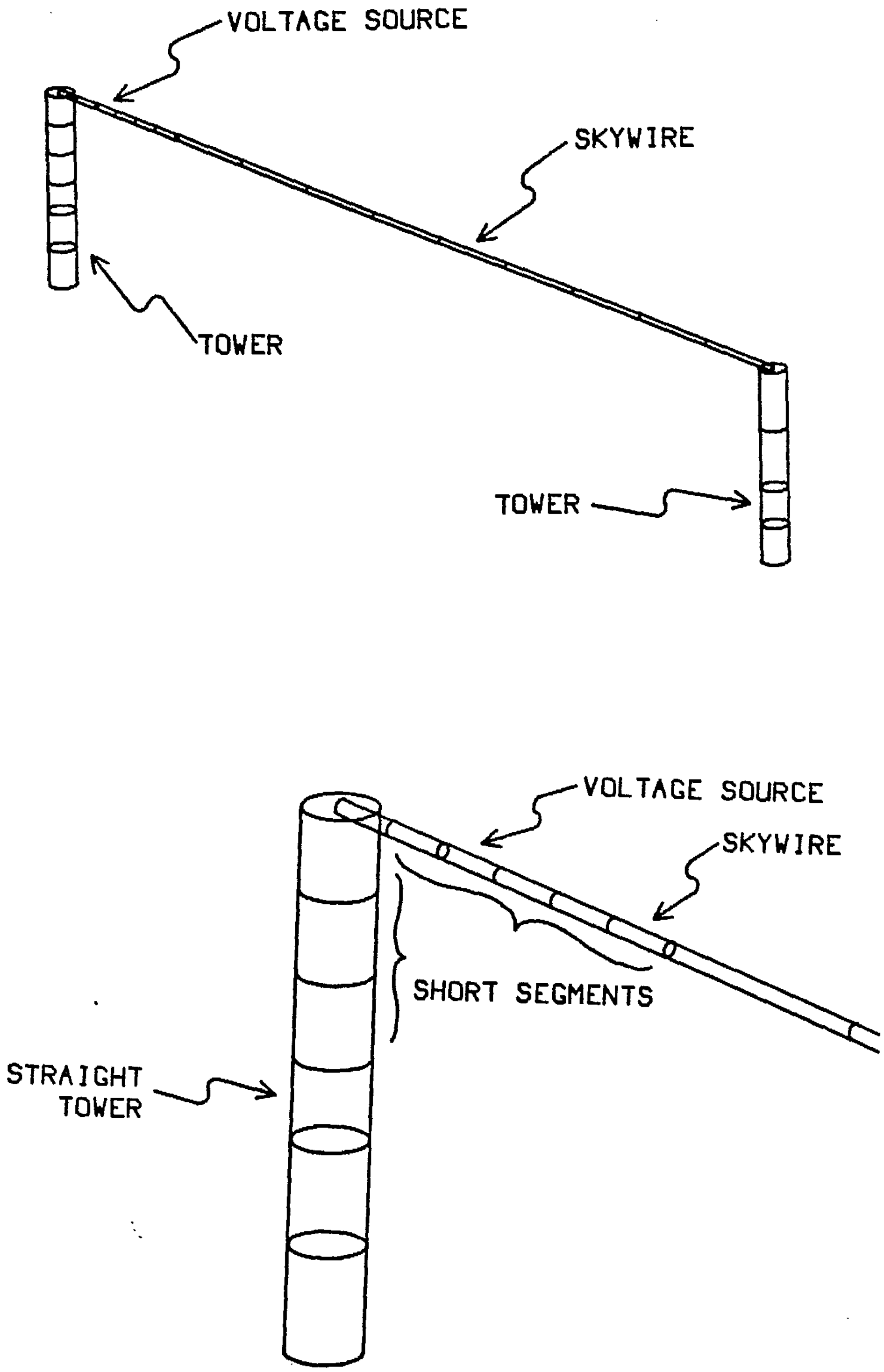


Figure 2.1 Computer model using a "straight tower" similar to the "single wire tower".

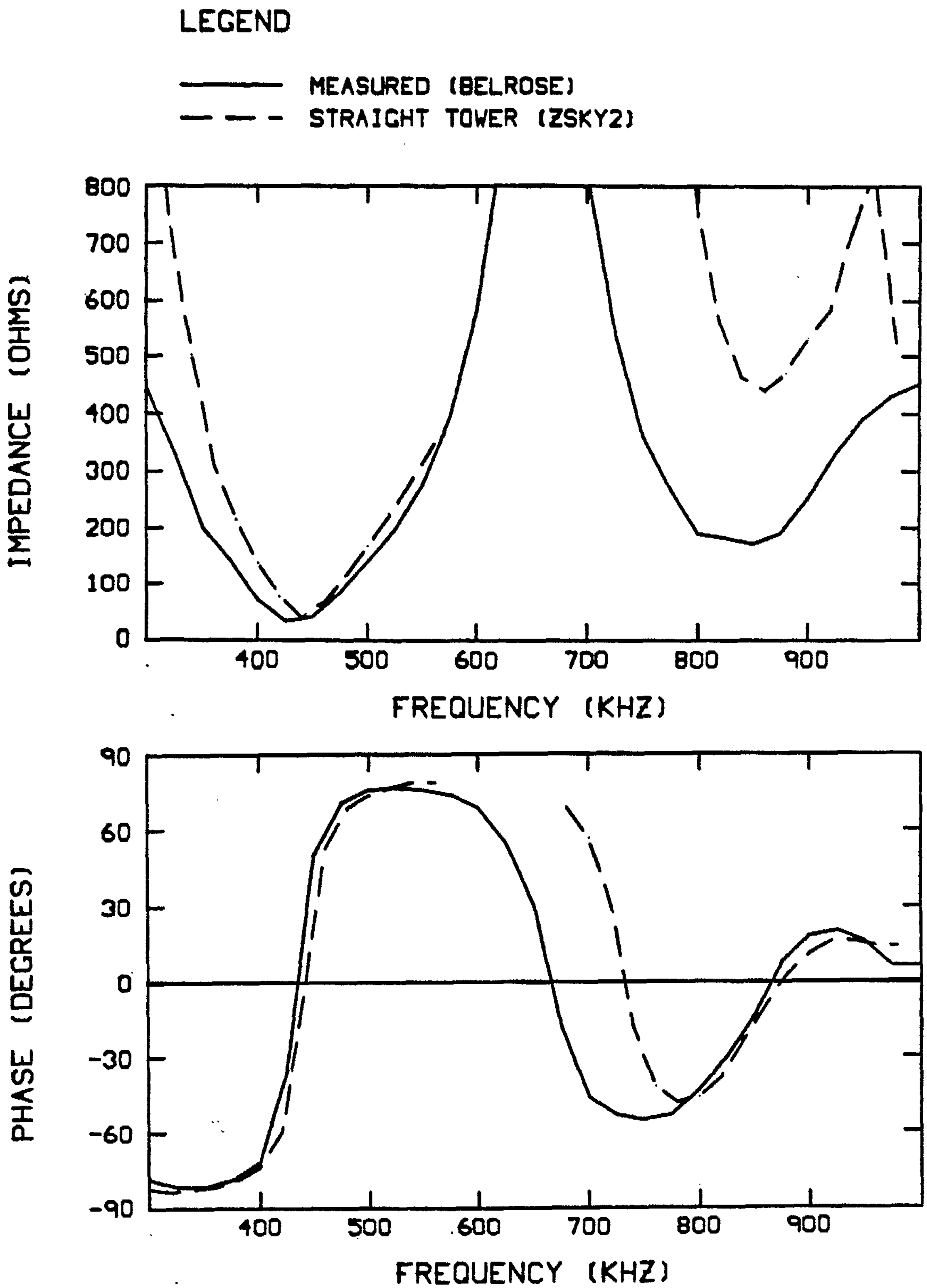
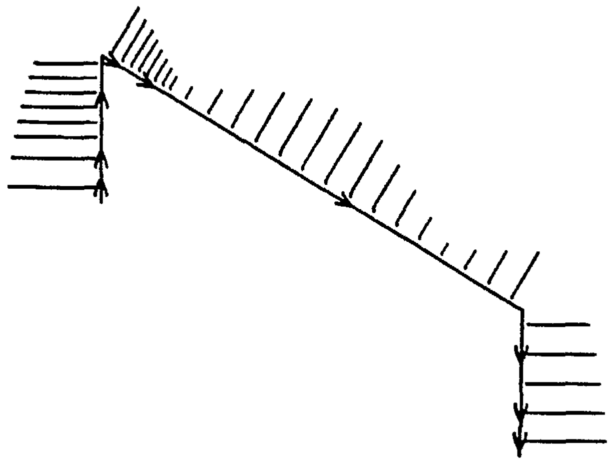


Figure 2.2 The loop impedance as a function of frequency for the "straight tower" model.



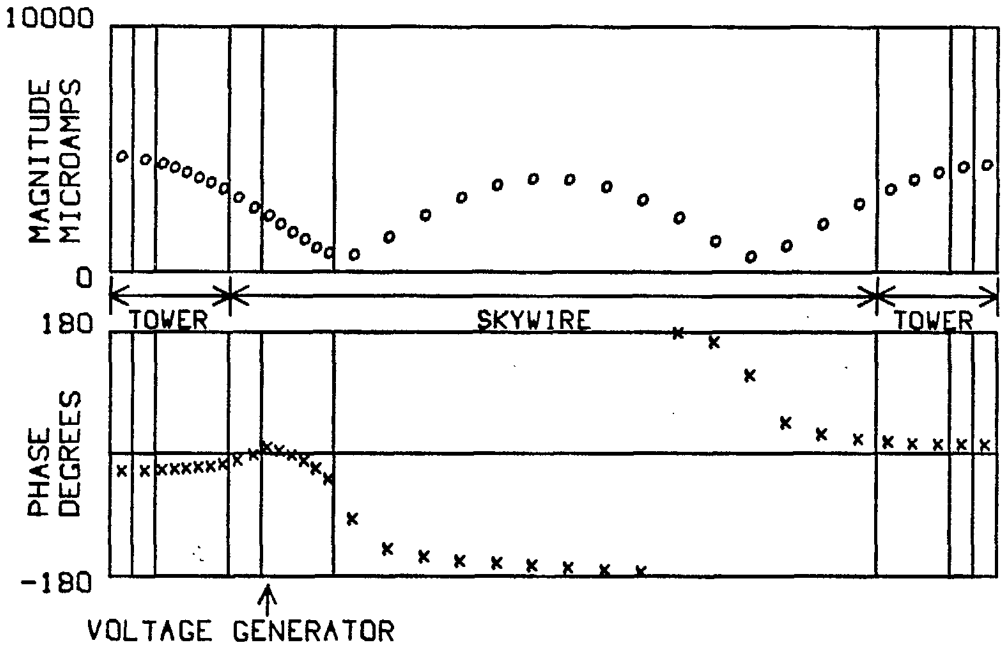
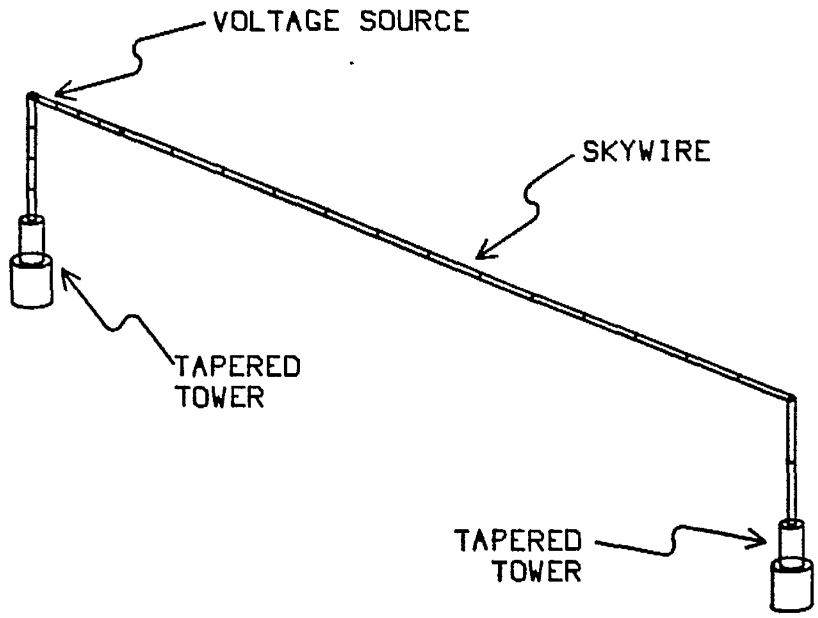


Figure 2.3 The RF current at the center of each segment at the two-wavelength loop resonance frequency of 860 kHz. In the upper portion of the figure, the arrowheads show the direction of flow of the current when its phase angle is zero degrees.



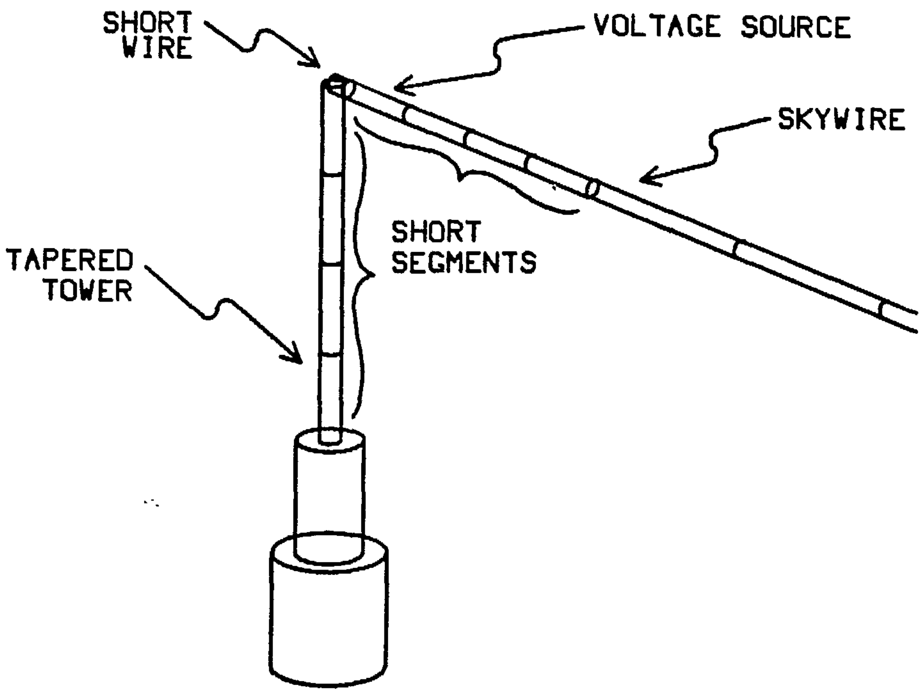


Figure 2.4 Computer model using a simple "tapered tower".

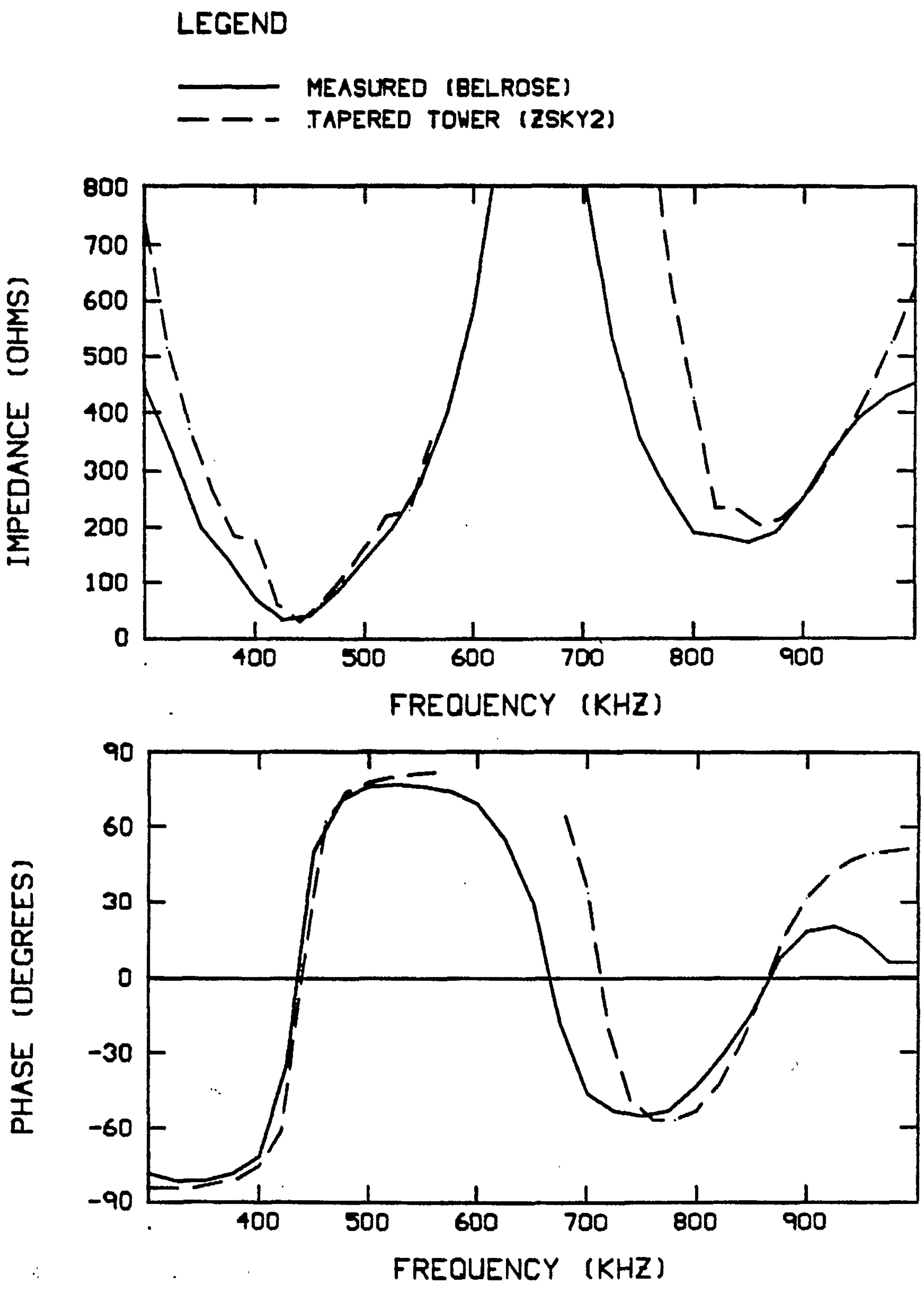


Figure 2.5 The loop impedance as a function of frequency for the simple "tapered tower".

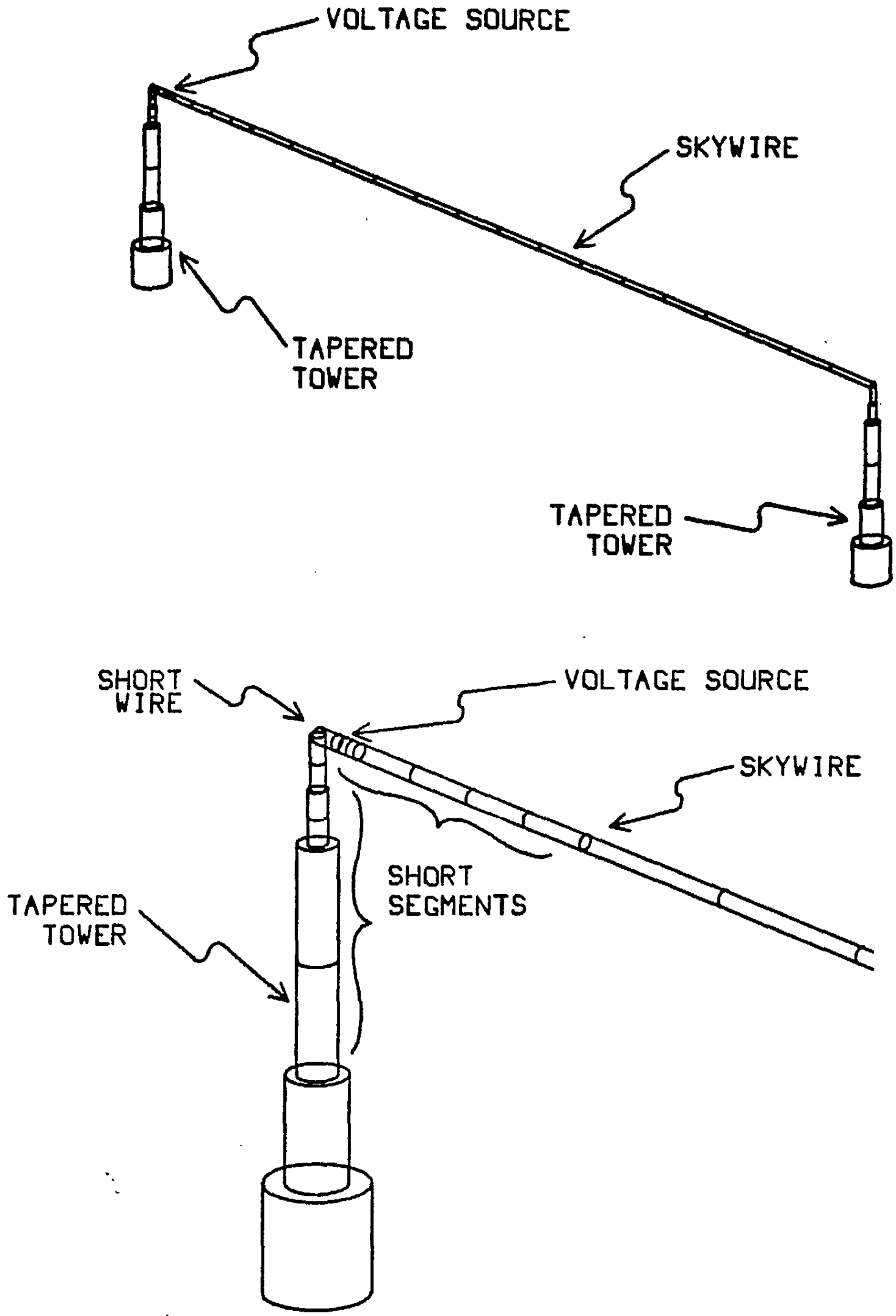


Figure 2.6 Computer model using a refined "tapered tower".

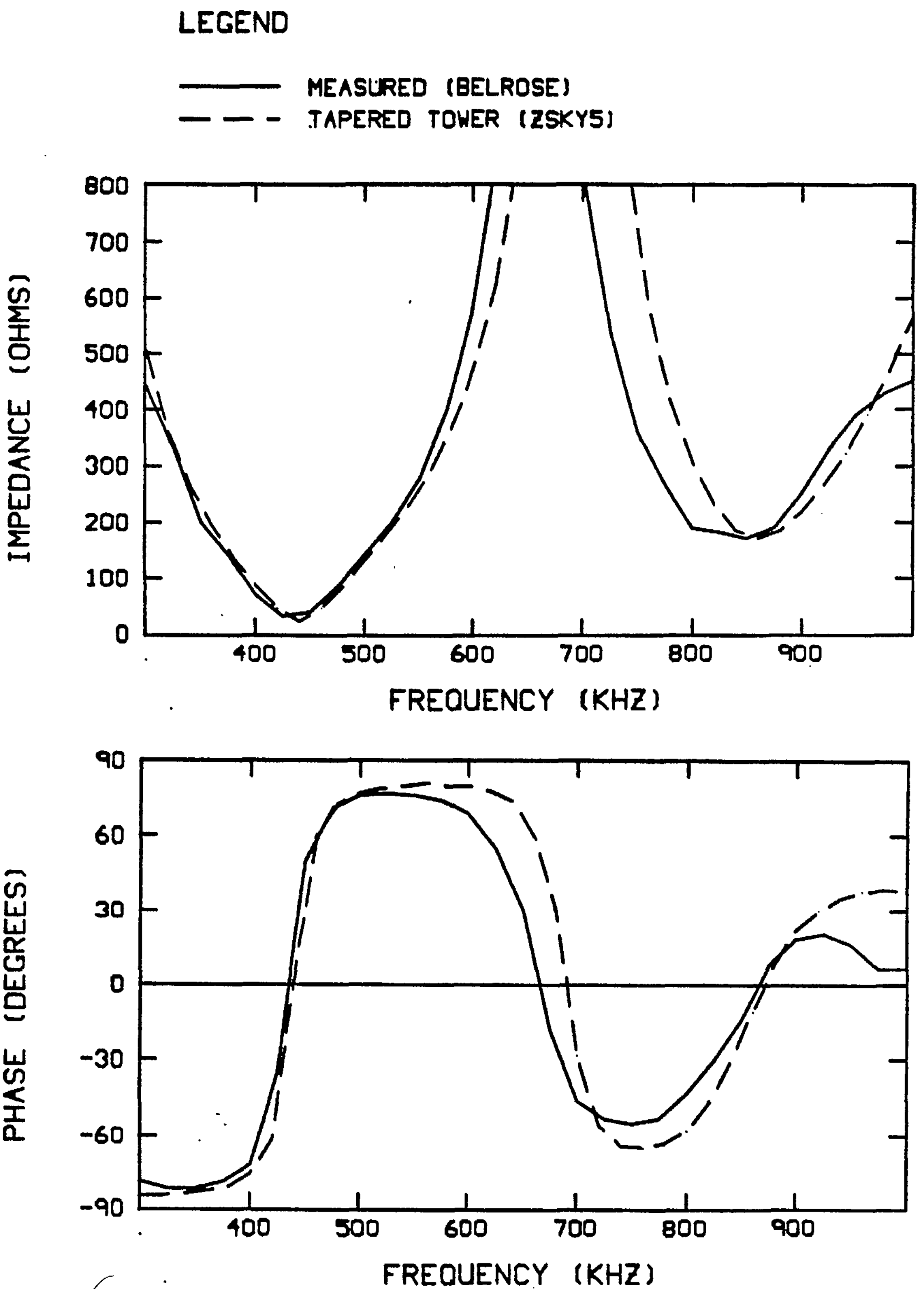


Figure 2.7 The loop impedance using the refined "tapered tower" model.

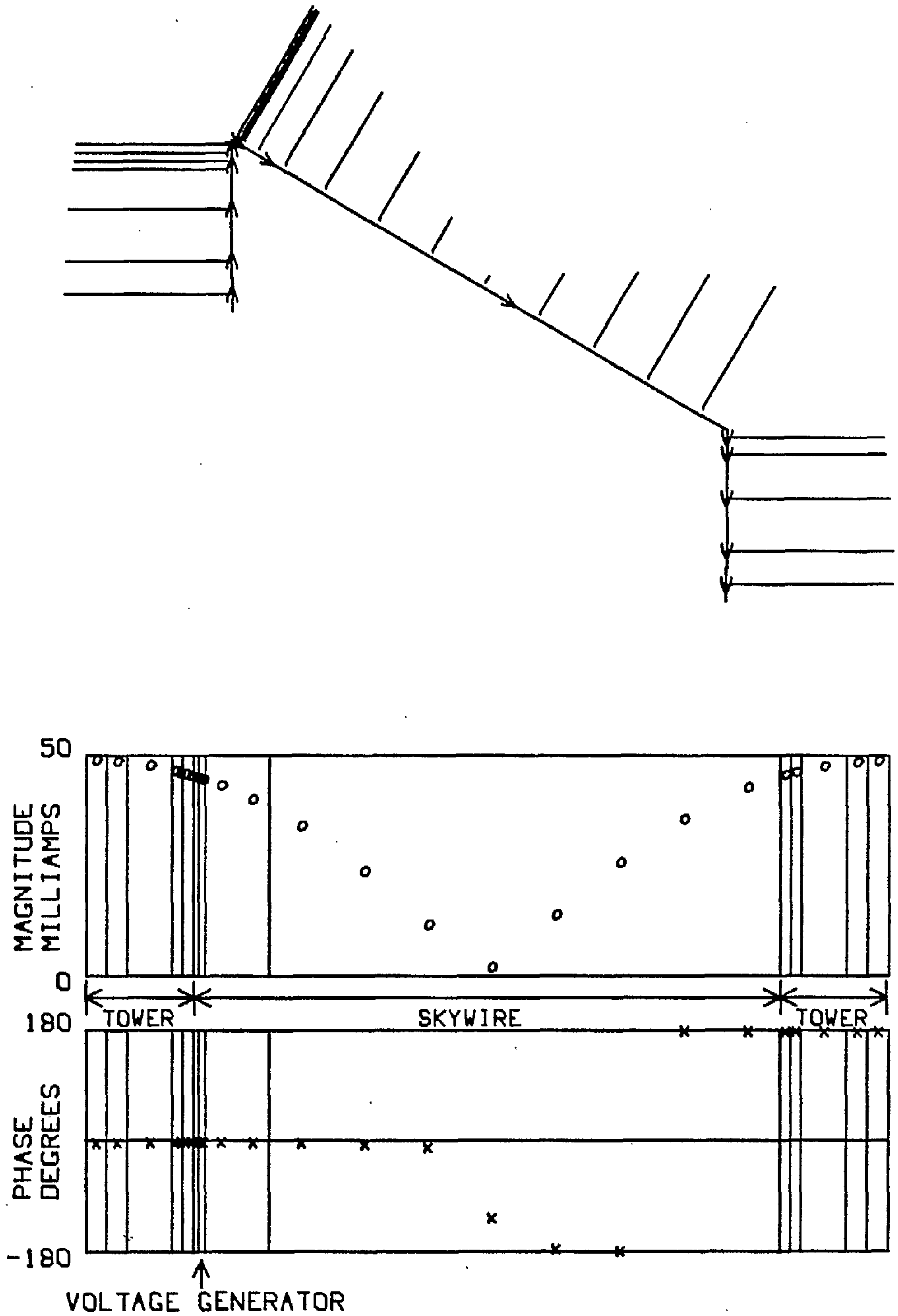


Figure 2.8 The RF current at the center of each segment at the frequency of one-wavelength loop resonance of 440 kHz. The choice of the number of segments is frequency dependent and is discussed on page 14. The vertical lines in the lower portion of the figure show the junctions between the wires in the model of Figure 2.6.

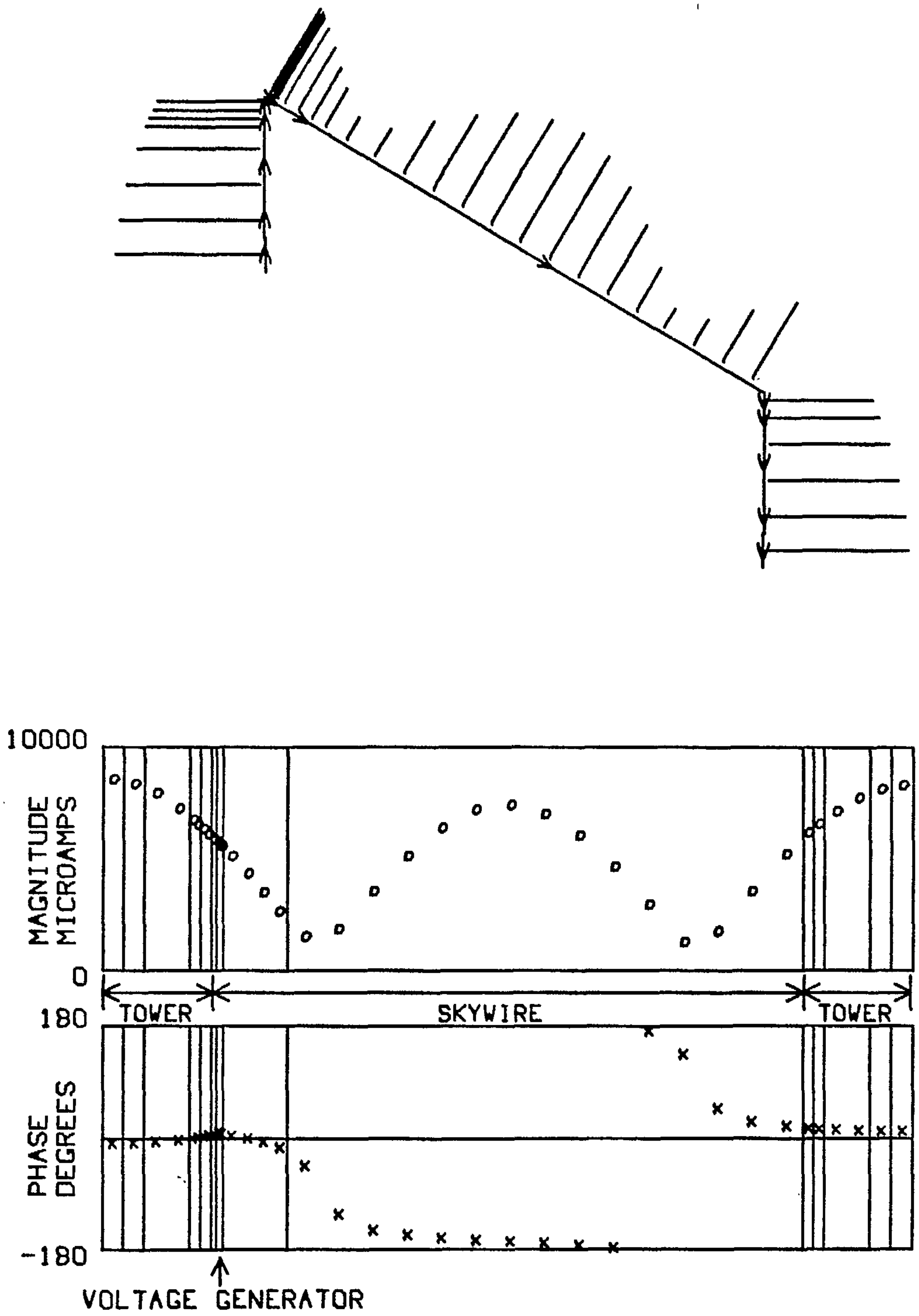


Figure 2.9 The RF current distribution at the frequency of two-wavelength loop resonance of 860 kHz.

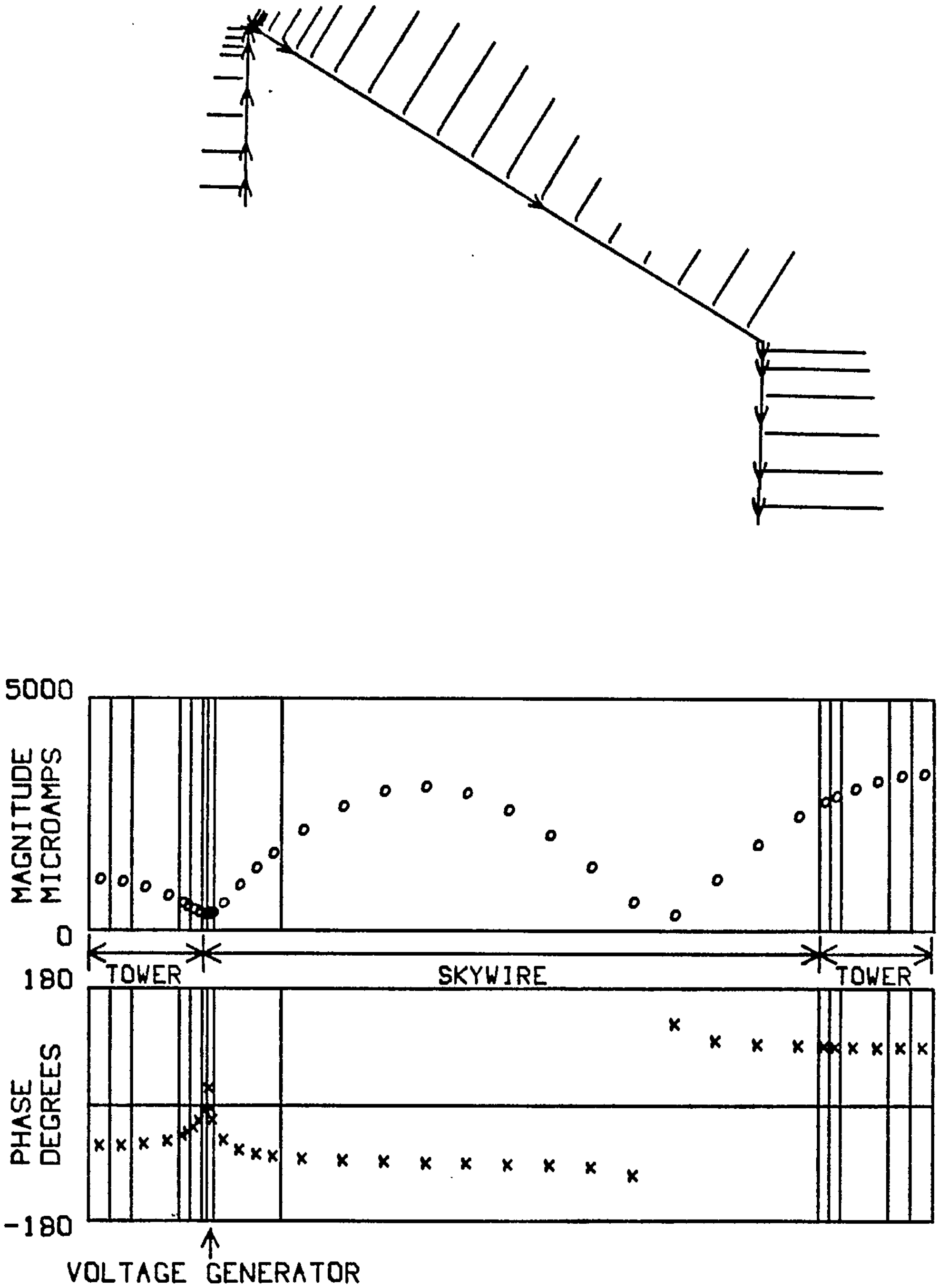


Figure 2.10 The RF current distribution at the anti-resonant frequency of 700 kHz.

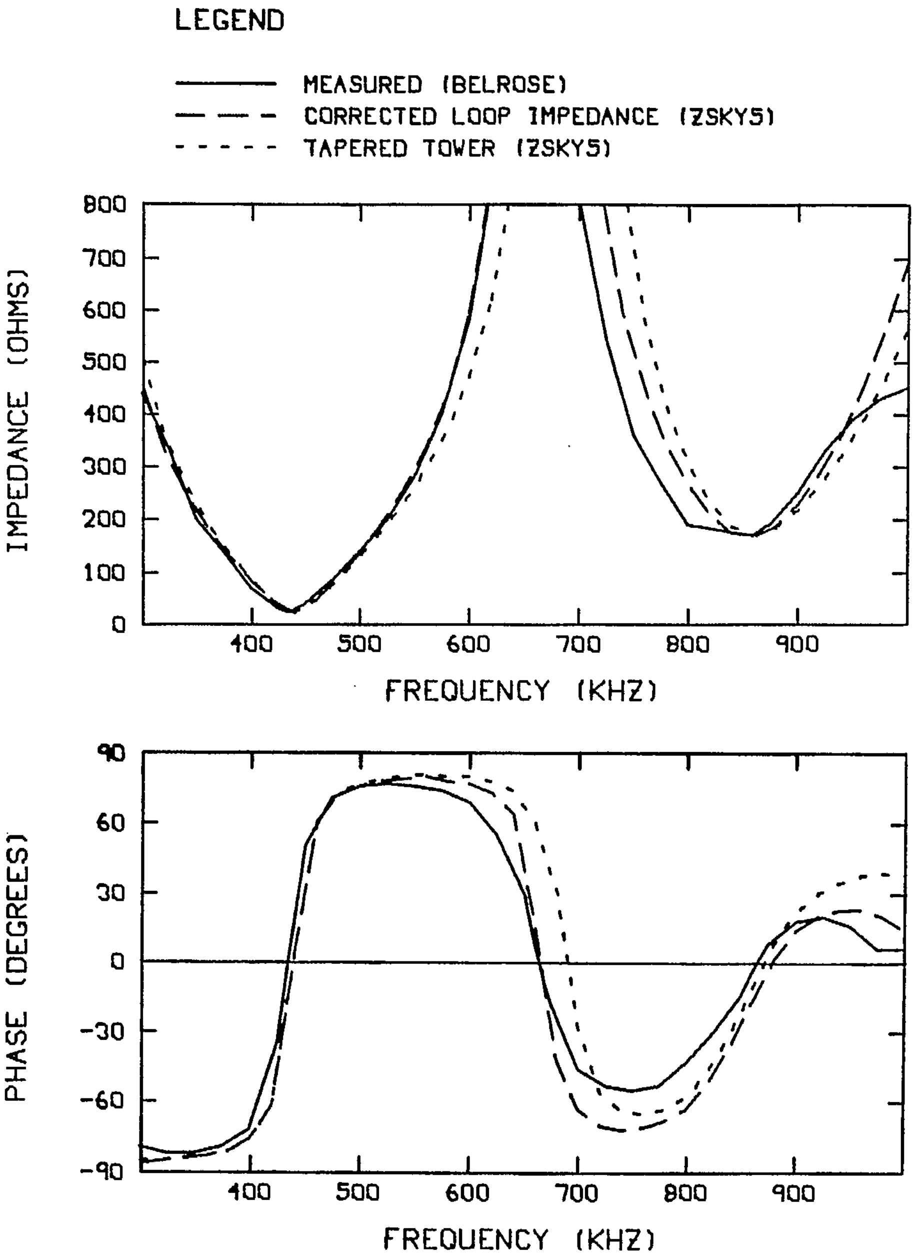


Figure 2.11 The anti-resonant frequency is shifted to agree with the measurement by accounting for the capacitance of the feed arrangement in the measurement model.

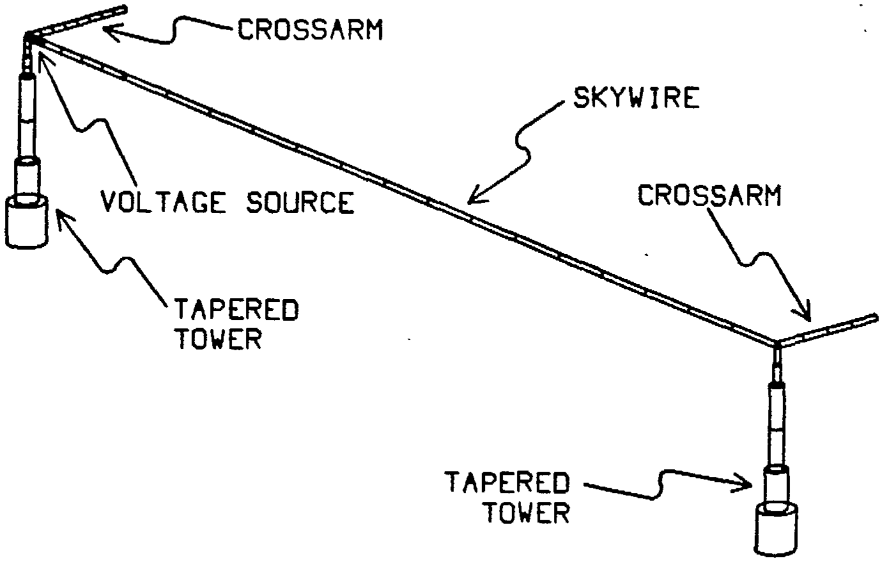


Figure 2.12 The tapered tower model with a wire on each tower representing top-loading due to the tower's crossarms.

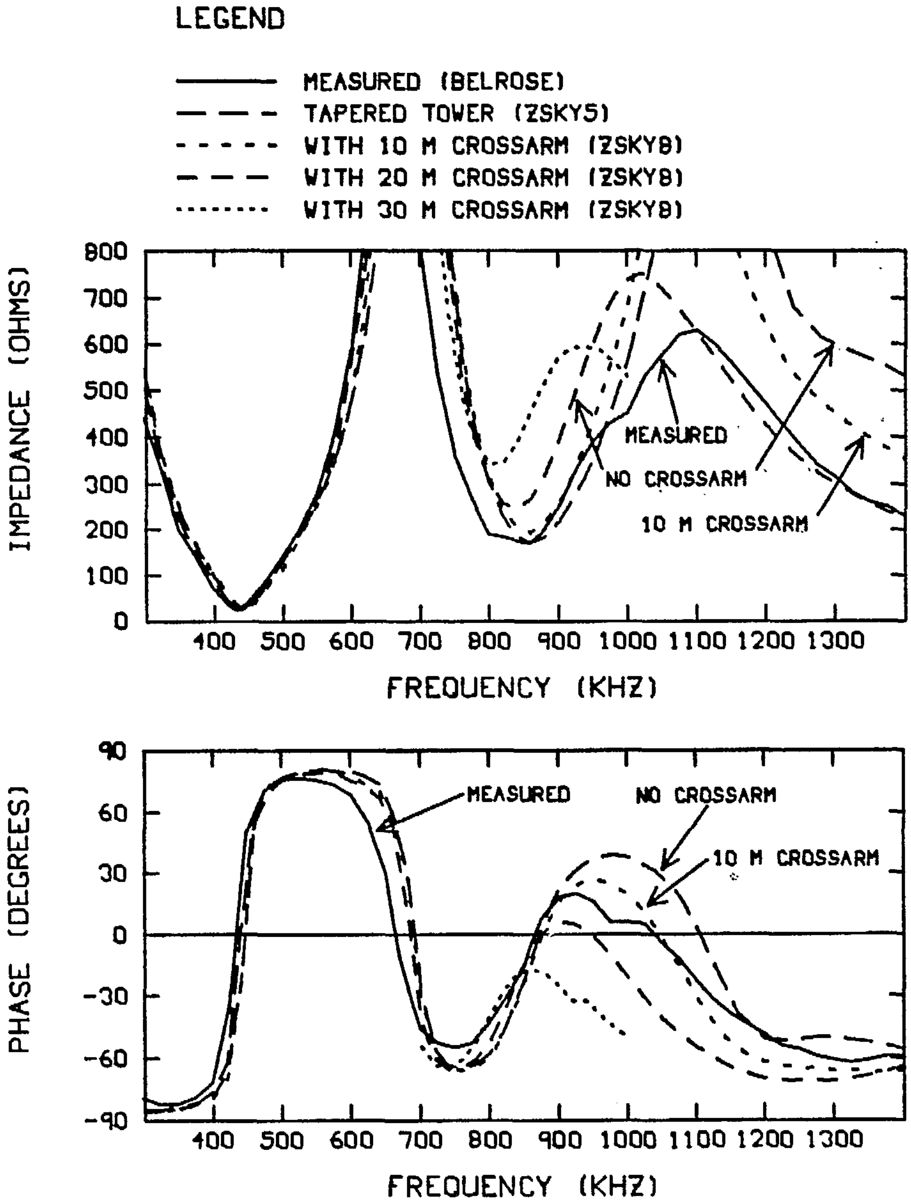


Figure 2.13 The loop impedance with a top-load crossarm of varying lengths, compared with measured values.

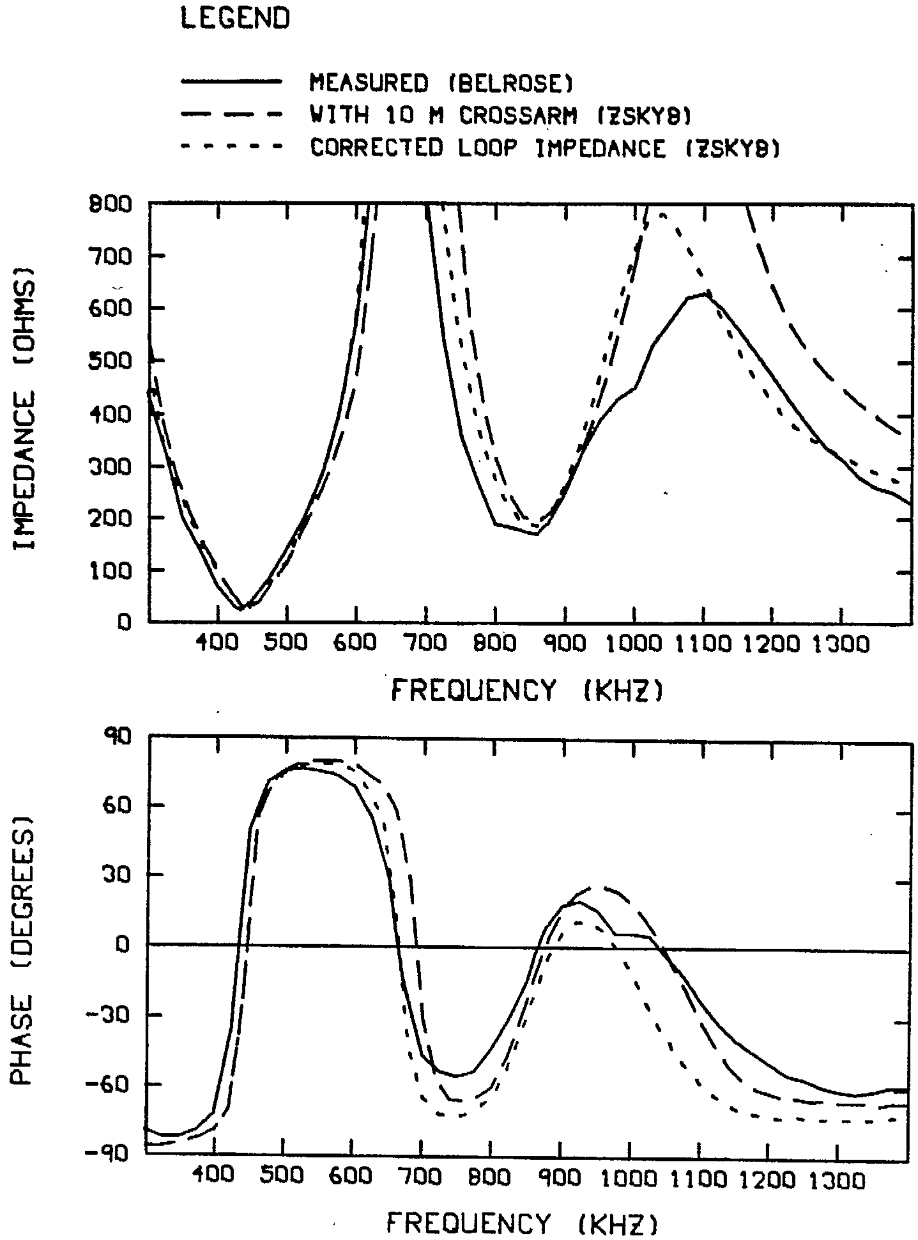
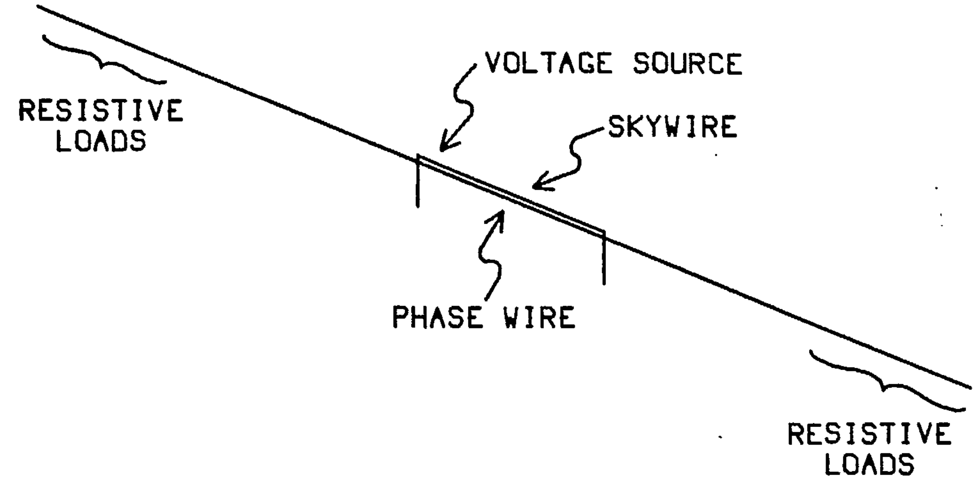


Figure 2.14 The loop impedance with a crossarm "corrected" with a capacitance in parallel with the generator.



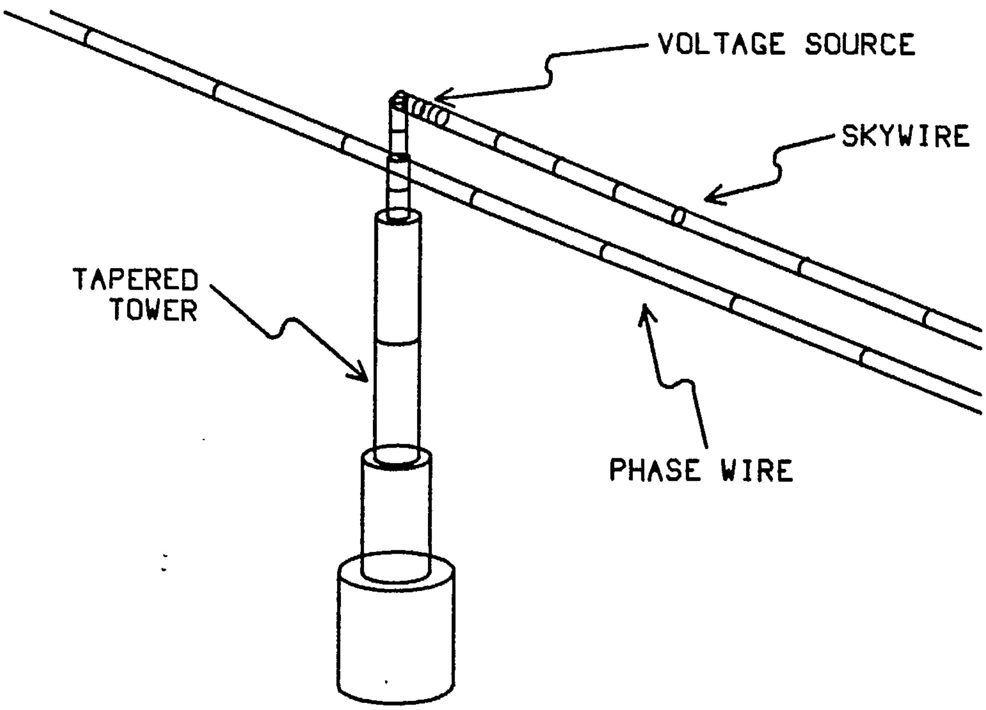


Figure 2.15 Computer model of a one span "power line", including a "long" phase wire terminated with distributed resistance.

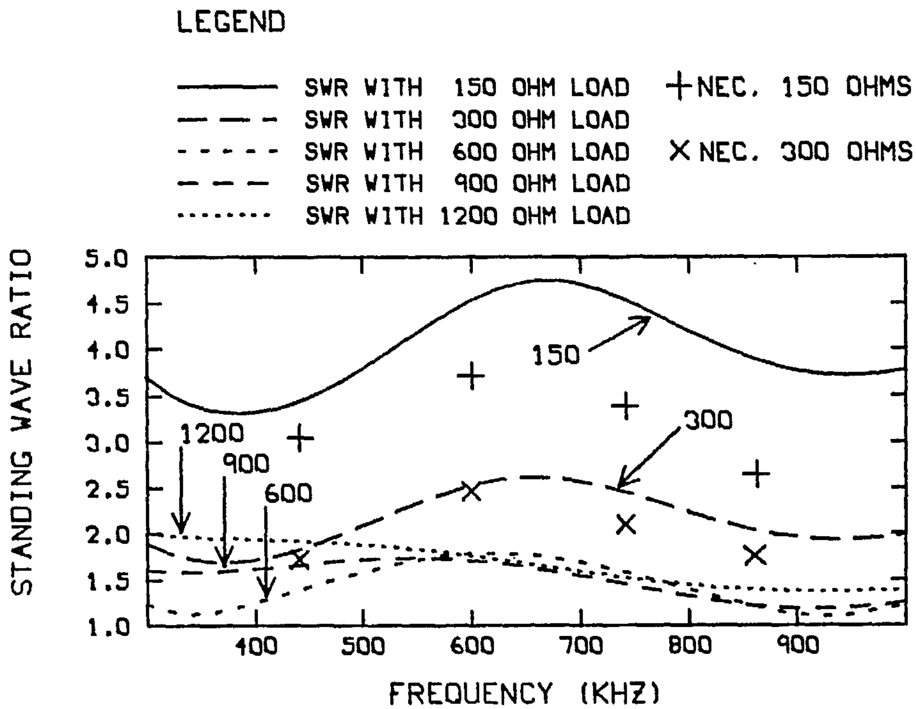


Figure 2.16. The SWR derived from the input impedance of an open-circuited, 274 m transmission line, with resistive loading distributed along its length.

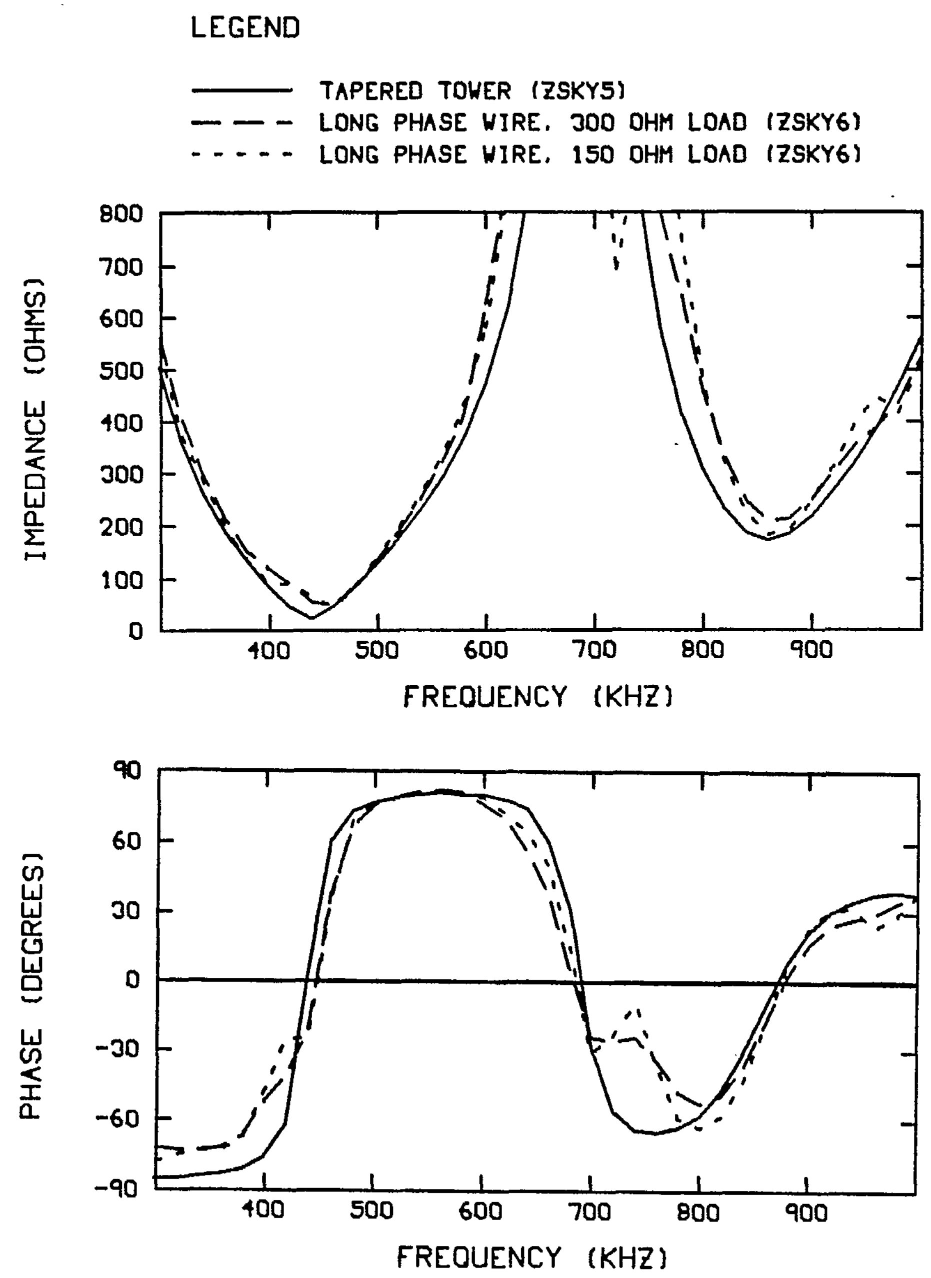


Figure 2.17 The loop impedance in the presence of the long, resistively loaded phase wire.

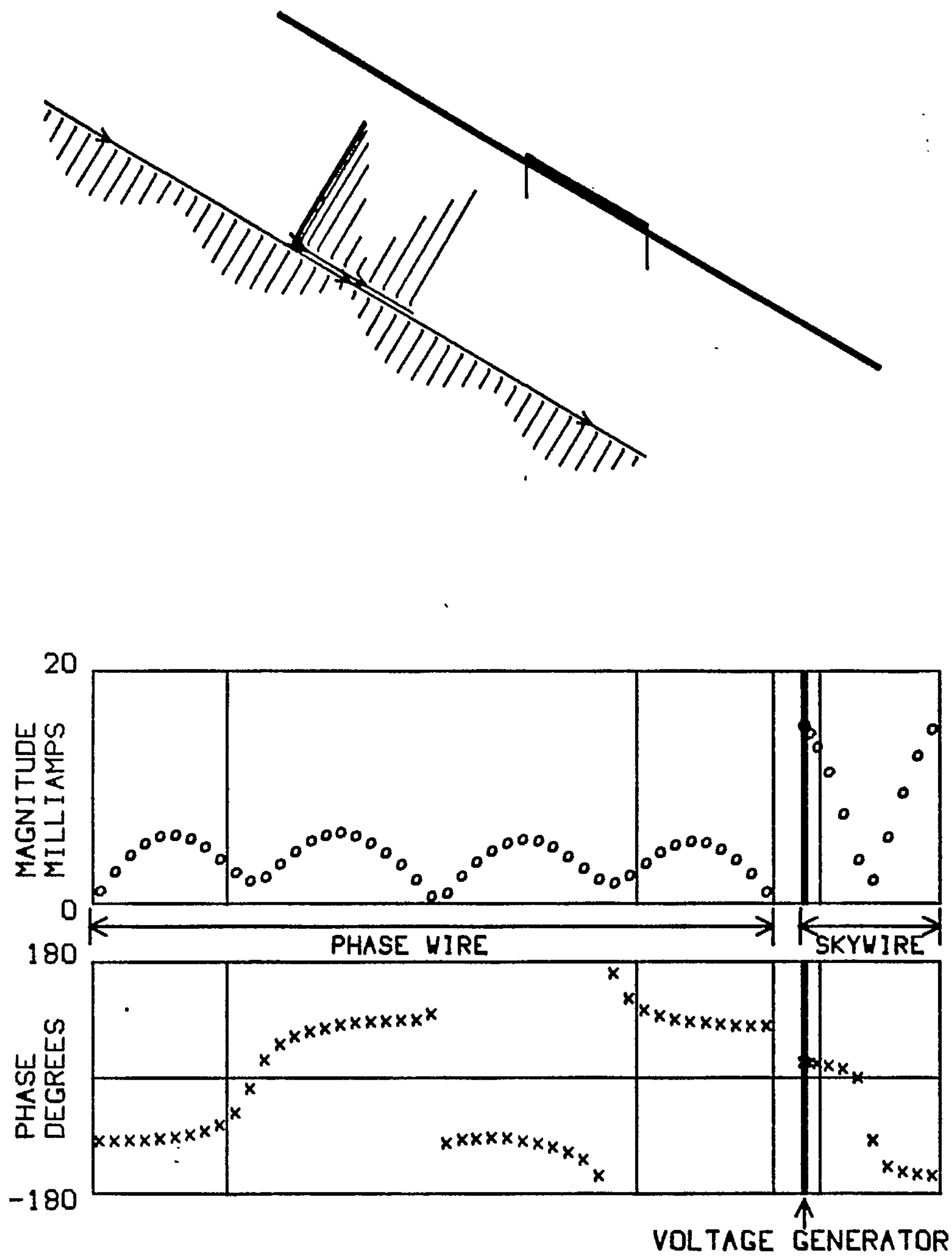
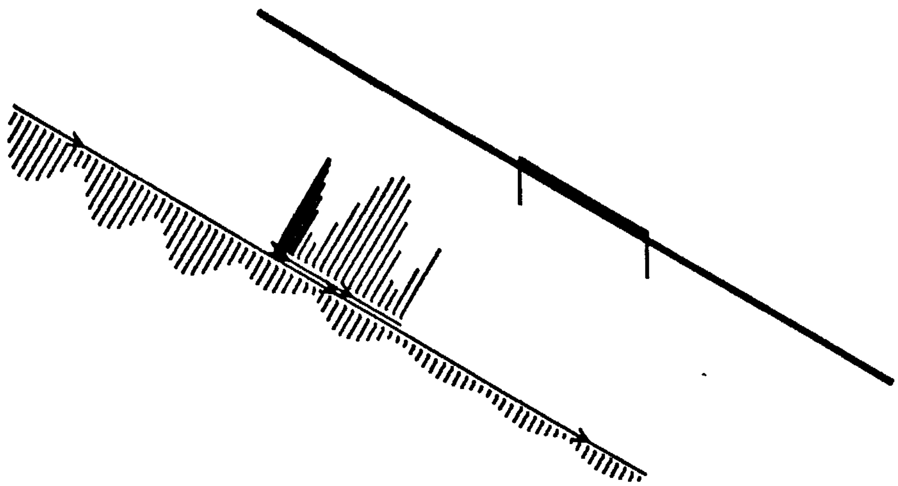


Figure 2.18 The RF current distribution at 440 kHz, with a 150 ohm distributed load.



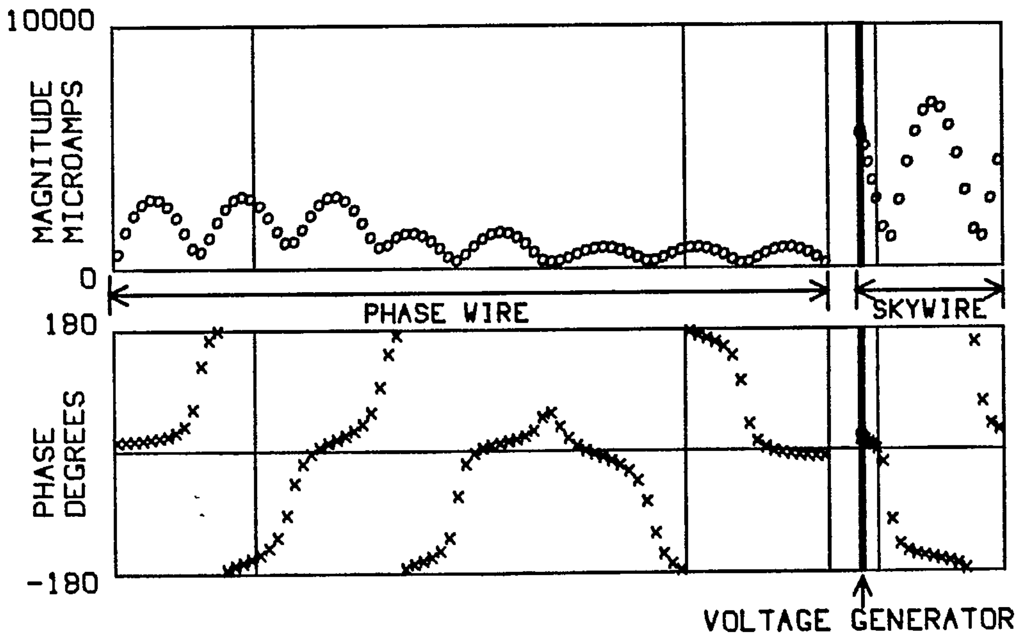


Figure 2.19 The RF current distribution at 860 kHz, with a 150 ohm distributed load.

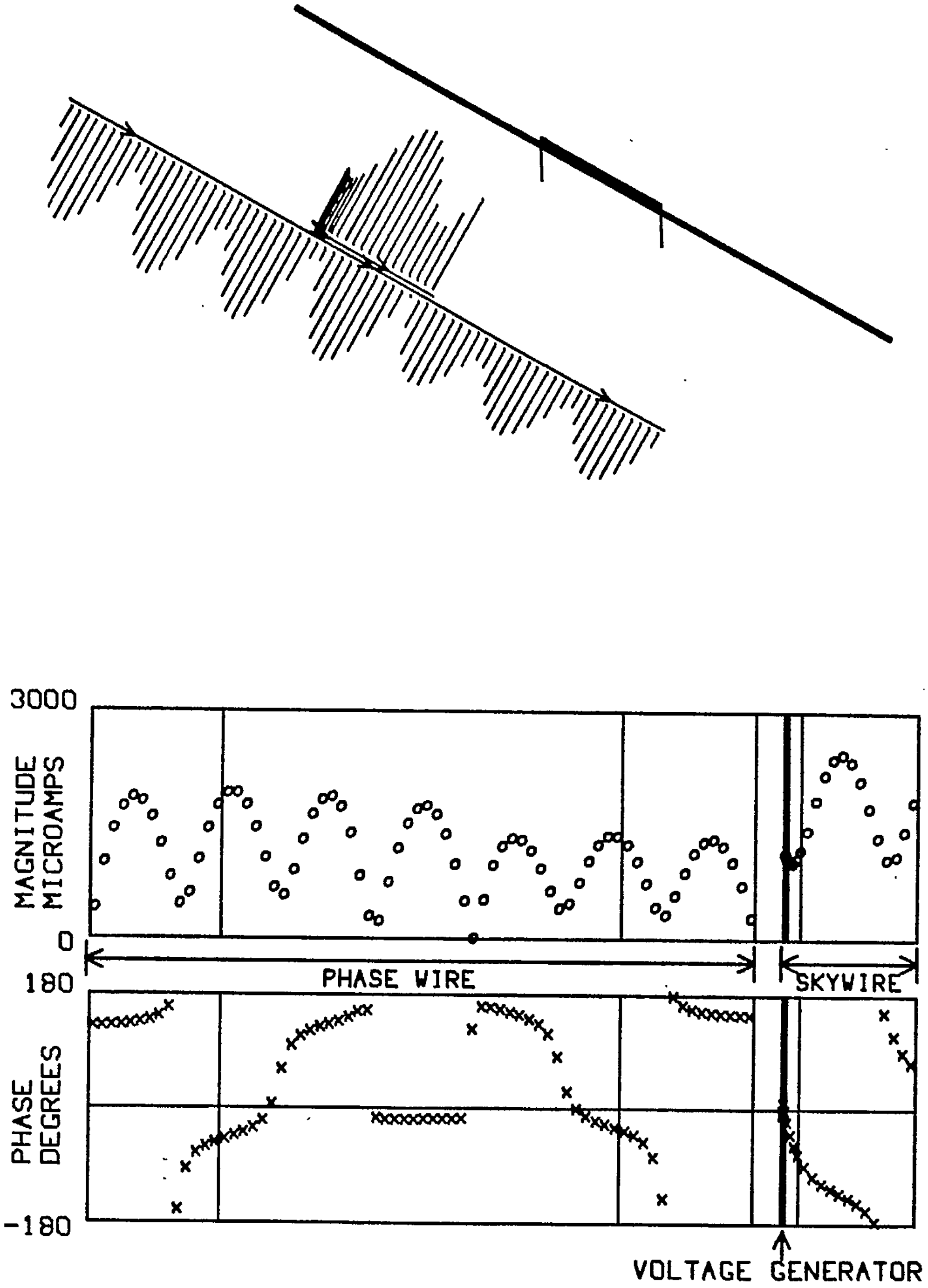
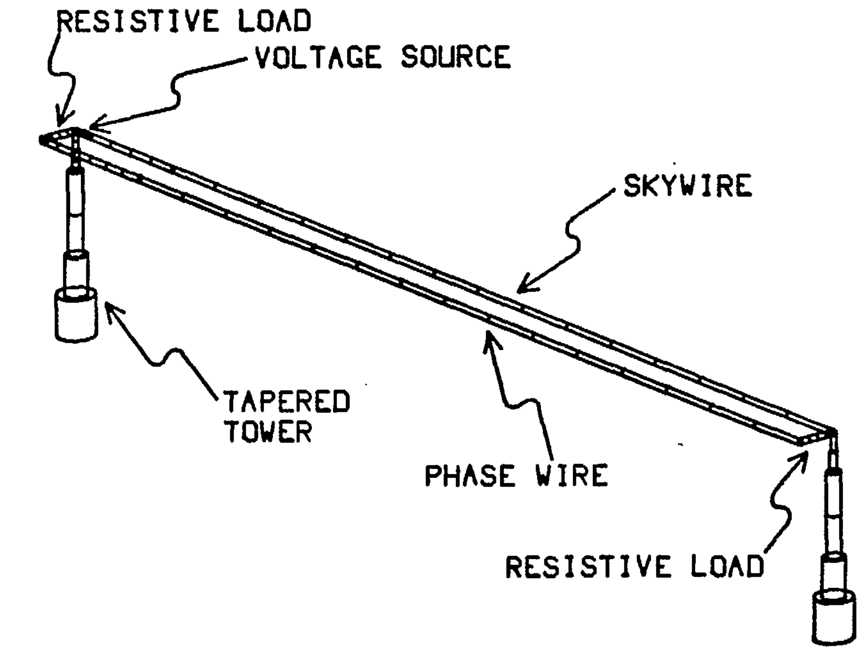


Figure 2.20 The RF current distribution at 740 kHz, with a 150 ohm distributed load.



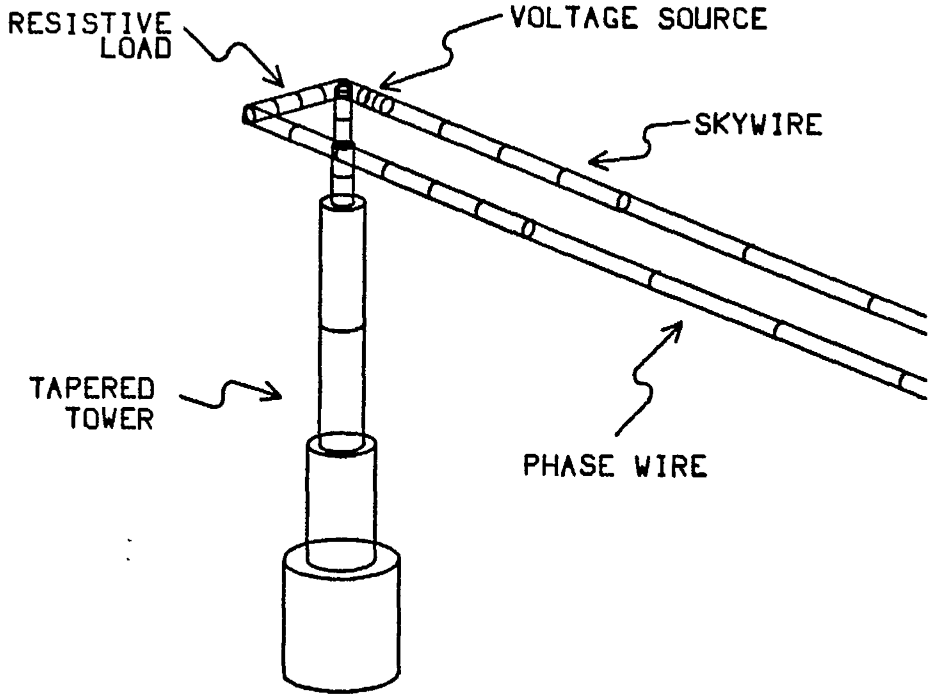


Figure 2.21 Computed model using a phase wire terminated to the tower through a series resistor.

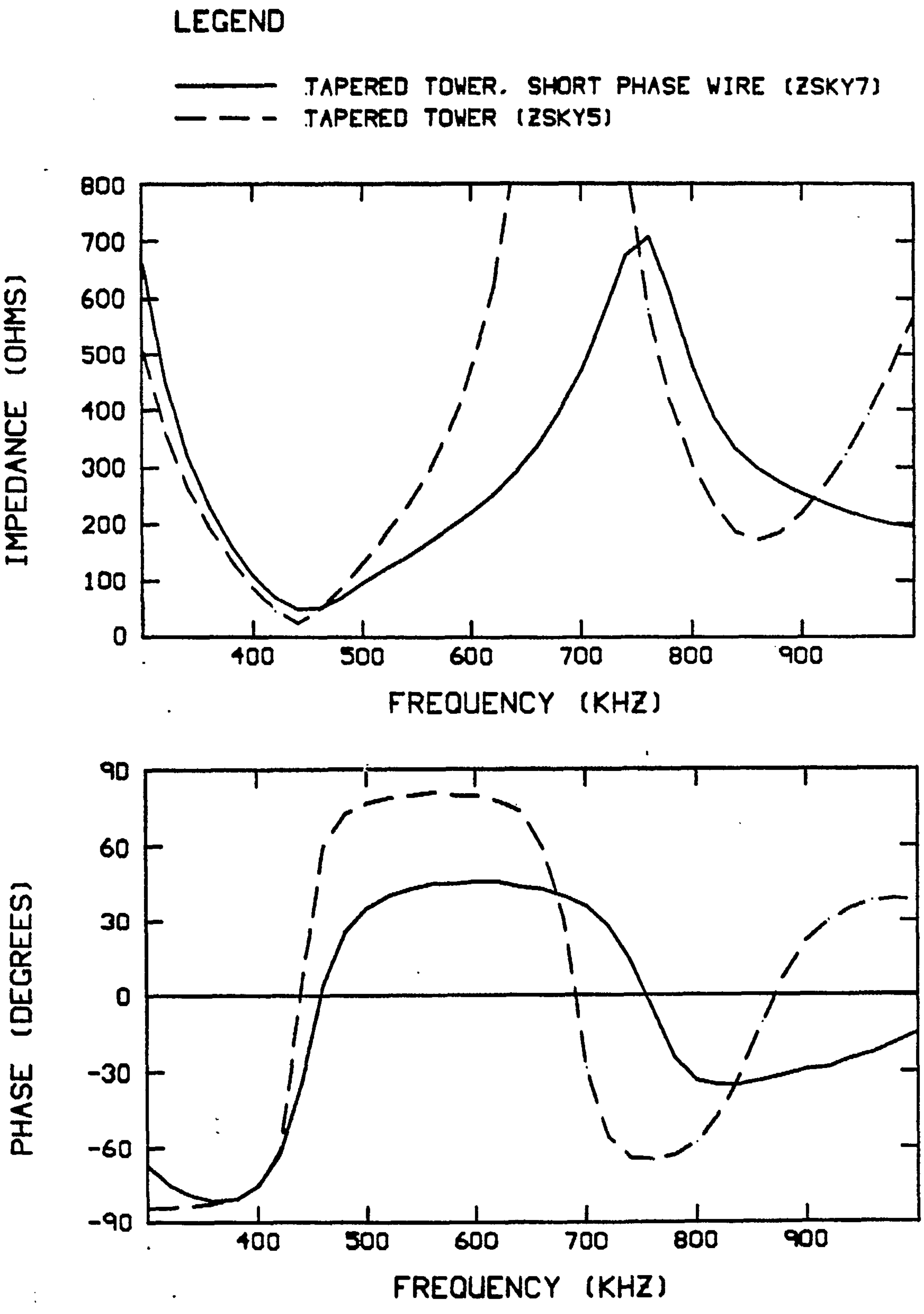


Figure 2.22 The loop impedance with a phase wire terminated to the tower, compared to the case of no phase wire.

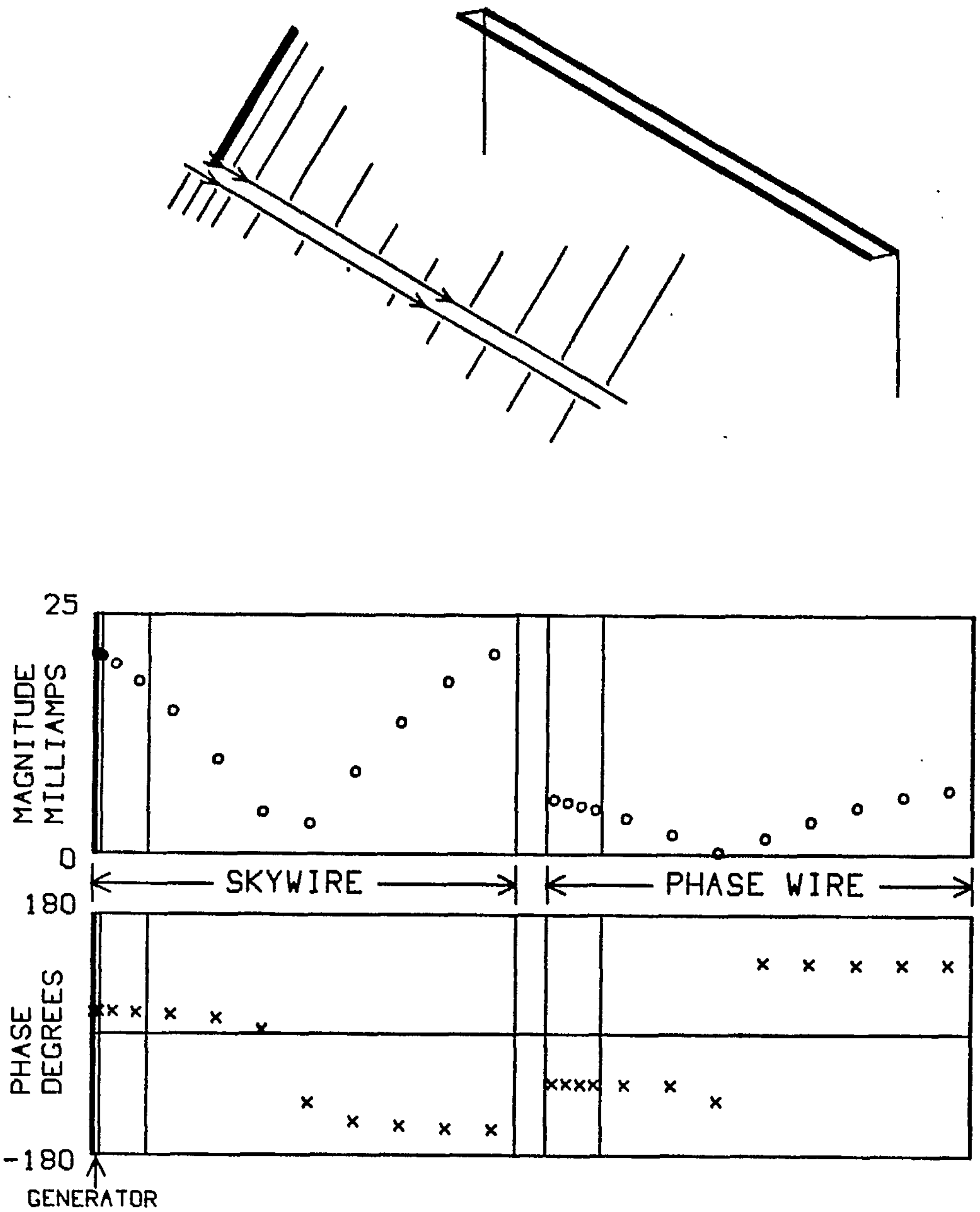
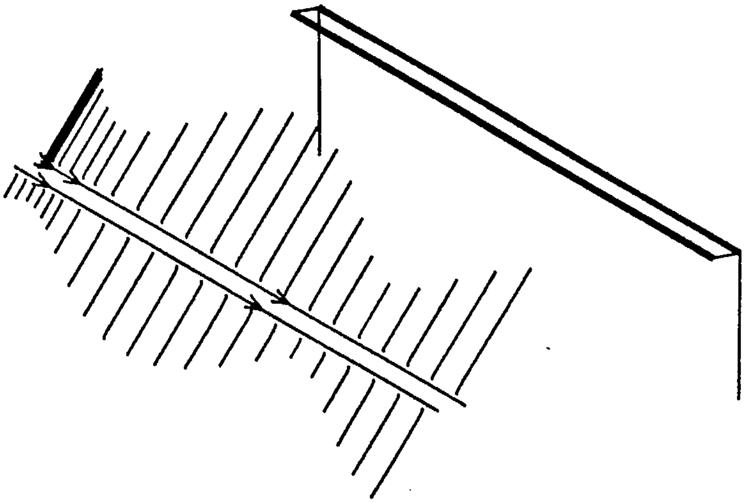


Figure 2.23 The RF current distribution on the skywire and the phase wire at 440 kHz.



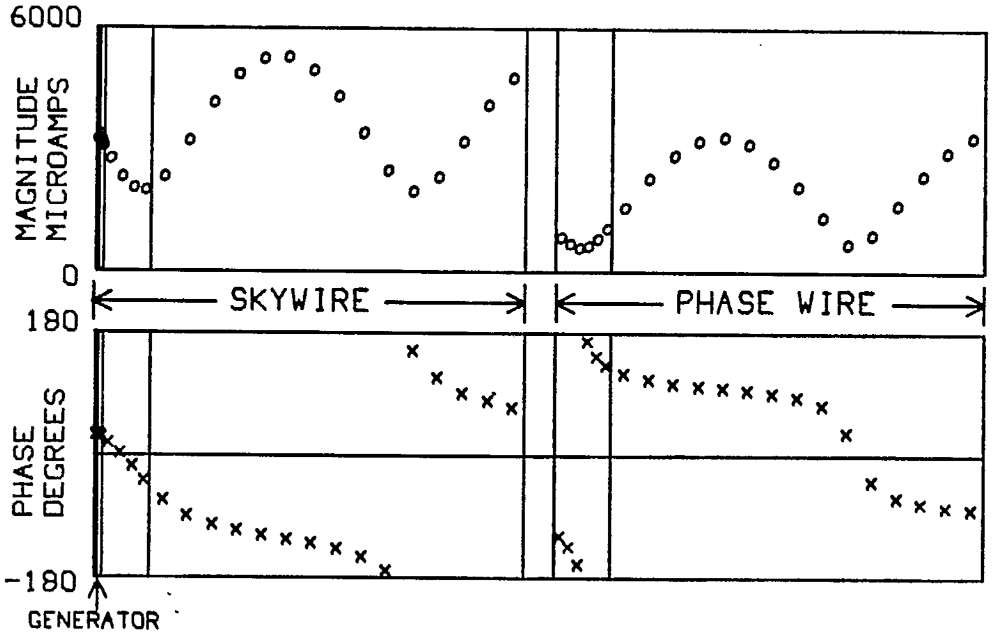


Figure 2.24 The RF current distribution on the skywire and phase wire at 860 kHz.

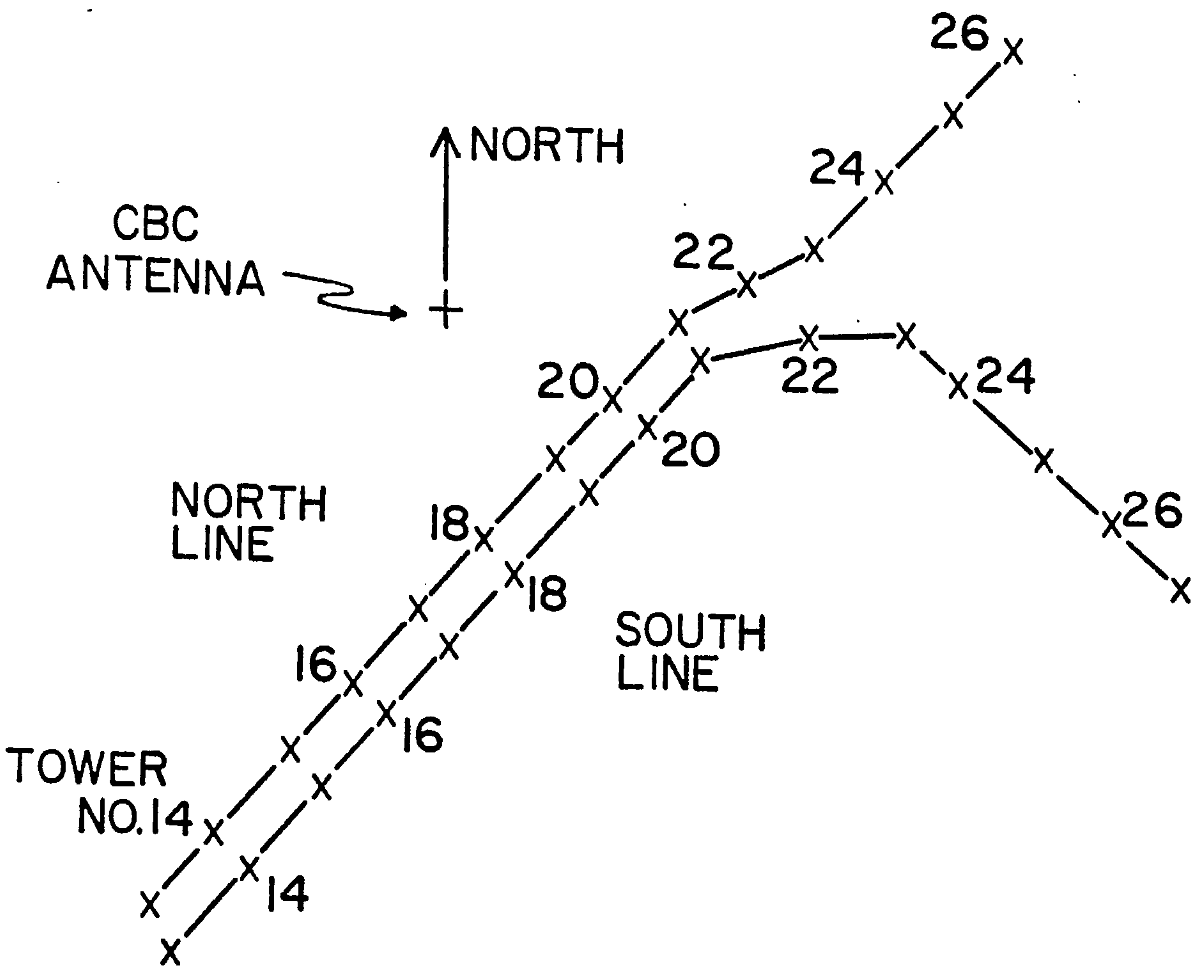


Figure 3.1 Plan of the site at Hornby, Ontario.

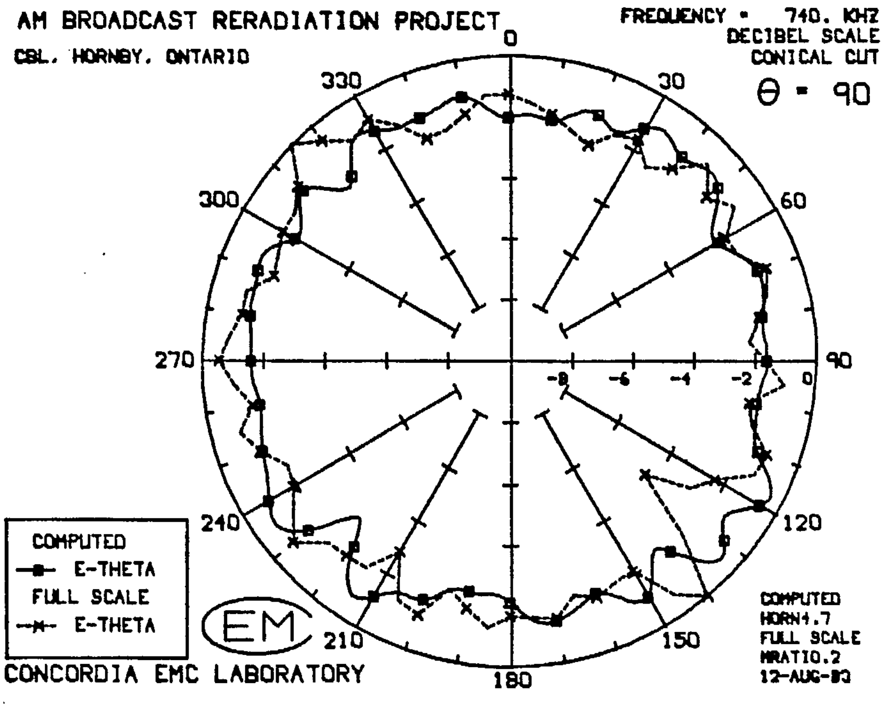


Figure 3.2(a) Comparison of the computer model's ratio pattern with the CBC's full scale measured ratio pattern, for CBL at 740 kHz.

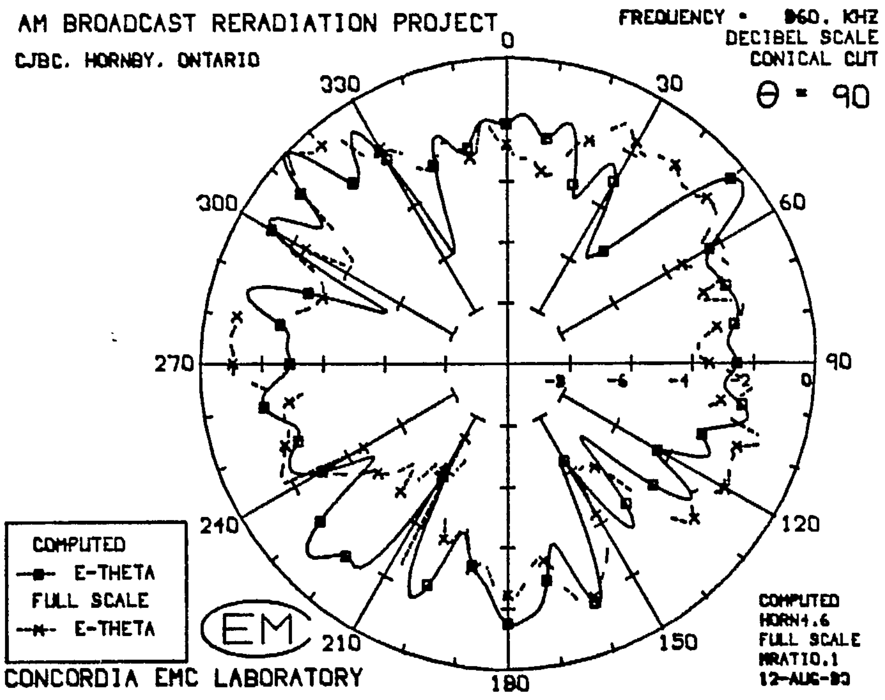


Figure 3.2(b) Comparison of the computer model's ratio pattern with the CBC's full scale measured ratio pattern, for CJBC at 860 kHz.

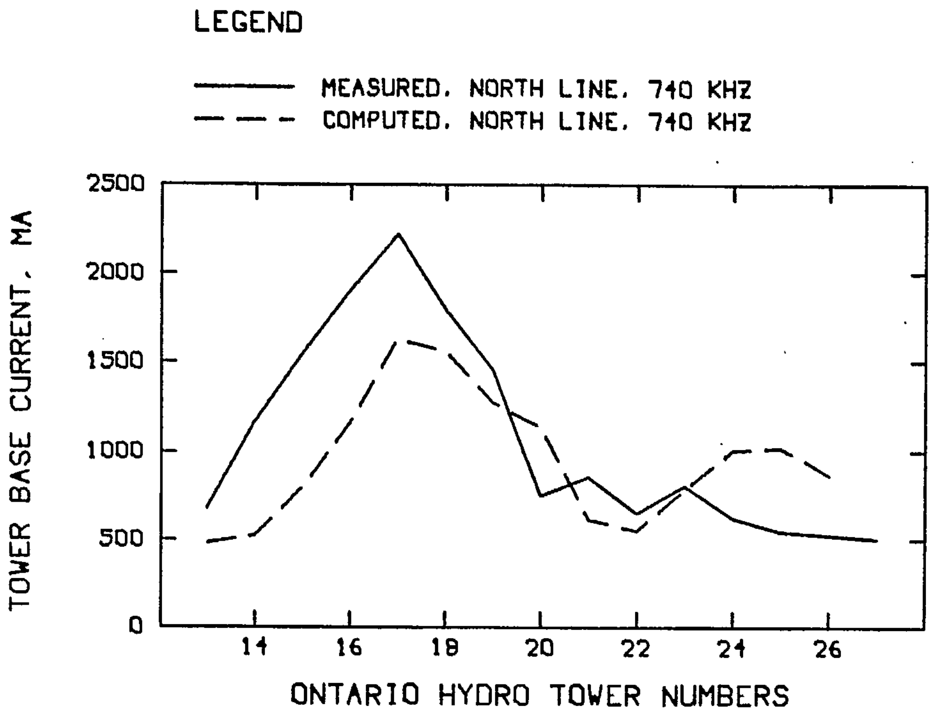


Figure 3.3(a) Ontario Hydro's measured tower base currents for the Hornby site, in comparison with computed tower base currents - North line at 740 kHz.

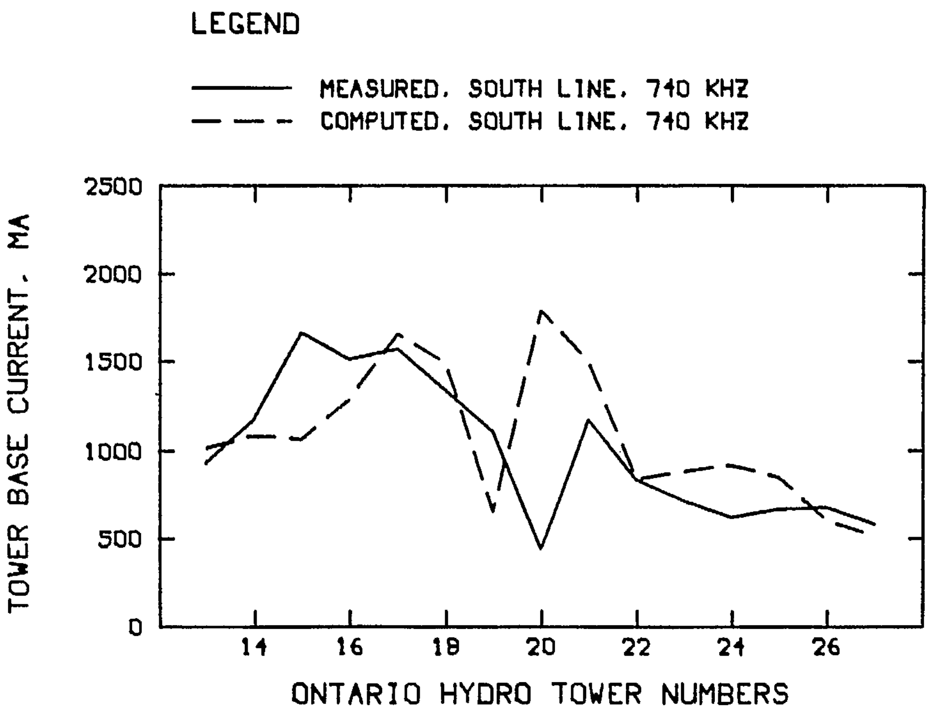


Figure 3.3(b) Ontario Hydro's measured tower base currents for the Hornby site, in comparison with computed tower base currents - South line at 740 kHz.

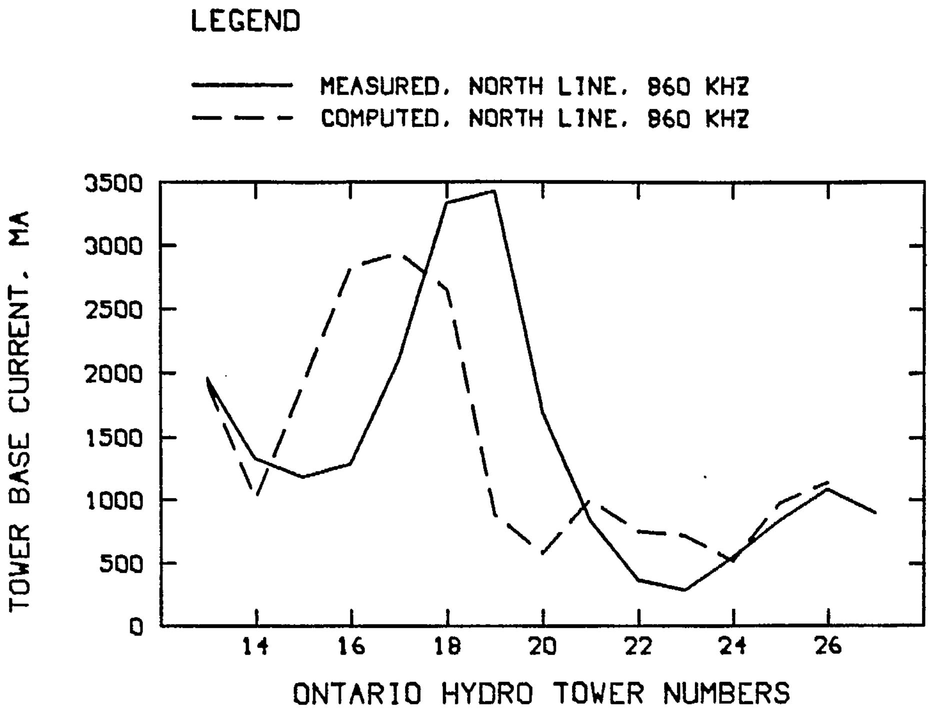


Figure 3.3(c) Ontario Hydro's measured tower base currents for the Hornby site, in comparison with computed tower base currents - North line at 860 kHz.

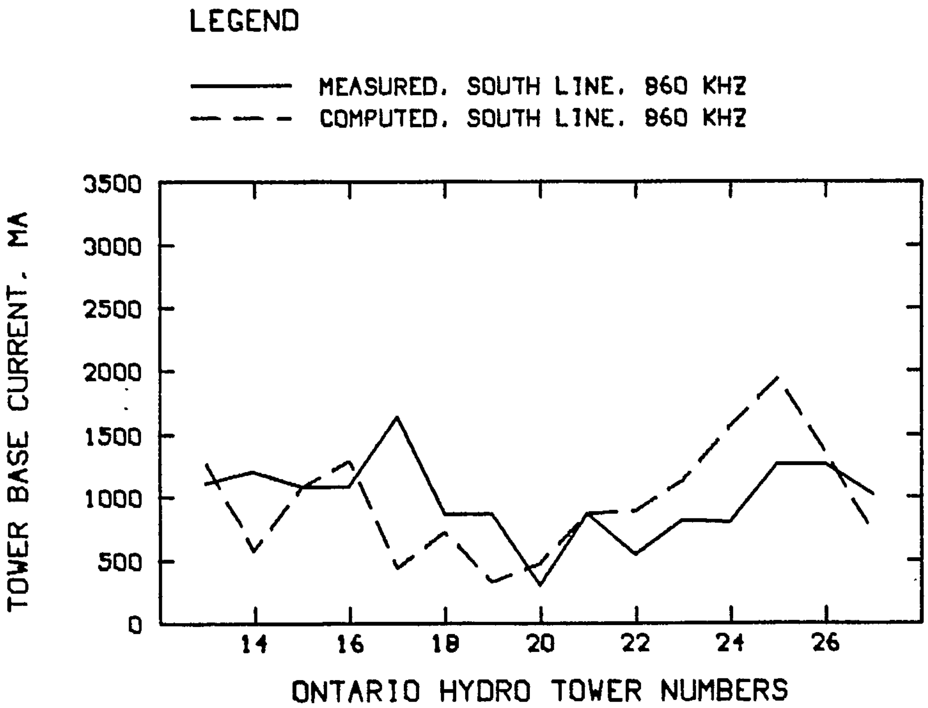


Figure 3.3(d) Ontario Hydro's measured tower base currents for the Hornby site, in comparison with computed tower base currents - South line at 860 kHz.

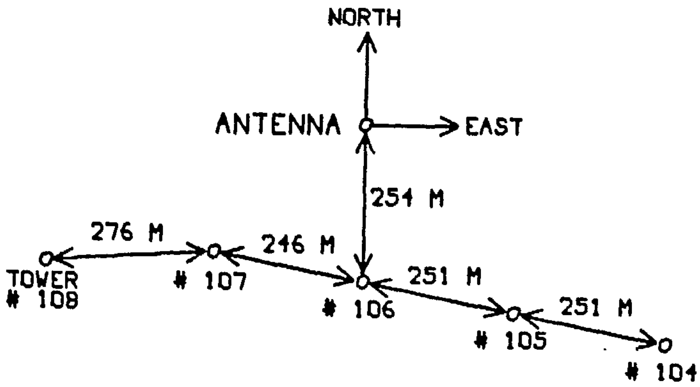


Figure 3.4 Plan of the five tower site at Thornhill, Ontario.

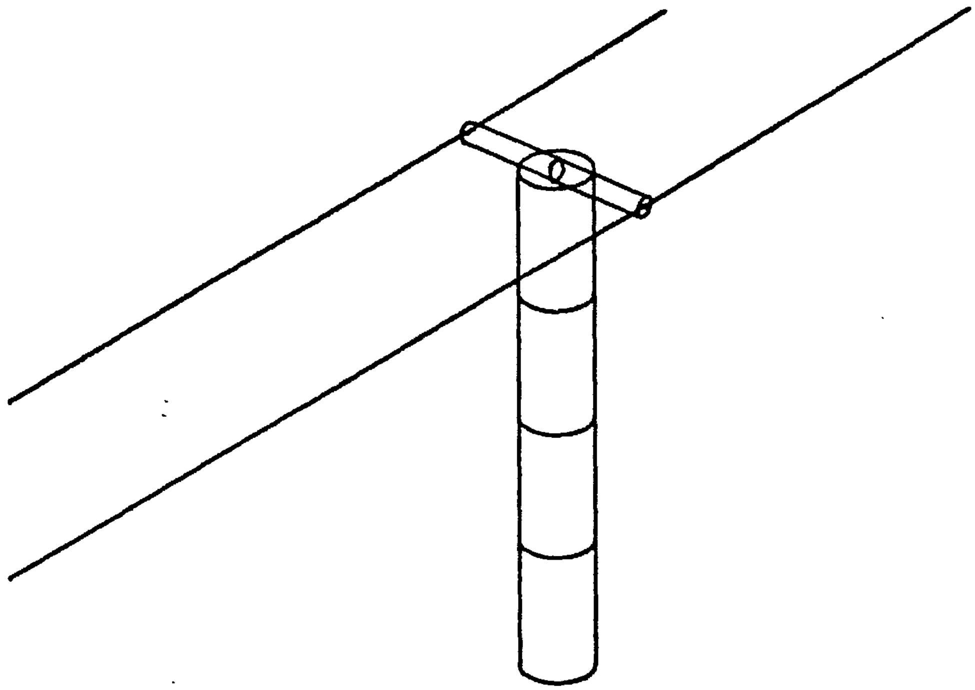


Figure 3.5 Tower representation used in the computer model of the Thornhill site.

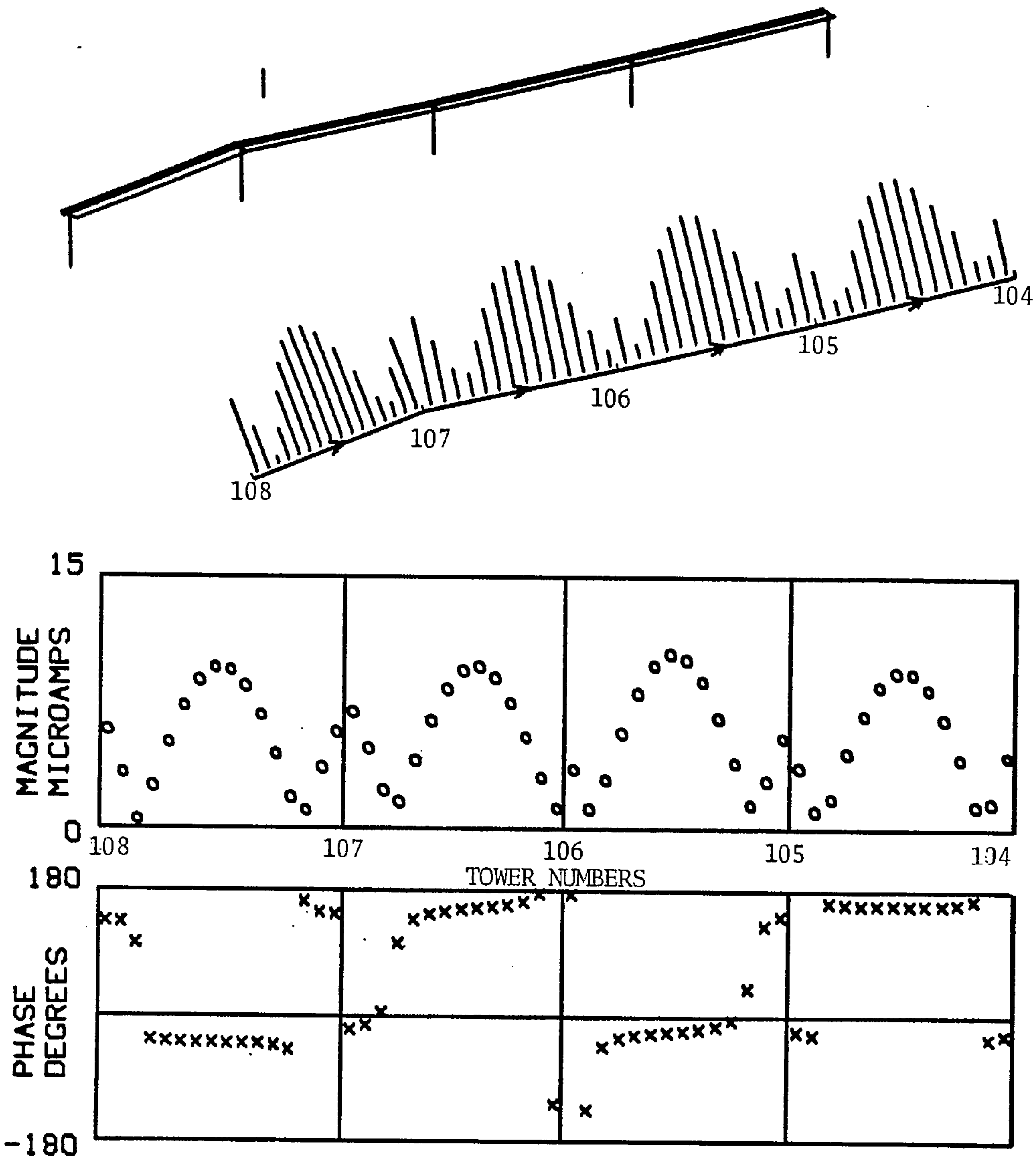


Figure 3.6(a) Current distribution at 825 kHz above perfect ground on North skywires.

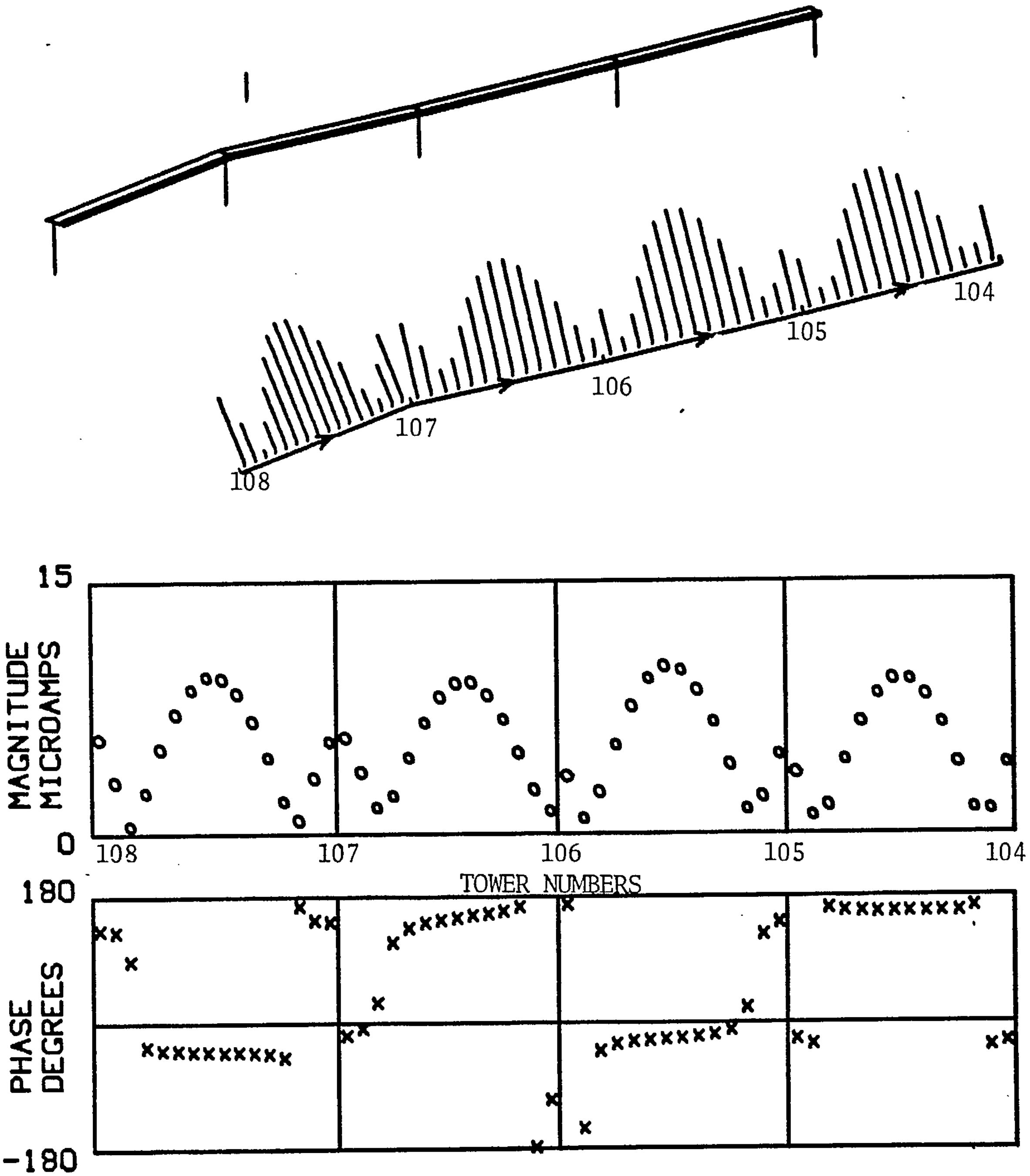


Figure 3.6(b) Current distribution at 825 kHz above perfect ground on South skywires.

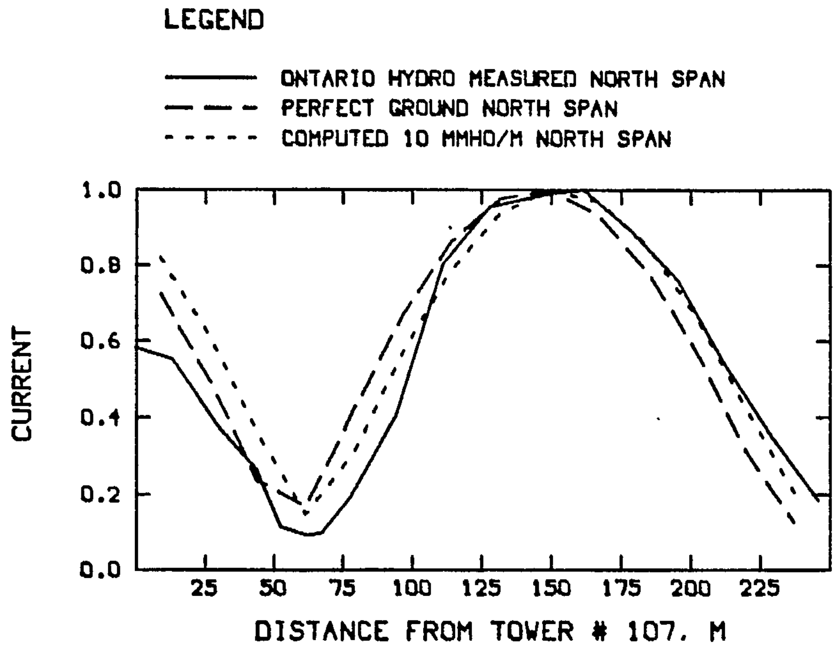


Figure 3.7(a) Comparison of Ontario Hydro's measured skywire current distribution at 825 kHz using perfect ground and ground conductivity 10 mmho/m - span 107 to 106, north wire.

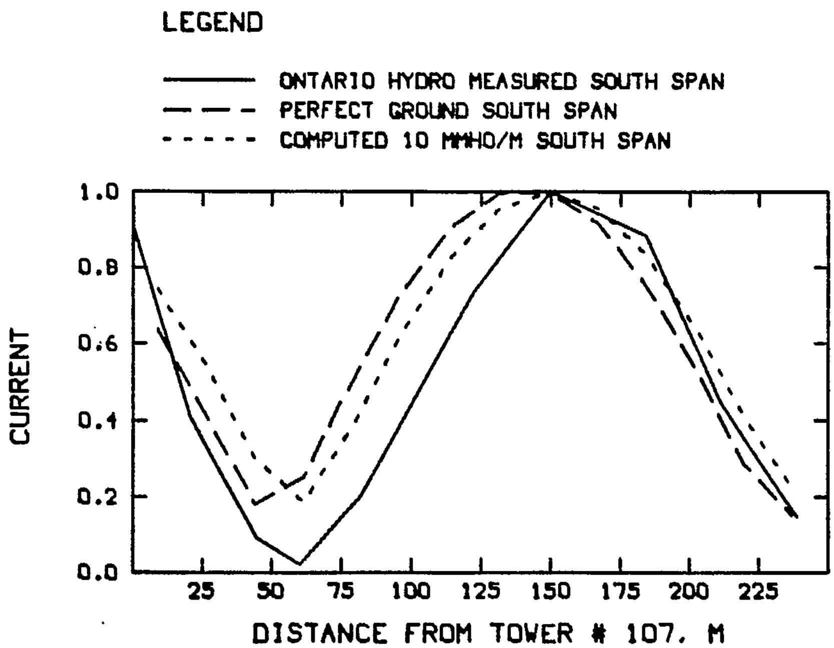


Figure 3.7(b) Comparison of Ontario Hydro's measured skywire current distribution at 825 kHz using perfect ground and ground conductivity 10 mmho/m - span 107 to 106, south wire.

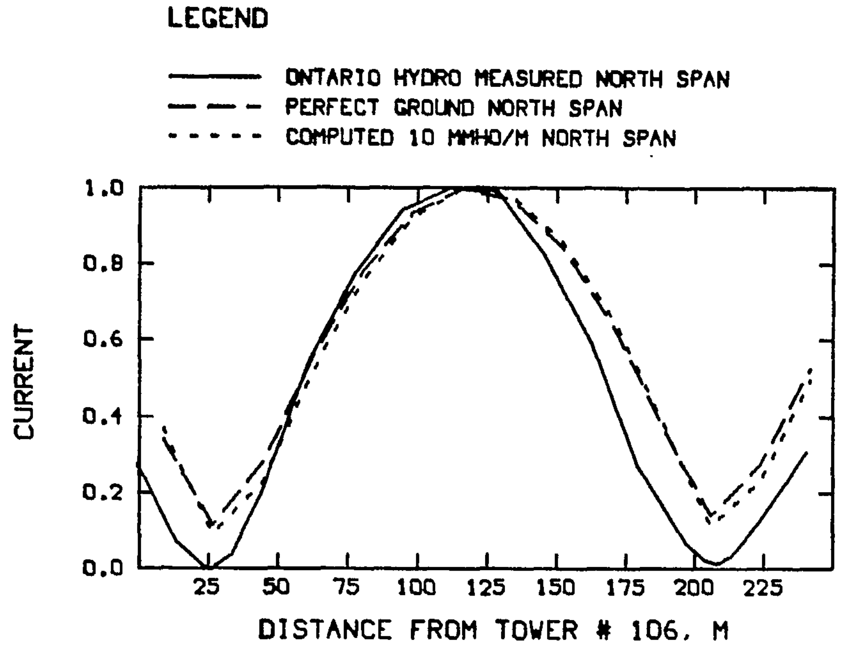


Figure 3.7(c) Comparison of Ontario Hydro's measured skywire current distribution at 825 kHz using perfect ground and ground conductivity 10 mmho/m - span 106 to 105, north wire.

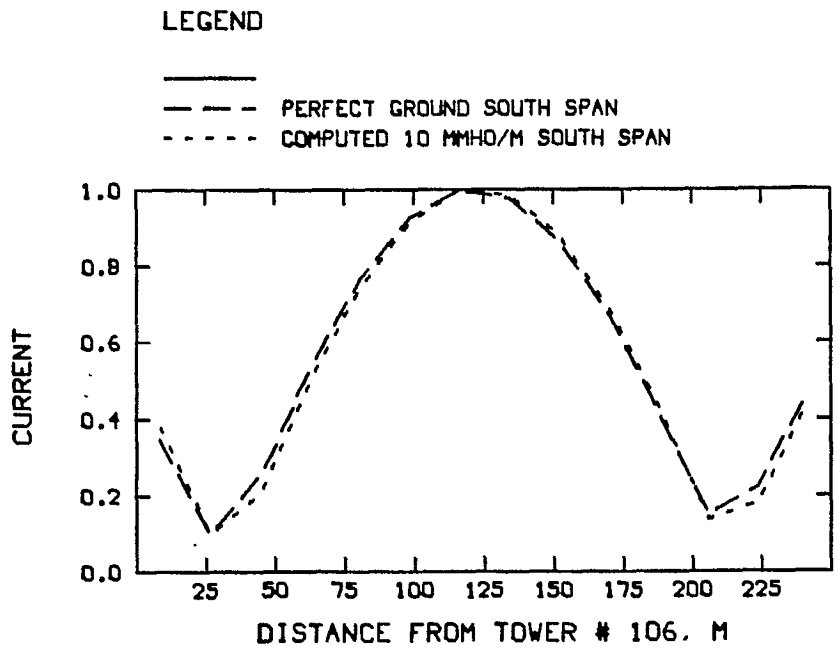


Figure 3.7(d) Comparison of Ontario Hydro's measured skywire current distribution at 825 kHz using perfect ground and ground conductivity 10 mmho/m - span 106 to 105, south wire.

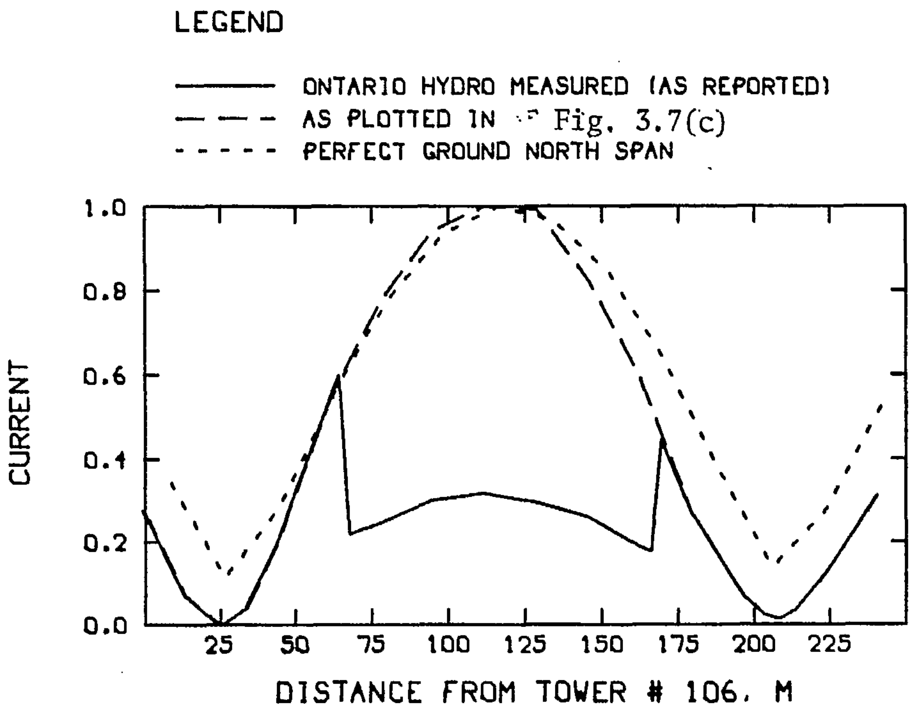


Figure 3.8 The measured RF current distribution which was plotted in Fig. 3.7 (c) was reported as the discontinuous curve, shown here.

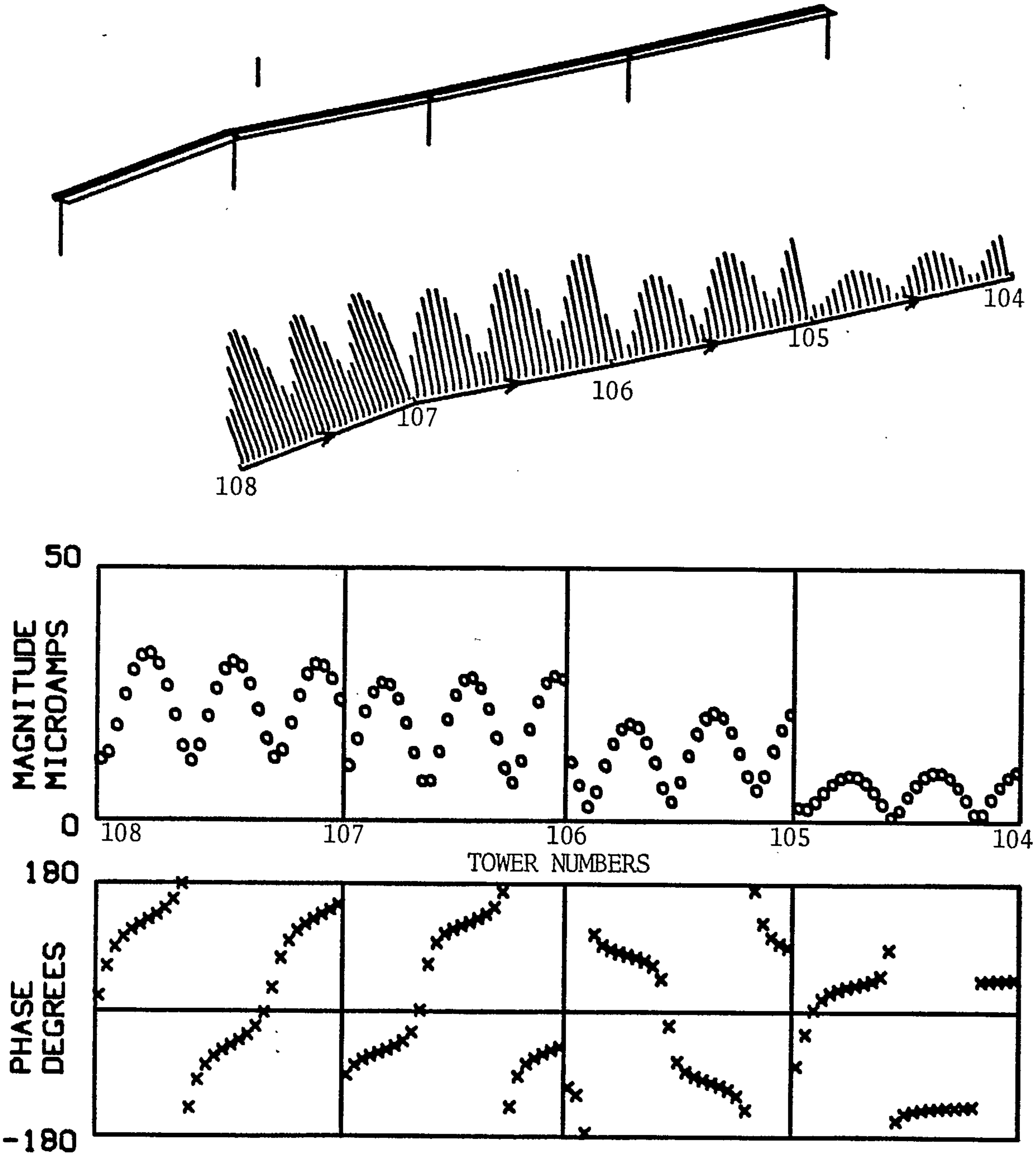


Figure 3.9(a) Current distribution at 1605 kHz above perfect ground on north skywires.

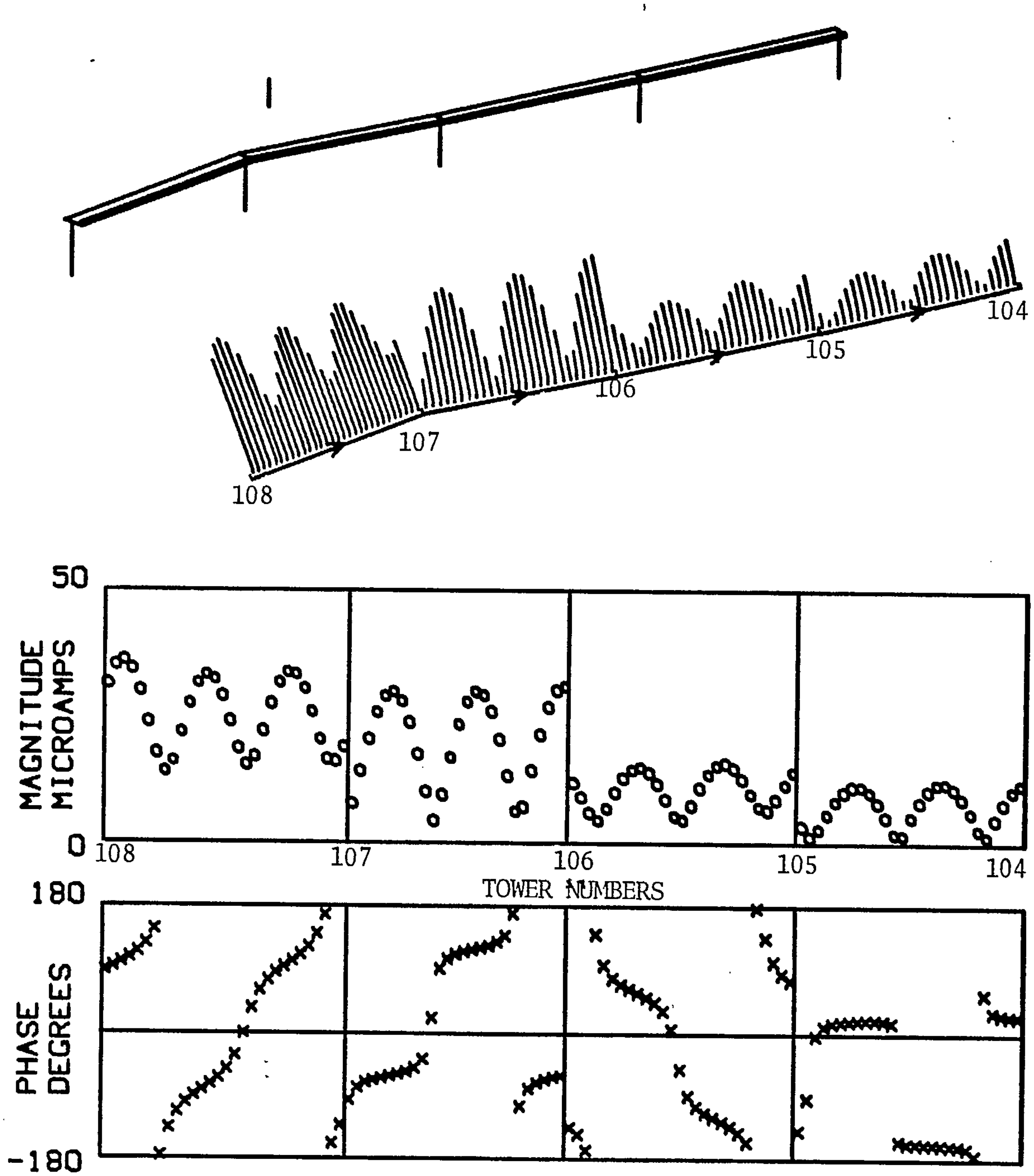


Figure 3.9(b) Current distribution at 1605 kHz above perfect ground on south skywires.

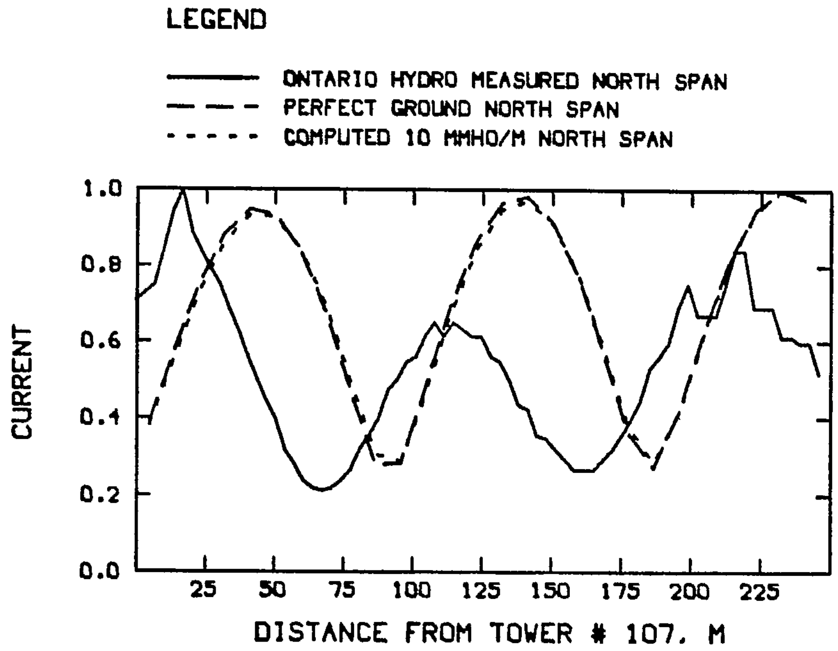


Figure 3.10(a) Comparison of Ontario Hydro's measured skywire current distribution at 1605 kHz using perfect ground and ground conductivity 10 mmho/m - span 107 to 106, north wire.

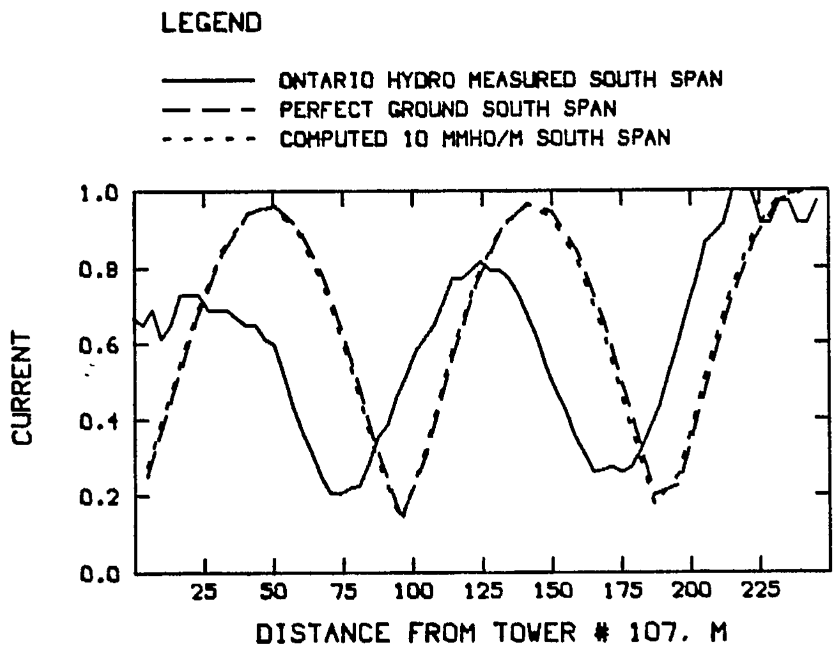


Figure 3.10(b) Comparison of Ontario Hydro's measured skywire current distribution at 1605 kHz using perfect ground and ground conductivity 10 mmho/m - span 107 to 106, south wire.

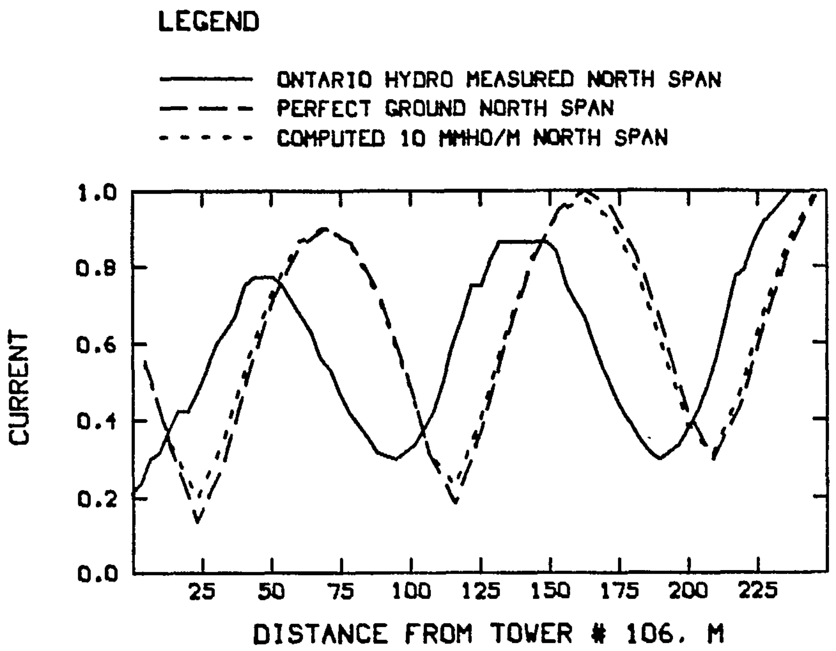


Figure 3.10(c) Comparison of Ontario Hydro's measured skywire current distribution at 1605 kHz using perfrect ground and ground conductivity 10 mmho/m - span 106 to 105, north wire.

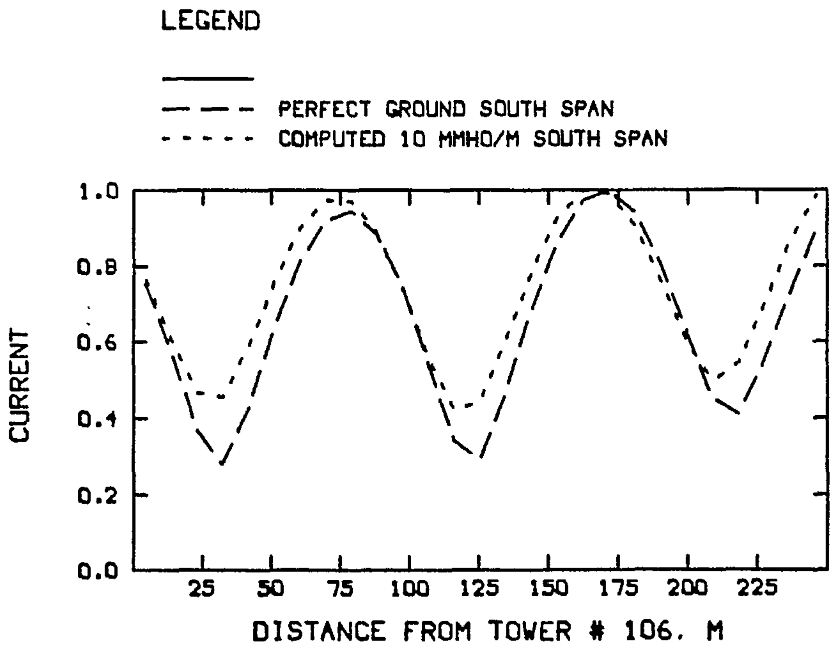


Figure 3.10(d) Comparison of Ontario Hydro's measured skywire current distribution at 1605 kHz using perfect ground and ground conductivity 10 mmho/m - span 106 to 107, south wire.

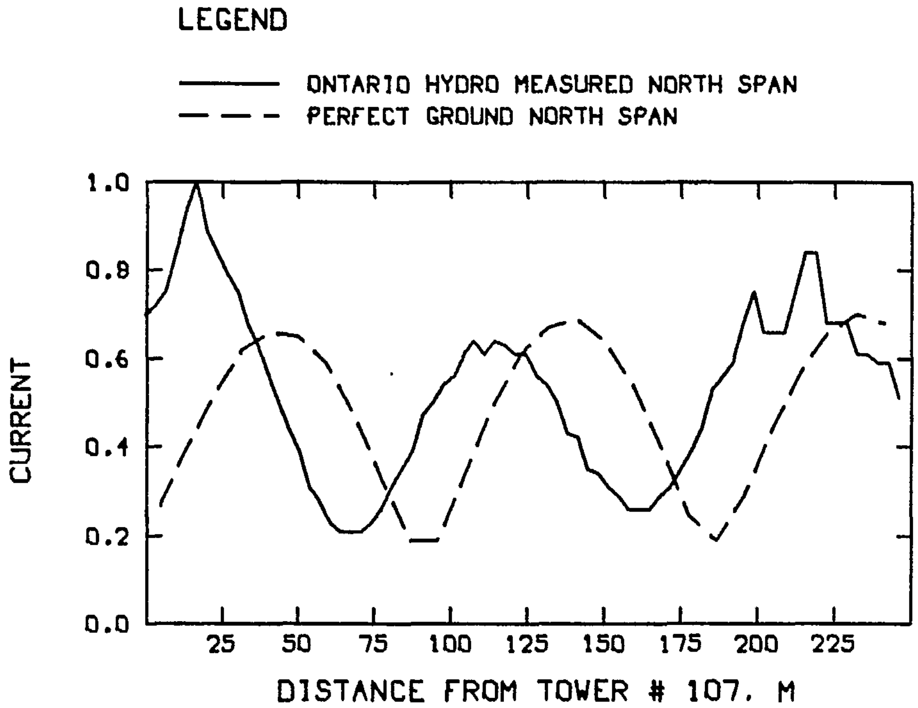


Figure 3.11(a) Comparison of the measured and computed RF current distribution at 1605 kHz, normalized with the same scale factor in all parts of the figure. Span 107 to 106, north skywire.

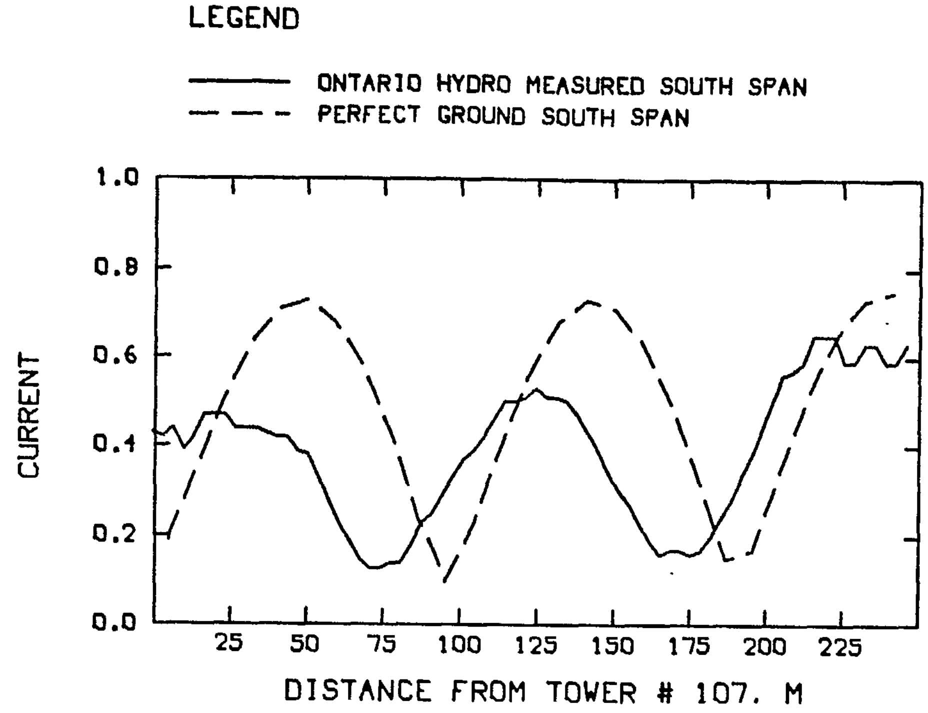


Figure 3.11(b) Span 107 to 106, south skywire.

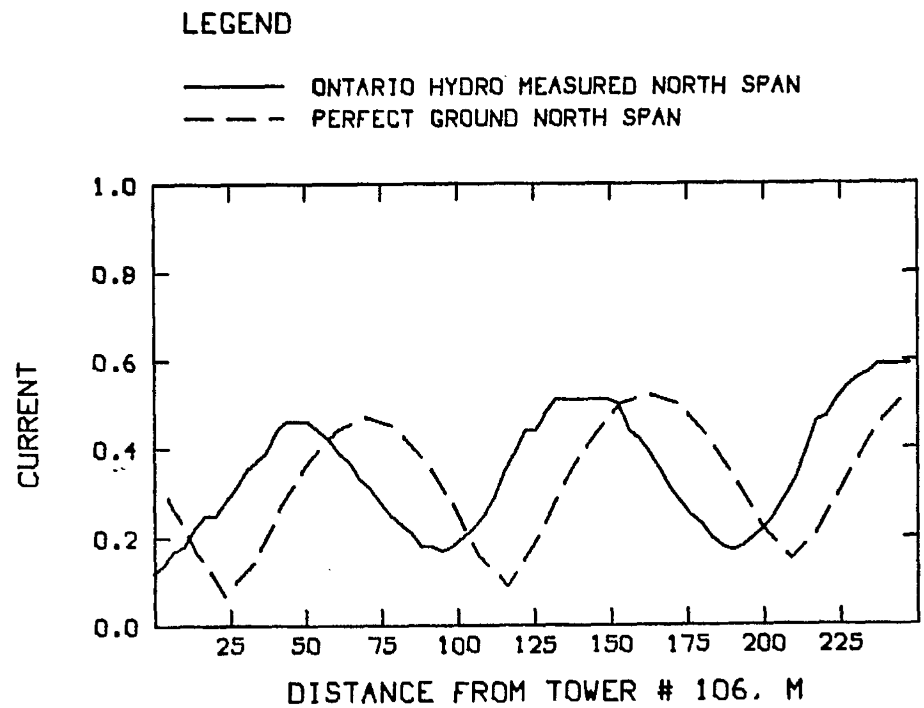


Figure 3.11(c) Span 106 to 105, north skywire.

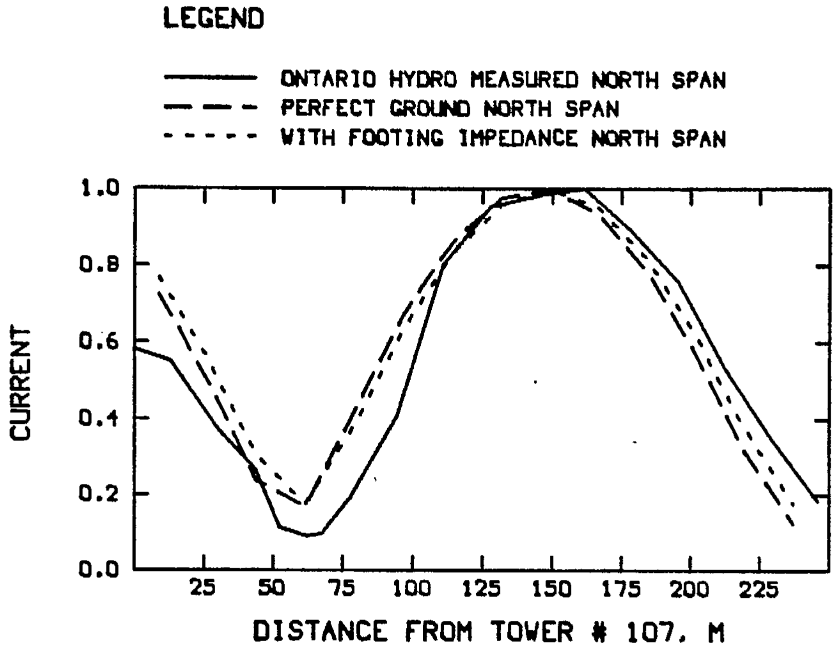


Figure 3.12(a) Comparison of the skywire current computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 825 kHz - span 107 to 106, north wire.

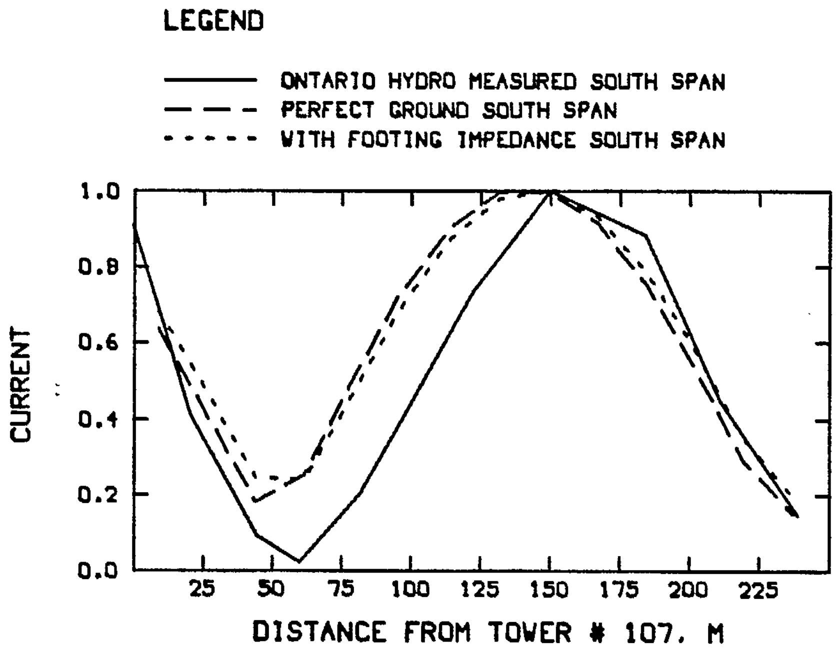


Figure 3.12(b) Comparison of the skywire current computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 825 kHz - span 107 to 106, south wire.

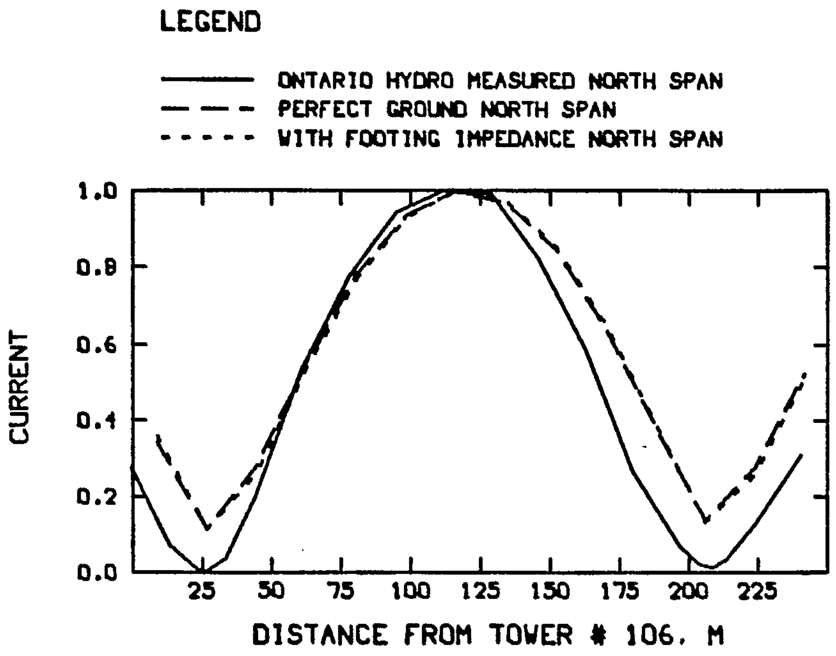


Figure 3.12(c) Comparison of the skywire current computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 825 kHz - span 106 to 105, north wire.

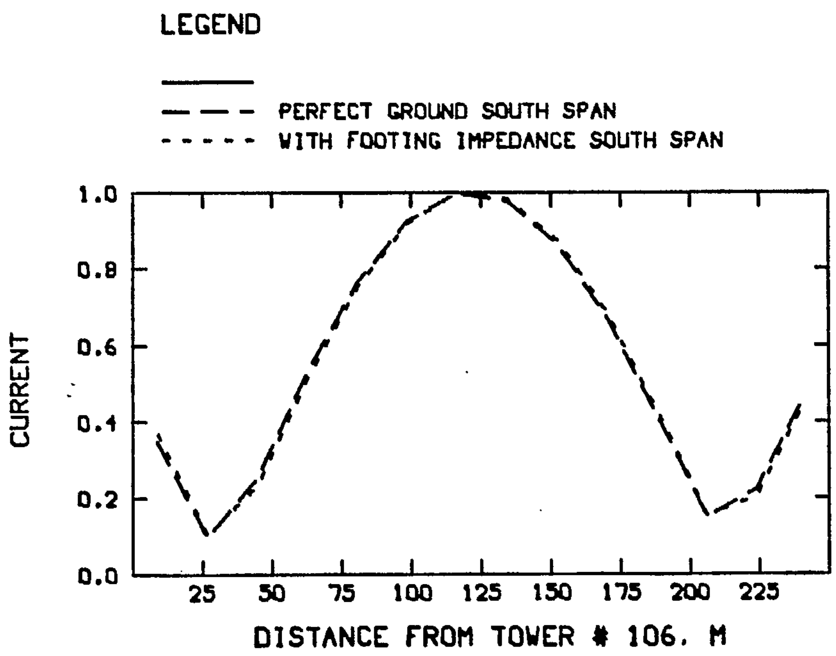


Figure 3.12(d) Comparison of the skywire current computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 825 kHz - span 106 to 105, south wire.

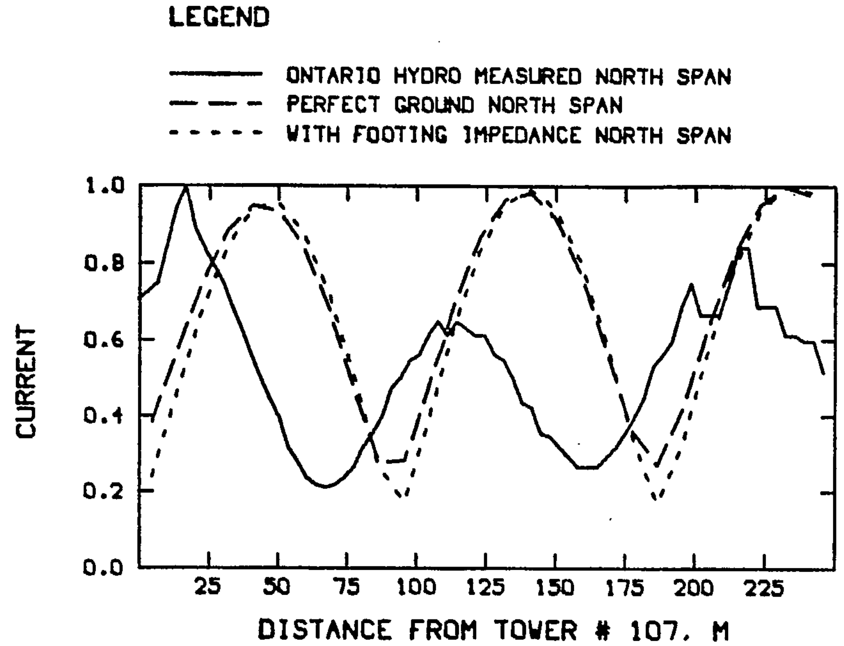


Figure 3.13(a) Comparison of the skywire current distribution computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 1605 kHz - span 107 to 106, north wire.

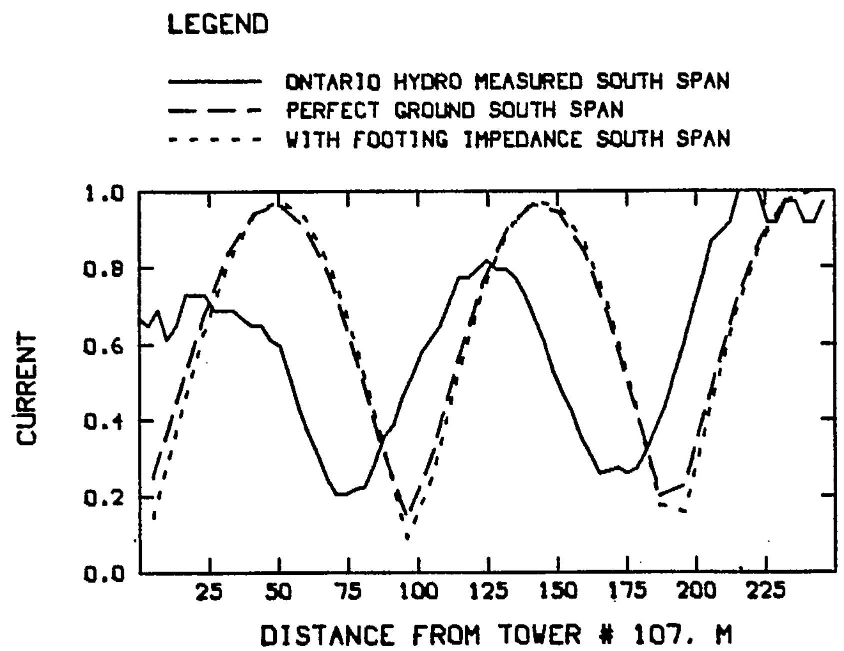


Figure 3.13(b) Comparison of the skywire current distribution computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 1605 kHz - span 107 to 106, south wire.

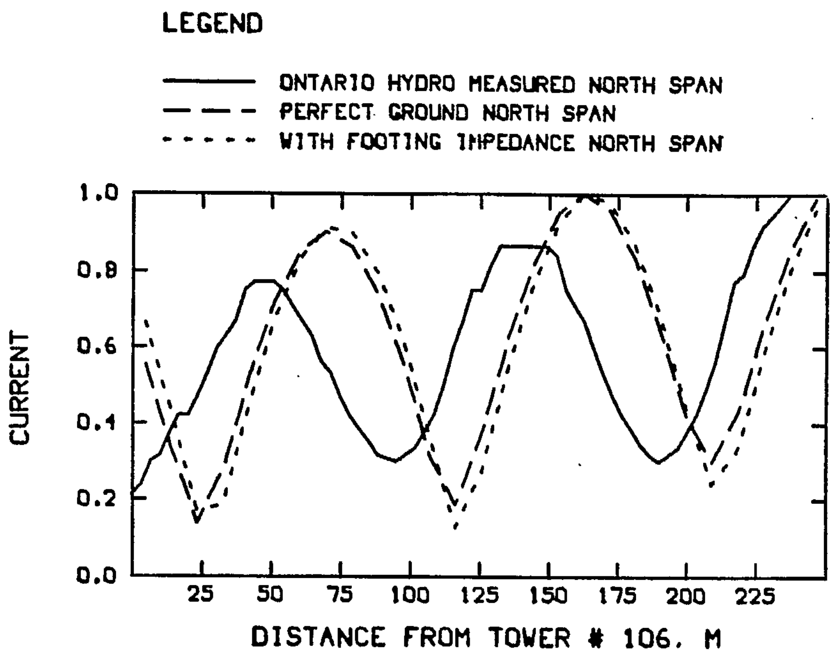


Figure 3.13(c) Comparsion of the skywire current distribution computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 1605 kHz - span 106 to 105, north wire.

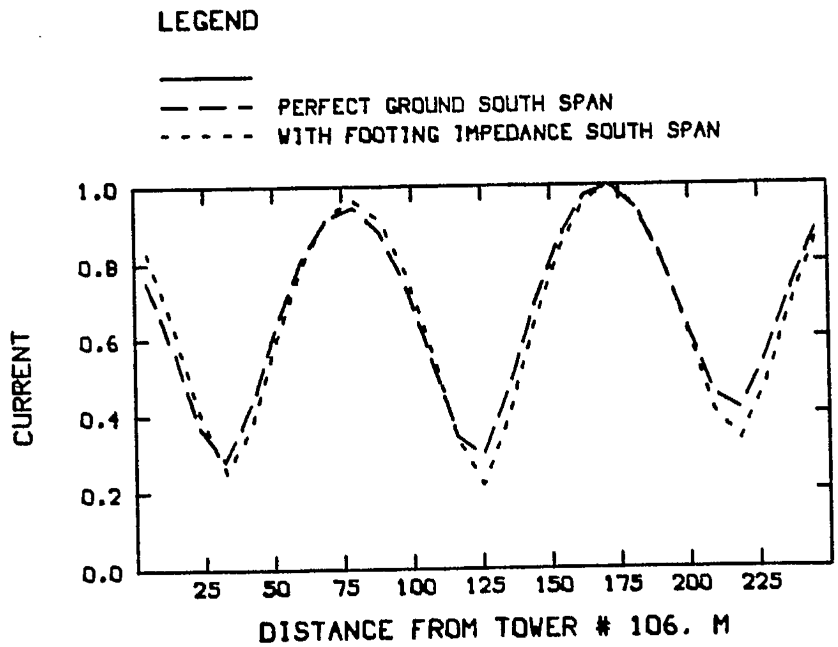


Figure 3.13(d) Comparison of the skywire current distribution computed including the tower footing impedance with that computed over perfect ground, and with Ontario Hydro's measurements, at 1605 kHz - span 106 to 105, south wire.

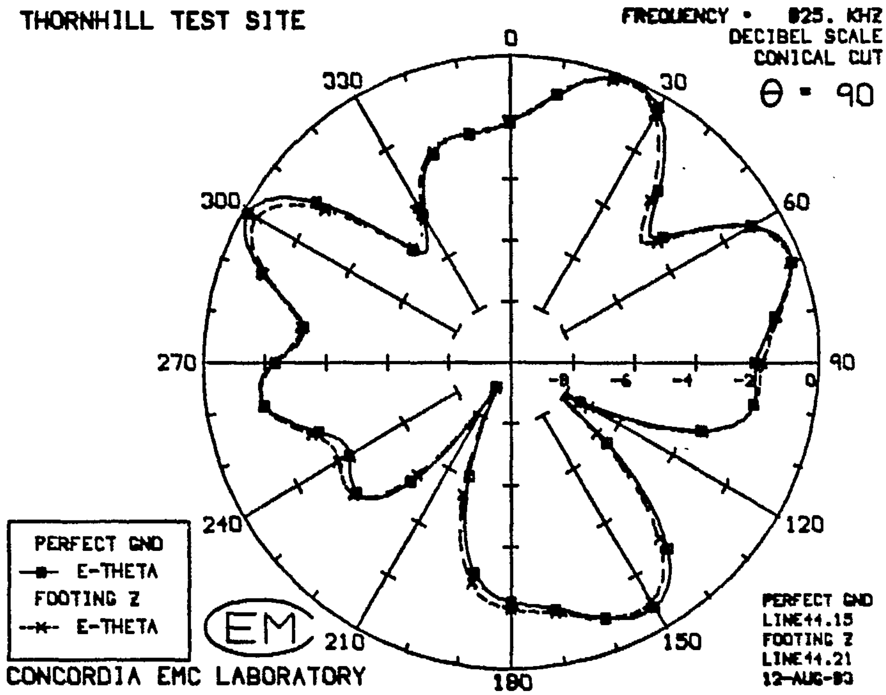


Figure 3.14(a) Comparison of the azimuth patterns with and without the tower footing impedance - 825 kHz.

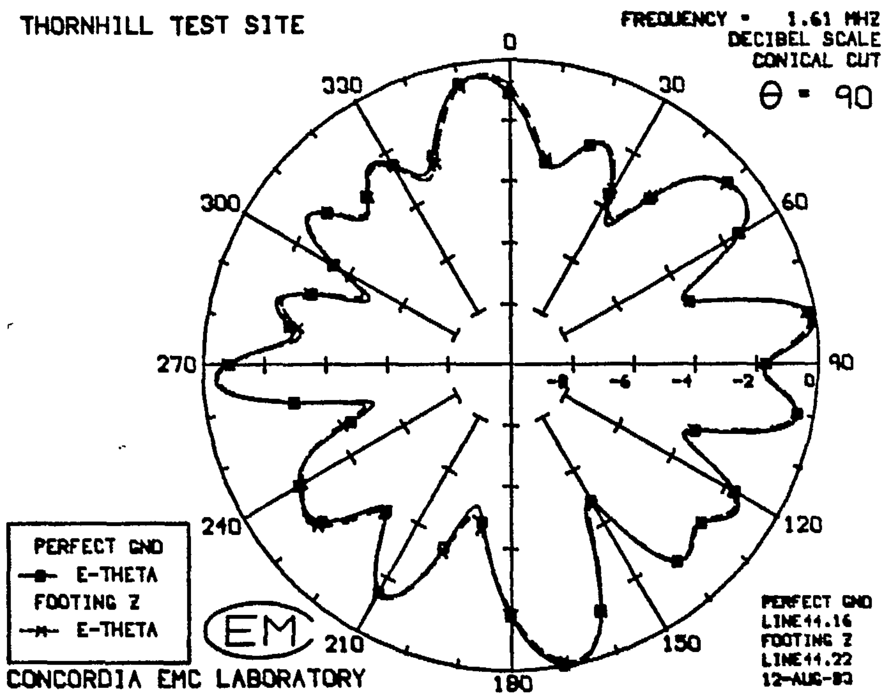


Figure 3.14(b) Comparison of the azimuth patterns with and without the tower footing impedance - 1605 kHz.

APPENDIX

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Corrective Measures for Minimizing the Interaction of Power Lines with MF Broadcast Antennas

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***Abstract*—New high-voltage power lines are often built in close proximity to MF/AM broadcast antennas. The "skywire" which joins the tops of the power-line towers creates closed loops for RF current on the power line and its image in ground, and these loops can be resonant in the MF band. If the broadcast antenna operates on such a resonant frequency, it induces large currents on the skywires and power-line towers, and "reradiation" from these induced currents can considerably alter the broadcast antenna's radiation patterns. This paper uses computer modeling to systematically examine several techniques for "detuning" the power line, namely: isolating towers from the skywire, series insulators in the skywires, stub detuners on the skywires, and short capacitively terminated stub detuners on the towers. The mechanism which makes each detuner effective is seen from the RF current distribution computed for the power line and detuner. The bandwidth of each detuner is assessed. Consideration is given to the difficulties that can arise in the implementation of each detuner design on a real power line. All of these detuner designs have been tested by scale-model or full-scale measurements. Only when detuning has been made a systematic economical procedure can this special EMC problem be regarded as solved.**

***Key Words*—Antenna radiation pattern distortion, power-line coupling, mitigation methods.**

I. INTRODUCTION

THE growth and expansion of our cities has been such that the isolated sites originally chosen for many MF/AM transmitters for commercial radio stations have come to be near built-up areas. The selection of a suitable "utility corridor" for the construction of high-voltage power lines to supply growing needs for power must satisfy many criteria, and proximity to an AM broadcast transmitter is not a major consideration. Power lines are built as close as a half a kilometer from broadcast transmitters. If the power line is resonant at the operating frequency of the broadcast antenna, strong RF currents are induced on the power line and these "reradiate" a field which can cause a major change in the broadcast-antenna-radiation patterns. An omnidirectional pattern becomes "scalloped" by the introduction of maxima and minima which can be as much as 6 dB below its average value. This pattern distortion can cause inadequate coverage of the station's service area. For directional broadcast antennas which must protect another station by maintaining a "null" in which the field strength does not exceed a specified low level over a specified arc, reradiation from the power line can cause the station to violate its licensing requirements. This paper explores means that might be used to make the power line transparent to the broadcast station by adding "detuners" to the power line which minimize the reradiated field. Detuners of various designs are systematically examined in order to better understand their basis of operation and the means for their optimization. It will be shown that the installation of these devices can effectively shift the resonances of the power line to frequencies which are sufficiently far from the operating frequency of the broadcast antenna so as to have a negligible effect.

In this work, the RF behavior of the power line is evaluated by computer modeling. The power line is represented by a "thin-wire" model, and a "thin-wire antenna analysis" computer program is run on a high-speed digital computer to determine the RF current distribution on each of the wires making up the power-line model, and to find the radiation pattern of the broadcast antenna in the presence of the power line. It is found that the power line has strong resonances in the MF band. To assess the effectiveness of each detuner design, the detuners are incorporated into the power-line model, and the behavior of the line-plus-detuners, as a function of frequency, is compared with the behavior of the line alone. The mechanism of operation which makes each detuner effective in suppressing the reradiated field is seen through a study of the RF current distribution on the power line, and this lends insight into the optimization of the detuner design.

These investigations of resonance and detuning have been carried out for a power-line configuration with dimensions representative of a site at Hornby, Ontario. Fig. 1 shows the base of the antenna and the towers of the two parallel power lines half a kilometer away. A 195-m tall broadcast tower radiates an omnidirectional pattern at operating frequencies of 740 and 860 kHz. The power line is 448 m from the broadcast antenna, or about 1.3 wavelengths distant at 860 kHz. The effect that power lines such as those at Hornby have on a broadcast antenna's pattern has been studied in this work using a straight power line with evenly spaced towers of dimensions corresponding to the average tower height and spacing at Hornby, as shown in Fig. 2. The towers are 50.9-m tall and the span length between towers is 274 m. The actual tower spacings at Hornby vary from 213 to 293 m, and have a statistical standard deviation of 21 m. If four short spans associated with a bend in the line are excluded, then the shortest span is 258 m and the standard deviation is reduced to 10 m, and so the power line is very nearly evenly spaced. The power-line model has an odd number of towers,

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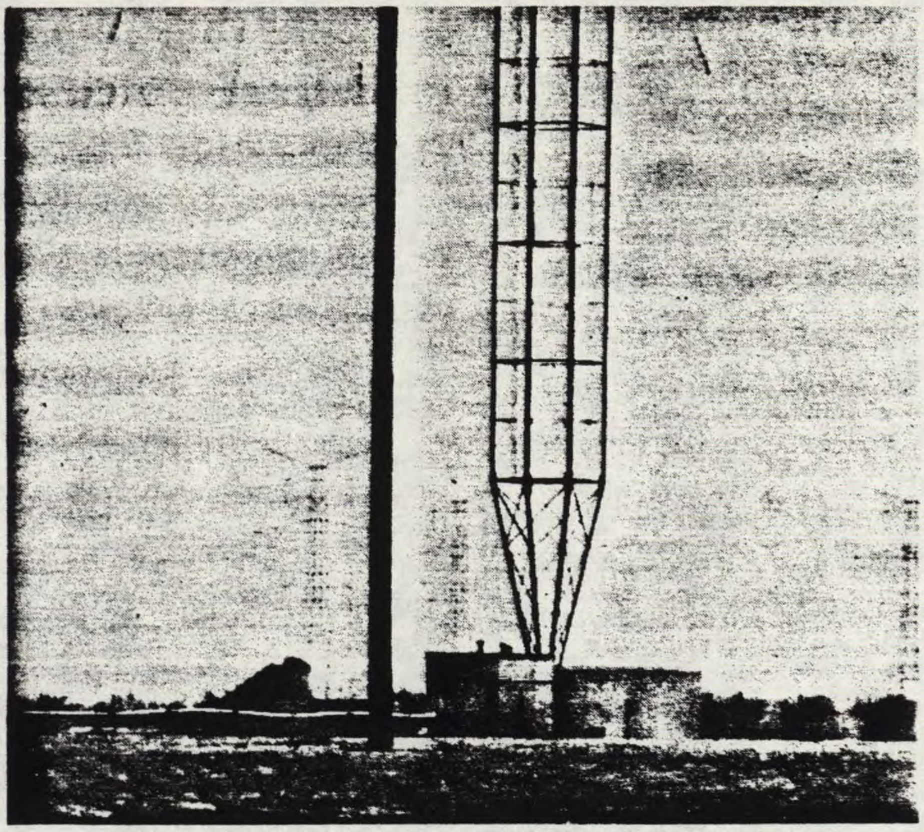


Fig. 1. Base of the broadcast tower at Hornby, Ontario, with towers of the nearby pair of power lines in the background.

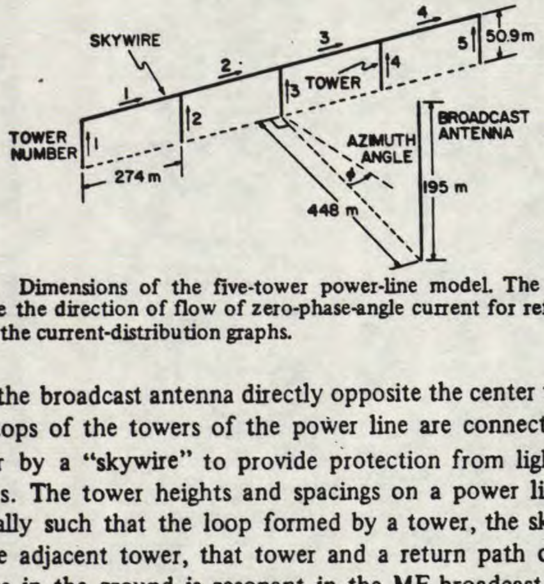


Fig. 2. Dimensions of the five-tower power-line model. The arrows give the direction of flow of zero-phase-angle current for reference on the current-distribution graphs.

with the broadcast antenna directly opposite the center tower. The tops of the towers of the power line are connected together by a "skywire" to provide protection from lightning strikes. The tower heights and spacings on a power line are typically such that the loop formed by a tower, the skywire to the adjacent tower, that tower and a return path on the images in the ground is resonant in the MF broadcast band, when it is an integer multiple of a wavelength in electrical length. For the model in Fig. 2, the geometrical length of this resonant path is equal to 752 m, which is two free-space wavelengths at about 800 kHz. Thus the broadcast antenna is operating near a resonant frequency of the power line and a strong reradiated field is expected. Field measurements taken at Hornby before and after the construction of the power line show that the power line does introduce an appreciable distortion of the "omnidirectional" pattern of the broadcast antenna. There being no better means available, the line was "treated" by disconnecting or "isolating" some of the towers of the power line from the skywire [1]. A heuristic procedure was used in which some of the towers were isolated and the resulting radiation pattern was measured. More towers were isolated and the pattern measured again, and the process repeated until it was found that the minimum in the pattern fell in the direction of Lake Ontario. It will be shown that isolating towers from the skywire generally does not reduce the reradiation from the power line to insignificant levels, but does modify the amplitude and phase of the reradiated field so as to change the azimuth directions of the minima, giving some control over the pattern. For a two-frequency broadcast transmitter such as that at Hornby, isolating a suitable set of towers to achieve a favourable azimuth pattern at one frequency generally yields an unfavourable pattern at the other. The need to resort to such an unsatisfactory "fix" motivates the search for more systematic methods of detuning which are proposed in this paper.

II. DEVELOPMENT OF THE COMPUTER MODEL

The development of a computational model of the power line of Fig. 2 which generates radiation patterns in agreement with measurements on a 600-scale model of the straight, evenly spaced power line has been reported in [2], and is summarized here. The power-line model was developed to represent Ontario Hydro's type V1S towers for a 500-kV power line, but could be adjusted to represent other tower types. At MF, the cross-sectional size of the tower, about 4 m/sq, is a few percent of the wavelength, and so the tower is electrically "thin".

It can be represented by a thin wire of length equal to the tower height. The wire radius is adjusted so that the cylindrical thin wire is electrically equivalent to the square cross section tapered tower. This electrical equivalence of the computer model to the 600-scale factor measurement model is determined by comparing the frequency dependence of the computer model with various radii with the resonant behavior of the measurement model, over a perfect ground, as described in [2]. The tops of the wires representing the towers are interconnected by a "skywire". The power line behaves electrically as a two-wire transmission line consisting of the skywire and its image in the highly conductive ground, with a characteristic impedance of about 200 Ω. This two-wire line is shunted by the tower impedance at regular intervals for an evenly spaced power line. Also, these towers are excited by the field of the broadcast antenna. Thus the skywire currents will be shown to exhibit the classic standing-wave patterns expected of a simple transmission line in resonance.

The power-carrying "phase wires" are parallel to the skywire but are insulated from all the towers of the power line. Since both the skywires and the phase wires are perpendicular to the electric field radiated by the broadcast antenna, neither is directly excited by that field. The towers are strongly excited because they are parallel to the excitation field, and the current from the towers flows onto the skywire to excite the skywire. The phase wires can only be excited as a secondary effect through coupling to the adjacent skywires, or by the radial component of the tower field. Fig. 3 shows the azimuth pattern of the power line of Fig. 2, not including the phase wires, as measured by Lavrench and Dunn [3] on a 600-scale factor model. At 860 kHz, the power line introduces large minima and pronounced lobes into the pattern of the "omnidirectional" broadcast antenna. Lavrench and Dunn tested the effect of phase wires by adding six phase wires representing the two three-phase circuits carried by the type V1S towers. The phase wires change the pattern by about 0.6 dB in the minima, where the overall pattern variation is about 8.3 dB. In subsequent measurements, Lavrench and Dunn have not included the phase wires. Balmain, in [4] measured the scattering from a 1000-scale factor model of a uniform power line, with all the towers connected to an overhead skywire, over a frequency range including the power line one- and two-wavelength loop resonances. Adding the phase wires to the model caused the resonant frequencies to be "shifted slightly" and reduced the magnitude of the resonance effect by 1 to 2 dB. In [5], Balmain and Belrose conclude that the phase wires have "little effect" when all the towers are connected to the overhead skywire. Silva, Balmain, and Ford in [6] use computer modeling to investigate the consequences of the construction of a power line near a directional array, and do not include the power carrying wires in the computer model. In this paper, an "equivalent" phase wire has been included in cases where it might be expected to have a significant effect.

A. Method of Calculating the RF Currents

The RF currents flowing on the broadcast antenna, towers and skywires are determined using the "Numerical Electromagnetics Code" (NEC) described in [7]. NEC uses the "Method of Moments", described in [8], in which each wire of the antenna is broken up into "segments" about one-twentieth wavelength long, and the complex amplitude of the RF current at the center of each segment is considered to be an unknown quantity. If there are N segments in total, then there are N unknown complex current amplitudes, and these currents are found by forming a system of N linear equations each in N unknowns. These equations enforce the boundary condition that the tangential component of the electric field must be zero along the axis of each wire. Each of these linear equations enforces this boundary condition at the center of one segment. The electric field is the sum of the excitation field plus the electric field due to the current on each of the N segments of the antenna, and so the linear equation involves all N unknown current amplitudes. Enforcing the boundary condition at the center of each segment in turn generates the set of N linear equations in the N unknown current amplitudes, which can then be solved. In this way a "self-consistent" RF current distribution is obtained, in that this current distribution gives rise to zero electric field along the axis of each of the wires of the antenna.

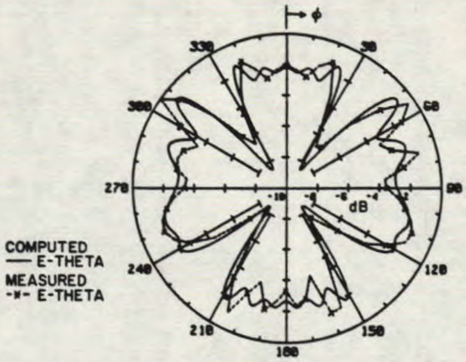


Fig. 3. Azimuth pattern of an omnidirectional broadcast antenna operating in the presence of a 13-tower power line at 860 kHz, in comparison with a scale-model measurement.

The RF current distribution is itself of interest because it can shed light on the mechanism which makes each of the various detuner designs effective. The RF current distribution is readily integrated to determine the radiation fields of the antenna. In this paper, the success of each scheme for "detuning" power lines is assessed by comparing the radiation pattern of the "detuned" power line with the azimuth pattern of an omnidirectional broadcast antenna with the scalloped pattern in the absence of detuning devices. The next section describes the specific parameter used in this assessment.

III. FREQUENCY DEPENDENCE

Fig. 3 shows the azimuth pattern of an "omnidirectional" broadcast antenna operating at 860 kHz in the presence of a power line having 13 evenly spaced towers with the dimensions shown in Fig. 2. The antenna is opposite the center tower of the line, and so the pattern is symmetrical about phi equals zero degree. The pattern has four sharp minima about 6 dB down from the pattern average value, and also has maxima about 2 dB larger than the average value. A single-number summary of the deviation of such a pattern from the omnidirectional is the "max-to-min ratio" which is defined as

$$\mathrm{MMR} = 20 \log (|E_{\theta,\max}|/|E_{\theta,\min}|)$$

and is about 8 dB for this pattern. If a detuning scheme reduces the max-to-min ratio to a small value then the pattern must be almost omnidirectional.

The power-line geometry of Fig. 2 is such that, in the azimuth plane, only the towers of the power line contribute to the radiation pattern. This is because any field point on the surface of ground is equidistant from a skywire segment carrying a current $I\,dl$ and from an image skywire segment carrying an equal and opposite current $-I\,dl$, and the fields radiated by the two segments exactly cancel. Thus the azimuth pattern is due to radiation from the towers alone. The max-to-min ratio reflects the strength of the RF currents flowing on the towers of the power line, and also the relative phasing of these tower currents.

B. Pattern Perturbation Spectrum

A study of the behavior of the power line as a function of frequency using the Numerical Electromagnetics Code requires that the matrix of coefficients described in Section III be formulated and solved separately at each individual frequency. Fig. 4 compares the frequency dependence of the 13-tower 600-scale factor measurement model [9], [10] with the computer model using 13 towers. The figure compares the max-to-min ratio of the azimuth pattern of the computer model to that of the measurement model, as a function of frequency. This "pattern perturbation spectrum" shows that, over wide frequency ranges, the power line has only a minor effect on the azimuth pattern of the broadcast antenna, and introduces as little as 1 dB of ripple. However, over two frequency bands from 380 to 540 kHz and from 800 to 1000 kHz, a major distortion is present. In these two bands, the power line exhibits resonant behavior and so carries strong RF currents. Fig. 4 shows that both the measurement model and the computer model exhibit three strong peaks in the response between 400 and 540 kHz, and that these peaks correspond closely in frequency. Both models display resonance at about 860 kHz, but the response of the computer model has a somewhat wider bandwidth than that of the measurement model.

C. Resonance Modes

The tower height and tower separation of the power-line of Fig. 2 is such that, at 400 kHz, the geometrical length of a path which goes up a tower, along the skywire to the adjacent tower, down that tower, and then forms a closed loop by returning along the tower and skywire images in the highly conductive ground, has a length of one free-space wavelength. The spectrum of Fig. 4 shows a strong resonance peak at 430 kHz, and the resonance mode will be called "one-wavelength loop resonance." The shift of 30 kHz upward in frequency indicates that the electrical length of this path is somewhat less than the geometrical length. The peak at 480 kHz comes about as a resonance of a loop consisting of a tower, the skywires for two spans, another tower, and the return path along the images, which is about two wavelengths long at that frequency. The 13-tower line shows a weaker resonance at about 515 kHz, which corresponds to an RF current mode spread over three spans, as discussed in [11].

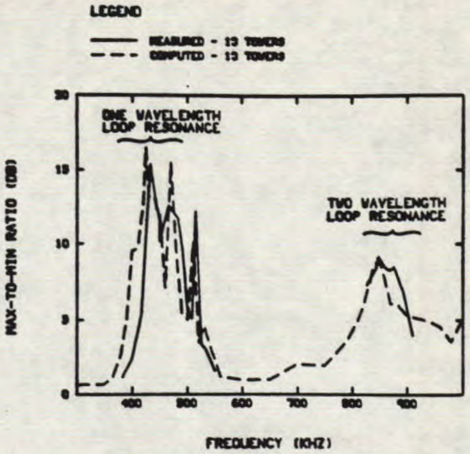


Fig. 4. The "pattern perturbation spectrum" calculated with 13 towers in comparison with the spectrum derived from azimuth patterns measured with a scale model.

When the tower-skywire-tower-and-images path is about two wavelengths in geometrical length, the power line exhibits "two-wavelength loop resonance," which accounts for the peak centered at about 860 kHz. There are also higher resonant frequencies in the commercial AM broadcast band, at which this path is about three wavelengths and about four wavelengths long.

The towers on any actual power-line are not precisely evenly spaced. For span lengths which cluster reasonably close to a "nominal" value, the effect of unequal spans is to make the resonance peaks in Fig. 4 wider in bandwidth, but not as tall. At Hornby, the spacings vary from 258 to 293 m, with four spans as short as 213 m. Neglecting these four short spans, the standard deviation of the span length is 10 m and represents about 3 percent of the resonant loop length, and the standard deviation of the resonant frequency can be estimated to be about 23 kHz. Thus the spectrum of Fig. 4 is expected to spread out and a broader resonance would be expected in the frequency range from about 840 to 880 kHz, centered at 860 kHz. Full-scale measurement for Hornby shows a strong scalloping of the pattern by the power line at 860 kHz, but only a small effect at 740 kHz. A detailed investigation would require the computation of the frequency response of the power line in a large number of cases with a random variation in the span length superimposed on the nominal value. In each case, a random-number generator would specify a set of span lengths, and NEC would be used to find the radiation pattern at a number of frequencies in the resonance range. It is expected that, if the random variation in the tower spacing is too large, the results of computations using the nominal spacing on an evenly spaced line would cease to be a useful guide.

Some sites have span lengths that are not closely clustered about a "nominal" value. In such a case, an individual span of resonant length at the operating frequency can introduce a significant change in the broadcast antenna pattern, espe-

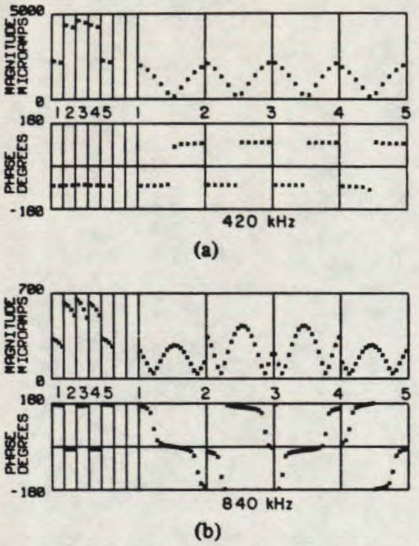


Fig. 5. The magnitude and phase of the RF current distribution on the towers and skywires of the five-tower power line. The numbers on the horizontal axis are the tower numbers. (a) 420 kHz. (b) 840 kHz.

cially if a null with a close tolerance must be maintained. Only those spans which are resonant need to be "detuned." It may be of interest for power companies planning a new line to avoid span lengths which would be resonant for a nearby station.

D. RF Current Distribution

An understanding of the RF current distribution on the power line at each resonant frequency is necessary for the design of detuning devices. Fig. 5 shows the magnitude and phase of the RF current flowing on the power line at two resonant frequencies. At frequencies well below the 420-kHz resonance, the RF current distribution on the skywire shows the linear-phase-with-distance behavior expected of a travelling wave, and has a magnitude of the order of 20 μA, compared to 2500 μA at resonance (both relative to a 1-V generator exciting the broadcast antenna). Fig. 5(a) shows the RF current distribution at 420 kHz in the frequency range of one-wavelength loop resonance. The RF current on each of the five towers is given at left, and the RF current on each skywire span is given at right. The tower numbers are given on the horizontal axis. The tower current is given at two points on each of the five towers of the power line, one point being 12.7 m and the other 38.2 m above the ground on the 50.9-m tall tower. The five towers carry RF currents which are all in phase. The RF current at ten evenly spaced points on each of the four skywire spans is given at right. The skywire current is fundamentally different at resonant frequencies compared to that at nonresonant frequencies. At resonance, the skywire current distribution shows the sharp nulls and constant-phase-with-distance of a classic standing wave, with the null at the center of each span. As the frequency is increased above one-wavelength loop resonance, the currents decrease to the order of 100 μA and become travelling waves once again. In the two-wavelength loop resonance frequency range, the current distribution is that shown in Fig. 5(b). The phase of the tower current changes by 180° from tower to tower. The skywire current is once again a standing wave, with the nulls and their associated sharp 180° phase reversals near the towers, and a maximum at the center of the span.

The one-wavelength loop resonance RF current distribution of Fig. 5(a), and that for two-wavelength loop resonance in Fig. 5(b) provide the essential information for the design of "detuners" for the power line, as discussed below.

V. DETUNER DESIGNS

Several different detuner designs will now be presented which fall into two categories. As discussed above, only the towers of the power line, and not the skywires, radiate in the azimuth plane. Most detuner designs suppress the RF current on the tower, and directly reduce the strength of the reradiated field. In contrast, the short tower-stub detuners induce a current which is equal and opposite to the tower current and so radiate a field which cancels that radiated by the tower. The following discusses the mechanism which makes each stub effective, and stub designs are presented which suppress both the one-wavelength and the two-wavelength loop resonance modes.

A. Detuning by Isolating Towers

It is common practice to disconnect or "isolate" some of the towers from the skywire in an attempt to reduce the level of the reradiated field. It has been shown by scale-model measurements in [3] and [5] that disconnecting one or more towers from the skywire can significantly affect the azimuth pattern. Isolating a tower from the skywire breaks up two adjacent resonant loops and might be expected to greatly reduce the current flowing on the towers which have been "open circuited" from the power line. The reduction in the tower current is not as large as might be expected, however, because, as shown by computer-modeling and full-scale measurement by Balmain [12], the "isolated" tower behaves as a free-standing monopole top-loaded by the crossarms, and will have a strong RF current induced on it by the broadcast antenna field.

Lavrench and Dunn [3] used a scale model of a straight power line with 13 evenly spaced towers, of the dimensions shown in Fig. 2, to investigate detuning by isolating towers. As described above, when all the towers are connected to the skywire, the power line is in two-wavelength loop resonance at 860 kHz and has the azimuth pattern shown in Fig. 3. The isolation of towers was investigated by disconnecting towers numbered 2, 3, and 4; 6, 7, and 8; and 10, 11, and 12 from the skywire, where tower number 7 is the one directly opposite the broadcast antenna. The resulting azimuth pattern is shown in Fig. 6, and is completely different from Fig. 3. There is a pronounced lobe at 0°, a minimum at 180°, and the minima in the original pattern have disappeared. The max-to-min ratio has been reduced from 9 to 5 dB, and so some improvement can be claimed.

The power line was then modeled using the NEC thin-wire computer program in order to determine the RF currents flowing on the towers. An isolated tower was represented by leaving a small gap between the top of the tower wire and

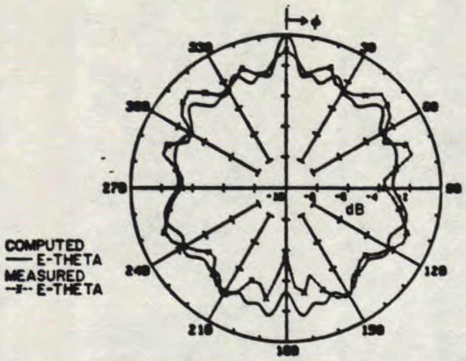


Fig. 6. The azimuth pattern for a 13-tower power line with towers numbered 2, 3, 4; 6, 7, 8; and 10, 11, and 12 isolated from the skywire, in comparison with a scale-model measurement.

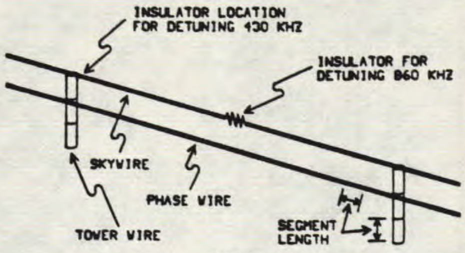
the skywire. The computed azimuth pattern in Fig. 6 agrees reasonably with the measurement. The RF current distribution on the towers of the power line shows that, in this specific example, the current on the "isolated" towers at the center of the power line, towers #6, 7, and 8, is stronger than the current on any of the connected towers. In the calculations and measurements reported here, the power-carrying "phase wires" have not been included in the model. Balmain, in [4], has carried out swept-frequency measurements for a power line model with some towers disconnected or "isolated" from the skywire, and with and without the phase wires. In those measurements, a 3- to 4-dB reduction in the resonant perturbation caused by the power line was found when the phase wires were added to the model. Evidently the phase wires can have a significant effect on the results obtained by isolating towers and so the phase wires should be included in a computer model intended for the study of detuning by isolating towers.

Isolating towers is an unsystematic technique because it is difficult to know in advance which towers on a complex site should be isolated to reduce the effect of reradiation. Also, in general, isolating towers does not eliminate the deformations of the radiation pattern caused by reradiation, but often simply changes the directions in which these occur. Isolating towers has been used by trial-and-error at some sites to determine which set of towers to isolate in order to put the pattern disturbances in directions in which least harm is done to the coverage of the station.

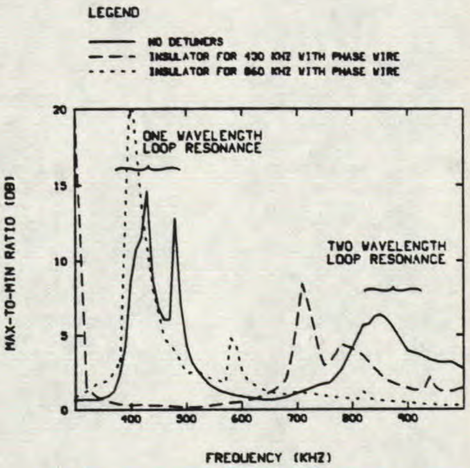
B. Skywire Insulator Detuners

The simplest means of suppressing the large RF currents which flow at resonance is to interrupt the current by introducing an open circuit at a point on the skywire where the standing-wave current has a maximum. As shown in Fig. 7(a), the "open circuit" is an "insulator" of large resistance and with a capacitance of about 27 pF, which is about 14 kΩ at 420 kHz and 7 kΩ at 840 kHz, both being much larger than the skywire-and-image transmission line's characteristic impedance of about 300 Ω. The skywire insulator has been proven effective by scale-model measurement in [13], where it was found that the "insulator" is required to have a resistance of about ten times the characteristic impedance.

The effectiveness of the skywire insulator and other detuners will be assessed here using a power line with five towers.



(a)



(b)

Fig. 7. (a) Location of the insulator in the skywire for detuning 430 and 860 kHz. (b) Pattern perturbation spectra with skywire insulator detuners.

Fig. 7(b) shows the pattern perturbation spectrum for a five-tower line, and can be compared with that for a 13-tower line in Fig. 4. The resonant behavior is similar, but the magnitude of the resonance peaks is smaller. The 13-tower line has a resonance at 515 kHz, for which the current distribution involves three spans of the skywire. However, the symmetrically excited five-tower line can only exhibit resonances involving one or two spans, and so the 515-kHz resonance is absent in Fig. 7(b). The analysis of a five-tower instead of a 13-tower power line represents an enormous saving in computer cost and was judged adequate for investigating the detuning of the principal resonance response.

For one-wavelength loop resonance, the insulator must be positioned on the skywire at a point where the skywire current in Fig. 5(a) is a maximum, that is, directly adjacent to a tower. The location of the insulator and the resulting max-to-min ratio as a function of frequency are shown in Fig. 7. The insulator suppresses the one-wavelength resonance mode completely, and alters the two-wavelength resonance mode because that mode also has a strong RF current at the location of the insulator. A new resonance mode is introduced which has a current zero at the location of the insulator, and which has a current maximum at the base of each tower. In this new mode, the path length of 325 m from a tower base, up the tower and along the skywire to the insulator is three-quarters of a wavelength, and so the resonant frequency is expected to be about 700 kHz, in agreement with the location of the peak in Fig. 7(b).

To "detune" the two-wavelength loop resonance mode, the insulator must be put at the center of the span because the RF current of Fig. 5(b) has a maximum at that point. Fig. 7(b) shows that the two-wavelength loop resonance mode is completely suppressed by an insulator inserted at that point, and also that the presence of the insulator has little effect on the one-wavelength loop resonance mode. This is because the RF current distribution for the one-wavelength mode in Fig. 5(a) is zero at the location of the insulator.

Power utilities dislike the idea of an insulator in series with the skywire. Although the insulator can be designed to "flash over" in the event of a lightning strike, the presence of the insulator prevents the skywire from carrying the large fault current that flows if the three-phase power line is operated with one phase wire broken. It has been suggested in [14] and [15] that a suitable inductive element could be designed with low impedance at 60 Hz, but a high impedance at RF frequencies, and could be capable of carrying the fault current. The detuner designs presented in the remainder of this paper do not require interrupting the current flow on the skywire at 60 Hz.

C. Skywire Stub Detuners

The skywire insulator is effective because it presents a high series impedance at the location of high RF current on the skywire, and so interrupts the current. An alternate approach is the introduction of a 0-Ω shunt impedance at the location of a voltage maximum on the skywire-and-image transmission line. A suitable short-circuit shunt element is the open-circuited quarter-wave transmission-line stub of Fig. 8(a). A voltage maximum coincides with the location of a current minimum on the skywire, so the position of the stub "*p*" should correspond to a zero in the current distribution on the skywire, for the resonance mode being "detuned". A more practical design of stub is the "bent" stub of Fig. 8(b), which can be hung below the skywire on an actual power line structure. For towers such as type V1S which carry two skywires, one skywire can be broken up with insulators, forming a bent stub which detunes the adjacent skywire. In [11] and [16], the behavior of the straight and bent stubs is shown to be very similar, and so the straight stub provides a convenient "model" for understanding the "bent" stub. In the same references, the max-to-min ratio is investigated as a function of the length of the stub wire "*s*" and of the location of the connection point to the skywire "*p*" in Fig. 8. Skywire stubs have been shown to be effective detuning devices by scale-model measurement in [17]. Reference [18] discusses an alternate "equivalent-circuit" approach to skywire stub design, but fails to make clear the necessity of positioning the stub at the location of a current minimum.

In [16], it is demonstrated that, to detune the power line at 430 kHz, the bent stub must be connected to the skywire at the location of the current minimum in the skywire current distribution in Fig. 5(a). Thus the stub connects to the skywire at the center of the span with "*p*" in Fig. 8 equal to 137 m. By trying stubs of various lengths, it was found that a bent stub of total length "$b + d$" equal to 175 m minimizes the max-to-min ratio of the azimuth pattern. Fig. 9 shows the pattern perturbation spectrum. The azimuth

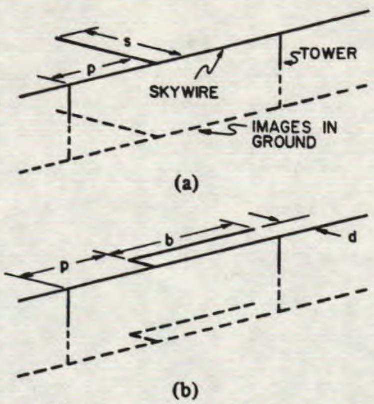


Fig. 8. The "straight" and the "bent" skywire stub detuners. (a) Straight stub, length *s*. (b) Bent stub, length $s = b + d$.

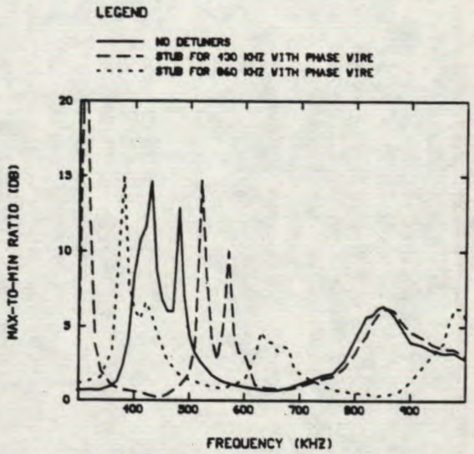


Fig. 9. Pattern perturbation spectra with "bent" skywire stub detuners.

pattern is quite circular with a near-zero max-to-min ratio at the "design" frequency of 430 kHz, and over a bandwidth of about 100 kHz centered at this frequency. New resonance peaks are introduced at 330, 520, and 560 kHz involving resonant-length paths for the RF current which include the detuning stub. The detuner for 430 kHz has almost no effect on the resonant behavior at 860 kHz, because at that frequency the detuner is about half a wavelength long and so presents an open circuit across the skywire-and-image transmission line. Thus the skywire stub is an effective detuner because it interrupts a resonance mode by presenting a short circuit across a high-impedance point on the transmission line. The resulting structure is nonresonant and the tower currents are correspondingly small.

To detune the resonance mode present at 860 kHz, the bent stub must be connected to the skywire at the location of the current minimum in Fig. 5(b). The stub was found to minimize the max-to-min ratio when its total length "$d + b$" was made 104 m or about three-tenths of the free-space wavelength. Fig. 9 shows that the stub effectively suppresses the two-wavelength loop resonance mode. The stub also alters the nature of the one-wavelength resonance response. The large max-to-min ratio at 380 kHz indicates that a null is introduced into the "omnidirectional" pattern which is 35 dB down from the largest value of the pattern.

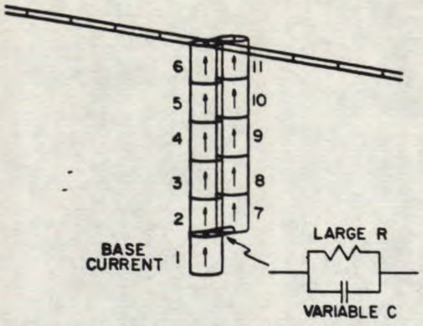


Fig. 10. The tower-stub detuner. The arrows give the direction of zero-phase current.

D. A Capacitively Loaded Tower-Stub Detuner

A common detuner design used in practical situations is a short stub which connects to one leg of the power-line tower near the top of the tower, runs down the tower separated from the leg by about a meter, and then is connected to the tower leg through a variable capacitance. One such stub is used on each of the four legs. The capacitance is adjusted to minimize a near-field parameter such as the current at the base of the tower on each tower leg. This "detuning" of a tower is often carried out after the top of the tower has been isolated from the skywire, in order to reduce the interdependence of the tuning capacitance values needed for adjacent towers, so that each tower may be "detuned" individually. Tower stubs are often used by consultants to detune towers. The tower stub has been shown to be an effective detuning device by scale-model measurement in [19].

A gross representation of such stubs is shown in Fig. 10. A wire of radius equal to the tower radius of 3.51 m is separated so that its axis is 8 m from the axis of the tower wire. This "stub" wire is connected to the top of the tower. The lower end of the stub is connected to the tower by a variable capacitance. This is modeled by joining the end of the stub to the junction between the first two segments of the tower wire, by a short wire. This short wire is "open circuited" by a large series resistance and loaded with a capacitance in parallel with the resistor. All towers are connected to the skywire. The computer model is less satisfactory if a thin wire is used for the stub wire, and so the fat stub wire shown in Fig. 10 was retained.

The tower-stub detuner is "designed" for a particular frequency by specifying a suitable value of the capacitance. All five towers of the powerline are "treated" with stubs, and all five capacitance values are kept equal. The procedure for choosing the capacitance is empirical and is illustrated by Fig. 11. Fig. 11(a) shows the max-to-min ratio of the azimuth pattern and the base currents for two towers, as functions of the capacitance. The max-to-min ratio can be reduced to 0.5 dB by choosing the capacitance equal to 2155 pF, which effectively "detunes" the power line. In the full-scale situation, the azimuth pattern is so difficult to measure that direct monitoring of the smoothness of the pattern is impractical. A near-field parameter, such as the base current on one or more towers must be relied upon. Fig. 11(a) shows the base current on the center tower of the five-tower power line,

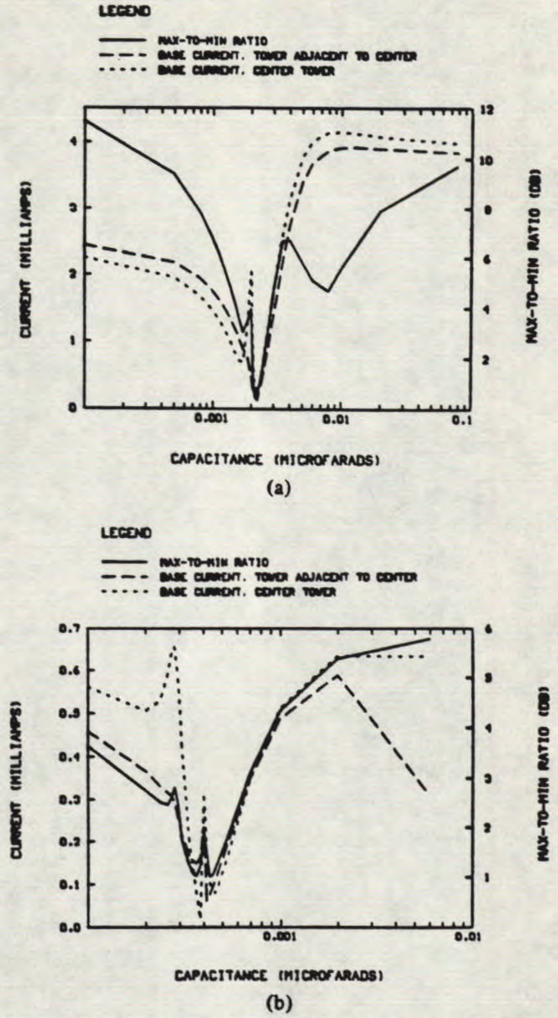


Fig. 11. The max-to-min ratio and the tower base currents as functions of the capacitance. (a) 430 kHz. (b) 860 kHz.

and also that for the tower adjacent to the center tower. The base current of the latter has a single minimum which coincides with the minimum in the max-to-min ratio. However, the base current on the center tower has two closely spaced minima separated by a sharp peak. At 1732 pF, the center-tower base current has a minimum where the max-to-min ratio is 3 dB, and has another minimum at 2155 pF, which is the capacitance that makes the azimuth pattern smooth. Thus Fig. 11(a) suggests that it is necessary to monitor more than one tower base current to avoid "tuning" the capacitance to a local minimum which does not make the azimuth pattern as smooth as it could be with this type of detuner.

Fig. 11(b) is a similar graph for the operating frequency of 860 kHz. The max-to-min ratio curve shows two suitable capacitance values, namely 367 and 429 pF, each of which reduces the max-to-min ratio to 1 dB and so effectively "detunes" the power line. In this case, both tower base currents possess a pair of minima separated by a sharp peak, and operating at either minimum for either base current is satisfactory in "detuning" the power line. In the measurement reported in [19], a capacitance value in the range 2 to 10 pF was required to detune a 200-scale factor model of a power-line tower with a tower stub. At full scale, this is 400 to 2000

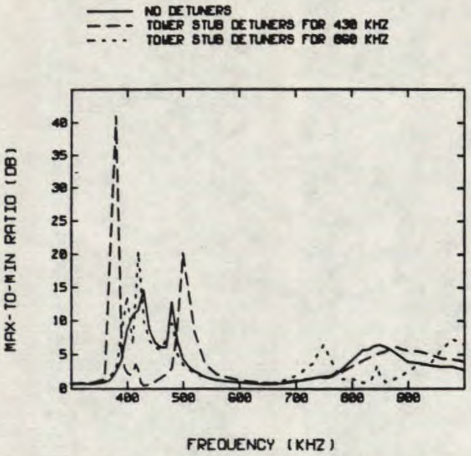


Fig. 12. Pattern perturbation spectra with tower-stub detuners for 430 and 860 kHz.

pF, which brackets the computed value of 429 pF.

The rapid variations in the base currents seen in Fig. 11 demonstrate that a small change in the capacitance can materially reduce the effectiveness of the tower-stub detuners. Thus these detuners may pose a maintenance problem. These rapid variations as a function of the capacitance are associated with a resonance mode in the tower and stub currents, as discussed below.

Fig. 12 shows the pattern perturbation spectra obtained with the tower-stub detuners. The 430-kHz stub with the capacitance chosen as 2155 pF is seen to be a narrow-band device, which gives rise to a 4-dB max-to-min ratio only 15 kHz away from its design frequency. It has been suggested in the context of the "detuning" of reradiation from buildings in [20] that using four such stubs, one on each leg of the actual power-line tower, tends to "broad-band" the device so that its bandwidth is wider than that of the gross model of Fig. 10. Fig. 12 shows that the tower stub introduces large resonance peaks at 380 and 500 kHz, which could cause problems for a broadcast transmitter carrying two stations. The stub has little effect on the resonant behavior in the two-wavelength resonance region near 860 kHz. Conversely, the detuner designed for 860 kHz with a capacitance of 429 pF does not greatly change the power-line behavior in the one-wavelength loop resonance frequency range. The detuner is effective over a wider bandwidth primarily because the stub is twice as long in terms of the wavelength than it was at 430 kHz. It is seen that the 860 kHz detuner also suffers from a local peak in the max-to-min ratio of height 3.5 dB only 15 kHz away from its design frequency. This peak is related to the behavior of the RF current distribution on the tower and stub as a function of the capacitance, and is investigated in the next section.

E. RF Current on the Tower and Detuning Stub

The tower stub is effective because a current is induced on the stub which is equal in magnitude and opposite in phase to the current on the tower, and so the field radiated from the tower is cancelled by the field radiated from the stub. That is, the phasor sum of the currents on segments #1 to 6 in Fig. 10 plus the phasor sum of the currents on segments #7 to 11 adds up to very nearly zero with the "best" choice of capacitance, even though the currents themselves are quite large. If the values of the currents are examined, it is found that the current on segment #1, the tower base, is very much less than the current on the tower body or stub, and, as shown in Fig. 11, can be made much less than its value with no detuner by an appropriate choice of capacitance. The tower body, segments #2 to 6, and the stub, segments #7 to 11, constitute a short two-wire transmission line which is short-circuited at one end and shunted by a capacitance at the other. For small capacitance values, the stub is open-circuited and carries little current. For large capacitance values, the stub is short circuited to the tower, and the current divides equally between stub and tower, and is in phase on the stub and tower. As the capacitance value approaches that for resonance with the inductive input impedance of this short transmission line at the operating frequency, the currents on the tower body and stub become very large and 180° out of phase with one another. This is a high-Q resonator because no ohmic losses have been included in the present model. In Fig. 11, perfect resonance of this LC system gives rise to the sharp narrow peak in the curves which occurs just below the capacitance value which minimizes the max-to-min ratio. For example, at perfect resonance with $C = 400$ pF in Fig. 11(b), the tower body current is about 3000 μA, whereas for least max-to-min ratio with $C = 429$ pF, these currents are about 1000 μA. If the value of the tuning capacitance changes with age or temperature, the effectiveness of the detuner can be sharply reduced.

The frequency spectra of Fig. 12 show that the tower stubs give rise to a narrow 3-dB peak falling near their design frequency, and this peak limits the bandwidth of the detuner. This peak occurs because with the capacitance chosen for least max-to-min ratio, the same capacitance will give perfect resonance at a slightly lower frequency. At perfect resonance, the detuner is less effective.

V. CONCLUSION

This paper has examined a number of techniques for "detuning" a power line in the MF/AM frequency band. These techniques have been analyzed by means of a computer model of a five-tower, straight, evenly-spaced power line, in which all the towers or all the loops are treated with detuning devices. The effectiveness of each method has been checked by scale-model measurements of other investigators which are not all reported here. It remains to be seen whether such techniques are effective or practical for full-scale power lines.

The method of isolating towers from the skywire is unsatisfactory because it does not, in general, eliminate reradiation, but simply changes the azimuth angles at which significant reradiation is present. Also, for a broadcast antenna that carries stations at two frequencies, the set of towers which should be isolated to "fix" the pattern at one of the frequencies generally results in a poor pattern at the other.

From the RF point of view, breaking the skywire with an insulator in series provides the widest-band "detuning" of the line. The next best technique appears to be the skywire stub, which has an adequate, but not wide, bandwidth. Aside from practical considerations concerning fault currents and the "security" of the power line against outages, the difficulty with both insulators and skywire stubs is that they must be positioned at an appropriate location in the RF current distribution on the skywire. For a real site with unevenly spaced towers of unequal heights, the computer-model-predicted RF current distribution for the skywires has not yet been tested against full-scale measurements of RF current on a real power line. For the computer model to be useful in predicting the exact locations for stubs or insulators, it would be necessary to establish precise agreement. The present computer model assumes a perfectly conducting ground, does not account for the deviation from perfect flatness of the ground which is present at any real site, and cannot include realistically long lengths of powerline because of computer resource limitations. The computer model has not, thus far, been made to include other nearby structures, such as buildings, which may significantly affect the RF current distribution on the power line. Because of these simplifications, the computer model alone may not be able to predict the RF current with the high precision that is needed to predict locations for skywire detuning devices. Ontario Hydro [21] has devised a system for measuring the RF current on the skywire by pulling a loop-probe along the skywire from tower to tower, and is using this system to compile a set of full-scale measurements. This direct measurement technique may prove essential for determining the necessary locations for skywire detuning insulators or stubs.

The short capacitively terminated tower stub has the advantage that it can be tuned effectively by monitoring the base currents of some towers, and that, in practice, if the towers are also isolated from the skywire, it appears to be possible to "tune" each tower individually, independent of the capacitance value used on adjacent towers. It must be emphasized that this latter result has not been tested in the present set of calculations. In this paper, all five towers were connected to the skywire and all towers were "tuned" together. The tower-stub design investigated by numerical computation in this paper is an effective detuner, but is quite narrow in bandwidth. Further investigations are needed using a more-detailed computer model of the tower which would allow realistically small radii for the stub detuners and allow a detuner on each of the four legs of the tower to be represented explicitly. The bandwidth with four detuners must be determined and the case of detuners on isolated towers must be investigated.

The prediction of the azimuth pattern for an actual site of realistic complexity has been addressed in [2], where the computer-model pattern was shown to be in reasonable agreement with a scale-model measurement. The problem of detuning a complex site must be dealt with as a next step in this work. The objective would be to find the minimum number of "detuning" devices of a specific design that are necessary to effectively suppress reradiation from the power-line, and to specify the locations of the devices on the towers or skywires. Further, guidelines must be developed for assessing in advance which towers or skywires of a complex site should be treated with detuning devices. Only when detuning has been made a systematic economical procedure can this special EMC problem be regarded as solved.

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