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Interim Report No. 1
September 1980

AM RE-RADIATION PROJECT

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Prediction by Numerical Computation of the Reradiation from and the Detuning of Power Transmission Lines

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1. Introduction

In the Final Report(1) of the first year of this project, it was established that computational methods are able to predict the reradiated field from a power line illuminated by an isotropic broadcast antenna, over a perfectly conducting ground. A computer model called the "single wire tower" model was developed and it was shown that, using this model, the azimuth patterns measured at NRC for the straight, evenly-spaced power line are matched, and also that the frequency dependence of the measured patterns is duplicated in the computed patterns. The "single wire tower" model was then applied to compute the azimuth pattern of the array of 27 towers on two power lines at Hornby, and also to the elementary "detuning" measure of loading the skywire at its center with a high resistance.

This report extends the application of the "single wire tower" model in several directions. The frequency dependence is studied over a wide range, and both "loop" resonances and "transmission line" resonances are identified. The currents flowing on the towers and skywires of the Hornby model are examined, and a model with more towers on the dogleg is constructed. The problem of null-filling is addressed by reproducing NRC's measured patterns for a two element array near a five tower power line. The problem of "detuning" by isolating towers from the skywire is studied. Finally, "detuning" by the use of stub traps is investigated for the case of three towers, by reproducing the NRC measured patterns.

2. Frequency Dependence over a Wide Range

The resonant behavior of the power line in reference (1) was understood as "two wavelength loop resonance". In this section the frequencies of other loop resonance modes are estimated, and another type of resonant behavior called "transmission line resonance" is described. The max-to-min ratio of the nine tower power line is computed over a wide frequency range and the various resonant modes are identified.

2.1 Modes of Resonance

Two types of resonance can occur on the power line : loop resonance and transmission line resonance. Loop resonance occurs when the electrical distance around a loop consisting of two towers, the connecting skywire, and the images, equals n times the wavelength. Fig. 2.1 is a sketch of the magnitude of the RF current distribution expected for several resonance modes. Two towers and the connecting skywire are shown schematically, and the current is sketched for one, two and three wavelength loop resonance. The frequencies at which this occurs can be estimated by equating the geometric distance around the loop to n times the wavelength. Thus

$$2d + 4h = n\lambda$$

and so the frequency is estimated as

$$f = nc / (2d + 4h)$$

where "λ" is the free space wavelength, and where "d" is the tower spacing and "h" is the tower height. If n = 1 the loop is said to be in "one-wavelength loop resonance", and for n = 2 there is "two wavelength loop resonance". In general the electrical distance around the loop is shorter than the geometric distance and so the frequencies determined by this equation are somewhat low.

The second mode of resonance becomes evident when the skywire and its image are viewed as a two-wire transmission line. The line is short-circuited every "d" meters by the towers. If the distance between two towers equals a multiple of a half-wavelength, the structure has a transmission line resonance. Thus in Fig. 2.1, the current for one-half, one and 1.5 wavelength transmission line resonance is compared with that for the corresponding loop modes. These resonances occur at wavelengths satisfying

$$d = n\lambda/2$$

and so at frequencies given by

$$f = nc/2d$$

It will be seen that this frequency estimate is high, and is in error because the towers do not present ideal short circuits across the two conductors of the transmission line. The line is in "half-wavelength transmission line resonance" or "half-wave T.L. resonance" for n = 1, and "one wavelength T.L. resonance" for n = 2.

Fig. 2.2 is a chart which maps out these estimates of the frequency of "loop" and "T.L." resonance as a function of the tower spacing, for towers which are 50.5 m tall, as in the Hornby scale models used at NRC. The T.L. resonant frequencies fall at somewhat higher frequencies than the corresponding loop resonant frequencies. Thus for the 275 m tower spacing used in the evenly-spaced power line model at NRC, Fig. 2.2 gives the theoretical estimates of the resonant frequencies shown in Fig. 2.3 . Thus at 400, 800 and 1200 kHz the simplified theory indicates that there will be one, two and three wavelength loop resonance, respectively. In addition, at about 550 kHz , the towers are half a wavelength apart, and at 1100 kHz they are one wavelength apart, and these are the T.L. resonant frequencies.

2.2 Computed Resonances for the Evenly-Spaced Power Line

Fig. 2.4 shows the max-to-min ratio as a function of frequency over a wide range for the straight, evenly-spaced power line with nine towers. The portion of the curve from 810 to 910 kHz is that reported in reference (1) Fig. 3.16 . Comparing Figs. 2.3 and 2.4, it is seen that two resonant peaks are expected in the range 400 to 600 kHz, but that three are present in the computation. This is discussed further below. The two wavelength loop resonance expected at 800 kHz is present in the calculation at 860 kHz. The one-wavelength transmission line resonance expected at 1100 kHz is found in the calculation at 1040 kHz, and the three wavelength loop resonance expected at 1200 kHz is seen at about 1300 kHz. The excessive amplitude of the curve here may be due to an inadequate number of segments on the computer model. The number of segments used in the computation of Fig. 2.4 was maintained constant as the frequency was increased. However, it is desirable to increase the number of segments in proportion to the frequency.

The third resonance peak seen in the 400 to 600 kHz range in Fig. 2.4 can be understood by postulating a hybrid resonance mode, as sketched in Fig. 2.5 . In this mode, a loop consisting of one tower, a skywire and its image in ground is considered to be short-circuited by the second tower. The short is "ideal" and introduces no phase shift. The resonant frequency is estimated by equating the sum of the tower height and the tower spacing to n times the half wavelength,

$$d + h = n\lambda/2$$

and so the resonant frequency is

$$f = nc / 2(d + h)$$

For 51 meter tall towers spaced 275 m apart, this resonant frequency falls at 460 kHz, between the one wavelength loop value of 400 kHz and the half-wave T.L. resonance of 550 kHz, and so explains the third resonance peak in Fig. 2.4 .

It is suggested later in this report that proper placement of the detuning stubs on the skywire calls for a knowledge of the current distribution. Figs. 2.1 and 2.2 may be useful in determining the mode of resonance and hence the current distribution, and so indicate an approximate location for a detuning stub.

3. Current Distribution on the Hornby Power Lines

In this section a new format for the plotting of current distributions is introduced. The interpretation of the current distributions for the straight evenly-spaced power line are discussed, and then the currents flowing on the power lines of the Hornby site model are described.

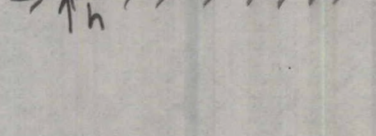
(voltage source on antenna = 1 v)? →

$\lambda|_{f=760\,kHz} = 395\ m$

$\lambda/2 = 197\ m$

$h = 50.6\ m\ , \quad h/\lambda = .128$

$s = 197\ m$



3.1 Interpretation of Current Distribution Graphs

The phase behavior of the current on the skywires of the power line indicates whether the power line is at or near resonance at the particular frequency of the plot. The current distribution on the straight, evenly-spaced power line is examined in this section to make clear this interpretation.

Figs. 3.1 and 3.2 show the currents flowing on the straight, evenly-spaced power line at 760 and 860 kHz. The format of the display lends itself to plotting the currents on complex structures such as the Hornby site model, or models using detuning stubs. Fig. 3.1(a) depicts the magnitude and phase of the tower currents. The plot shows the current at two points on each tower. The left hand point is near the base, at 12.6 m above the ground on the 50.6 m tall tower. Thus for tower # 1 the current at this point is about 300 microamps with a phase of about 90 degrees, and the current on the center tower, tower # 5, is about 500 microamps with phase of about 135 degrees. The right hand point for each tower is the current at a height of 38 meters from the ground. From the graph it is seen that the current tapers in magnitude going from tower to tower away from the center of the power line, and that the phase differs by 180 degrees on adjacent towers. Part (b) of Fig. 3.1 shows the magnitude and phase of the skywire currents. The graph shows that the phase can be decomposed into a constant term plus a linear-with-distance term. The former indicates a standing wave on the skywire. The latter is a travelling wave. Thus on the skywire connecting towers 5 and 6, the phase indicates that an almost pure travelling wave is present. However, on the skywires elsewhere, there is a constant phase component with a weaker travelling wave component superimposed, and so the current is mainly a standing wave.

Fig. 3.2(a) and (b) show the RF currents on the towers and skywires of the evenly-spaced power line at 860 kHz. Recall from the Final Report(1), Fig. 3.16 that for this case, 760 kHz is on the skirts of the resonance curve, whereas 860 kHz is near the peak. Thus Fig. 3.1 shows typical "below-resonance" behavior, and Fig. 3.2 shows "at-resonance" behavior. Note that "at-resonance" the currents are very much larger than "below-resonance". Thus the vertical scale in Fig. 3.1 is 220 microamps, but is 550 microamps in Fig. 3.2. The phase behavior of the skywire currents provides a clear indication of resonance. Thus "at-resonance" in Fig. 3.2(b) the skywire current is an almost pure standing wave, and has constant phase with position, with a negligible travelling wave term. As the frequency is changed away from resonance, the skywire current acquires an ever-increasing travelling wave term. Thus at 760 kHz in Fig. 3.1, which is on the skirts of the resonance curve, the skywire current has a strong "standing wave" constant phase component, but also an easily seen linear progression of phase with distance.

This behavior of the skywire current's phase can be used to interpret the currents flowing on the Hornby site model, as discussed below.

3.2 Hornby Site Current Distribution

An analysis of the plan of the site at Hornby shows that the tower spacings vary from about 215 to about 290 m. In Fig. 2.2 it is seen that these loop sizes lie below or just below two wavelength loop resonance at 740 kHz, while at 860 kHz the larger tower spacings are expected to be in strong resonance. This is borne out by the azimuth patterns presented in reference (1) Fig. 3.38 and 3.39, which show weak scalloping at 740 kHz but a much stronger effect at 860 kHz.

Fig. 3.3 shows the numbering scheme for the towers on the Hornby site, and is an aid in the interpretation of the current distributions of Fig. 3.4 at 740 kHz and Fig. 3.5 at 860 kHz. Fig. 3.4 shows that at 740 kHz, the phase of the current on most skywires is strongly a travelling wave, and so the loops are below resonance. The current on the towers on both the front and rear line is strongest near the broadcast antenna. Also, the front line does not "shield" the rear line at this frequency, because the currents on both lines have about the same magnitude. The current on the dogleg, towers # 12, 10 and 8 of the rear line, is strong and is not seen to decrease with distance from the broadcast antenna. Note that the behavior of the current on the skywires directly opposite the antenna is different from elsewhere. The current has a zero value at a point on this skywire, between towers 2 and 1 on the front line and towers 2 and 1 on the rear line.

Fig. 3.5 shows the current at 860 kHz. Note the change of vertical scale, indicating that the currents are about 4 times as strong as at 740 kHz. At this frequency, the larger tower spacings are expected to be in strong "two-wavelength" resonance. Indeed, the phase on the skywires between towers 4 and 2, 1 and 3, 3 and 5, and 5 and 7 on the front line has a strong constant component. Similarly, a strong standing wave component is evident between towers 4 and 2, 1 and 3, and 5 and 7 on the rear line. There is overall a greater degree of "constant phase" behavior than at 740 kHz, although the picture is nowhere near as clear as it was for the evenly-spaced power line case.

The current magnitudes at 860 kHz behave quite differently than at 740 kHz. Thus in Fig. 3.5, on the front line the current is strongest on towers 3, 5 and 7 near the antenna, and the current noticeably tapers going from tower 15 thru 17, 19, 21, and 23 to 25. The towers of the rear line show even more interesting behavior. The currents are for the most part weaker than on the front line, suggesting that a significant degree of shielding is operative at frequencies near resonance. Also, note that going along the rear line onto the dogleg, from tower 69 thru 71, 73, 75 and 77 to 79, the current increases greatly. This suggests that the towers of the dogleg which have been omitted from the model must carry strong currents, and so the azimuth pattern for the actual site is expected to be somewhat different from the computations and measurements in reference (1), and is presented in the next section.

3.3 Hornby Model with More Towers on the Dogleg

Fig. 3.6 shows the azimuth pattern where 5 additional towers are included on the dogleg. Thus in the plan of Fig. 3.3, towers # 8, 10, 12, 14, 16, 18, and 20 are included on the dogleg. In comparison with reference (1) Fig. 3.38, it is seen that the azimuth pattern does not change greatly. Fig. 3.7 shows the RF current distribution on the model. The tower and skywire currents on the front line are almost the same as in Fig. 3.5, except that the maximum current is reduced by about 100 microamps. The currents on the towers and skywires of the rear line are now somewhat stronger than before. Also, the current on the additional towers of the dogleg clearly decreases with distance along the dogleg, suggesting that enough towers are now included on the dogleg. Note also that the small tower to tower spacings on this part of the dogleg, averaging about 850 m (see reference (1) Fig. 3.32) are clearly below two wavelength resonance in Fig. 2.2, and this is confirmed in Fig. 3.7 by the travelling wave current seen on the skywires connecting these towers.

3.4 Summary

The current distribution graphs of Fig 3.4 and 3.5 are useful in assessing whether the frequency of the broadcast antenna is near a resonance of the power line, without having to resort to expensive frequency-sweep computations. The strength of the RF current on the towers and skywires near the ends of the power line relative to the strength of the current near the antenna indicates whether enough towers have been included in the model. Also, the detailed distribution and strength of the

RF current may be a good guide to the placement of detuning stubs on the skywires.

4. Prediction of Null-Filling by Computation

Many MF radio stations must employ a directional broadcast antenna in order to meet a licencing provision which stipulates that the radiated signal must be below a specified level over a specified arc in order to avoid interference with another station which operates on the same frequency. When a power line is constructed near such a broadcast array, even small amounts of RF energy reradiated by the power line into the "protected arc" can violate the station's licencing provision.

In this project, attention has thus far been directed to the prediction of the "scalloping" of the circular azimuth pattern of an omnidirectional broadcast antenna by reradiation. In the case of "scalloping", the broadcast engineer's chief concern is that the level of the RF signal be sufficiently strong in all directions. Thus deep minima in the "omnidirectional" pattern must be avoided. It has been found in this project that it is useful to view the towers of the power line as an "array antenna" which has a radiation pattern that in general consists of some strong "main lobes" plus a great many "sidelobes". The large minima in the omnidirectional antenna's pattern are caused by the tower array's main lobe, and so the prediction of "scalloping" is essentially the prediction of the magnitude and phase of the power line tower array's main lobe.

The case of "null-filling" is different. Here, the "main lobe" of the power line tower array will generally not fall in the direction of the broadcast array pattern's minimum, unless the geometry happens to be most unfavorable. Otherwise, it will be the sidelobes of the power line tower array's pattern which coincide with the direction of the pattern minimum and which are responsible for reradiation in that direction. Thus the prediction of "null-filling" is the problem of predicting the sidelobes or "fine details" of the tower array's radiation pattern.

The measurement portion of this project has provided some results by which the success of the computation of null filling can be assessed. Interim Report # 1(2) uses the two-element antenna of Fig. 4.1 to generate a figure of eight pattern with the maxima oriented "broadside" at 0 and 180 degrees. The measured minima are 38 dB down from the main lobes. A power line of five towers is then introduced into the array's main lobe at 180 degrees, and the pattern is measured with and without the skywire connecting the towers.

4.1 Results of Null-Filling Computations

Fig. 4.2 compares the computed and the measured azimuth patterns for the two element array, and demonstrates that an accurate pattern is computed for the array. The position of the five tower power line relative to the array is shown in Fig. 4.3. The dimensions are those used in the computation. At 1000 kHz, the "loop size" is (2x300)+(4x50.6) = 803.3 m, which is 2.67 wavelengths. This is well above the frequency at which "two wavelength" resonance would be expected, as can be seen from Fig. 2.2. Thus the power line is essentially non-resonant.

Figs. 4.4 and 4.5 compare the results of the computation with the measured pattern for the cases of "towers only" and "towers plus skywires" respectively. The towers were modelled as in reference (1) by using the "single wire tower model" with the tower radius of 3.51 m and the skywire radius of 0.71 m. The towers were taken to be 50.6 m tall. With no skywire, the 5 element "tower array" reradiates strongly into the minimum of the directional array. The computed pattern is not identical to the measured one, but it is seen that the "three lobe" structure of the minimum of the measured pattern is reproduced well particularly for the minimum at 270 degrees. Also, the level of the computation accurately "predicts" the level of the measured pattern in the minimum.

For the case of towers interconnected by skywires, Fig. 4.5 shows that the reradiation effect is not as strong. The measured pattern is quite assymetric. The agreement in Fig. 4.5 must thus be considered acceptable.

4.2 Conclusions

Further investigation of the problem of the prediction of null-filling by computation must await the availability of more measured patterns. It would be of particular interest to have a knowledge of the frequency dependence of the reradiated field at frequencies near the operating frequency of the directional array. Simply changing the frequency of the oscillator is not adequate because the directional properties of the array change dramatically and tend to mask the behavior of the reradiated field from the power line. Instead, a frequency sweep using a simple non-directional antenna to excite the power line would reveal the resonant frequency of the power line. Then, a directional array could be set up at three different frequencies chosen to be below resonance, at resonance, and above resonance, and the pattern recorded. For each of these three patterns, the spacing and height of the elements of the array would have to be changed in order to maintain the figure of eight pattern. This set of three patterns would provide a sound basis for further computational study of null-filling.

5. Detuning by Isolating Towers

By breaking the electrical connection between the top of the tower and the skywire, the tower is "isolated" and two adjacent resonant two-wavelength loops are broken. Interim Report # 4(3) showed for the straight, evenly-spaced power line that isolating 9 of the 13 towers resulted in a large reduction in the degree of scalloping of the omnidirectional pattern. Interim Report # 5(4) showed that a similar reduction can be achieved for the pattern of the full Hornby site model. This section investigates the utility of the computer model in predicting the patterns with some towers isolated.

5.1 Simple Model

The simplest possible model of the isolated tower is that of Fig. 5.1 and is obtained from the "single wire tower model" of the power line in reference (1) Fig. 4.3, by disconnecting the tower wire from the skywire and separating the top of the tower wire from the skywire center by a "gap" which is at least as large as the skywire radius. The tower can never be fully "open-circuited" from the skywire, in the sense that there is capacitive coupling between the tower and skywire which cannot be suppressed. In this model, the amount of capacitive coupling can be controlled by adjusting the size of the gap between the tower top and the skywire. An additional complication enters in that the NEC computer code forces the current to be zero on an open end such as the top of the "isolated" tower. Thus the charge on the end of the tower wire is forced to be zero and so a mechanism for capacitive coupling between the tower top and the skywire is deliberately suppressed by the computer program. This difficulty can be partly overcome by using more segments on the tower wires, and so 3 segments per tower were used instead of two as for previous models.

The required gap size in Fig. 5.1 was chosen empirically by computing the azimuth pattern for a gap size equal to the skywire radius, twice that radius and four times that radius. The computation was done to match Fig. 12 in reference (4) which uses a 13 tower power line with towers # 1, 5, 9 and 13 connected to the skywire and all others isolated. The "best" single wire tower model of reference (1) was used, with 50.6 m tall towers of radius 3.51 m, and a skywire of radius 0.71 m. Fig. 5.2 compares the measured pattern to that computed with a gap size of four times the skywire radius. The two patterns are similar and differ mainly near zero and 180 degrees.

Figs. 5.3(a) and (b) show the RF currents on the towers and skywires of the power line. It is seen that the "zero-current-at-a-free-end" assumption of the NEC program results in the current on the top segment of each tower being only half the value of the current on the bottom segment. Note that this is not so for towers 1,5,9 and 13 which are connected to the skywire. The three "center" towers carry the largest currents, and in fact carry twice as much current as the adjacent connected towers. In the phase behavior, it is seen that the towers can be grouped into five "center" towers with phase of about one hundred degrees, and two groups of "outer" towers with phase averaging about 40 degrees. The grouping is also evident from the skywire phase behavior. It is seen that the "outer" skywires connecting towers 1 to 5, and towers 9 to 13 carry primarily travelling wave currents. However the "center" skywires connecting towers 5 to 9 carry strong standing waves.

5.2 Frequency Dependence

An initial investigation of the frequency dependence of the detuning achieved by "isolating" towers was carried out by isolating only towers # 3 and 7 on a nine tower, straight, evenly-spaced power line. The azimuth pattern was then computed and the max-to-min ratio determined over a range of frequencies, and the results are shown in Fig. 5.4 . It is seen that at some frequencies, such as 810 kHz, the power line has been detuned effectively but at others, such as 910 kHz, the max-to-min ratio is worse. If the skywire and its image are viewed as a transmission line, a tower connected to the skywire presents a line-to-line impedance across the transmission line that is sufficiently close to a short circuit to allow the frequency dependence of the resonances to be understood in terms of a graph such as Fig. 2.2 . However, the "isolated" tower presents an unknown line-to-line impedance across the transmission line, and so the frequency dependence cannot be graphed without extensive computations. Such a graph might be useful as an aid to determining which towers to isolate to effectively detune a given power line.

5.3 Conclusion

The agreement between the measured and computed patterns in Fig. 5.2 needs to be improved for the computer model of the isolated tower to be considered satisfactory. An improved model could then be used to investigate the problem of which towers to isolate to detune a given power line configuration. In view of Fig. 5.4, isolating some towers without a systematic understanding of the effect on resonant frequency can make the scalloping of the pattern worse than it was with all towers connected to the skywire.

6. Detuning with Stubs

It has been demonstrated in Interim Report # 7(4) that the "parallel stub" shown in Fig. 6.1 shifts the resonant frequency of the power line and effectively suppresses the currents on the towers and skywires. The detuning stubs can be analysed by computer modelling, as is demonstrated in this chapter. The measurements in reference (4) were carried out using the large, detailed 200 scale factor towers, with three towers on the turntable, and one skywire connected to the top crossarm on the side of the tower near the monopole.

6.1 Behavior with no Detuning Stubs

The "single wire tower" model serves to represent the 200 scale towers, as will be shown in this section. Fig. 6.1 shows the geometry of the three tower model, which was used without the detuning stubs for the results of this section. The dimensions were (full scale) : tower height 50.6 m(166 ft) ; tower separation 274.3 m(900 ft) ; distance to antenna 448.1 m(1470 ft) ; tower 'equivalent radius' 3.51 m ; and skywire 'equivalent radius' 0.71 m . At 860 kHz, the computed azimuth pattern is that shown in Fig. 6.2 as crosses. The measured pattern, which is shown as a solid line, is taken from reference (4) Fig. 13 and was measured at 172 MHz. The patterns are in good agreement although the slight shift in the depth of the minima and the angles of the maxima and minima suggests that a small discrepancy exists either between the frequency of the computation and the measurement, or in the model dimensions between the two cases.

Lavrench(5) measured the azimuth pattern at a set of frequencies, and the max-to-min ratio of these patterns is plotted in Fig.6.3 . It is seen that the power line is resonant at about 860 kHz. The max-to-min ratio was computed at the same frequencies, and is also plotted in Fig. 6.3. The agreement is considered satisfactory. The width of the two resonance curves is comparable, which is notable because previous computed resonance curves have been too narrow. Also, note that with only three towers the azimuth pattern is "scalloped" much less than with 13 towers, and indeed the "scalloping" of less than 1 dB at CBL's frequency of 740 kHz hardly requires "detuning" at all.

For later reference , the RF currents flowing on the three towers without detuning stubs at 860 kHz are plotted in Fig. 6.4 . The currents on the three tower model behave as expected from previous work. The current is strongest on the center tower. The phase changes by 180 degrees from tower to tower. The current on the skywires is a standing wave because it has constant phase with position, indicating the frequency is near the power line's resonant frequency. The current peaks at about the center of the skywire, and has nulls with corresponding abrupt 180 degree phase reversals at about 60 m from each tower.

6.2 Pattern with One Detuning Stub

The azimuth pattern at 860 kHz with one detuning stub is reported in reference (4) Fig. 17. The geometry of the experimental model differs somewhat from that of Fig. 6.1 in that the stubs were located near tower # 2 on the skywire from tower 1 to 2, and near tower # 3 on the other skywire. Also, the stub was "hung" below the skywire in the measurement but located at the same height as and behind the skywire in the calculation. The measurement was repeated for stub spacings "d" varying from 0.32m(12.5 inches) to 1.27 m(50 inches) full scale and no change was noted in the pattern. For convenience, the computer model was set up as shown in Fig. 6.1, with the stub behind and at the same level as the skywire. The skywire's 'equivalent radius' of 0.71 m was used for the stub as well, and so to avoid overlapping of the stub and the skywire, "d" had to be chosen greater than 1.42 m. A spacing of one-twentieth of a wavelength or 17.4 m at 860 kHz was chosen. The length of the stub was one quarter wavelength at 860 kHz, or 87.2 m. Thus the stub in the computation had an electrical path (d+l) which is significantly longer than that used in the measurement. In spite of these differences, the computer model reproduces the measured pattern very closely as shown in Fig. 6.5 . Unfortunately, no measured data is available for the frequency dependence.

Fig. 6.6 shows the currents on the towers and skywires in part (a) and on the connecting links and stubs in part (b), respectively. In comparison with Fig. 6.4, the tower and skywire currents have been reduced by a factor of six. The skywire currents are completely altered in character. The skywire can now be divided into two portions, each carrying a travelling wave. The two portions are separated by the null in the current that occurs at about forty percent of the length of the skywire distant from the tower nearest the stub. Fig. 6.7 is a sketch of the pattern of the current flow on the model. The currents are primarily travelling waves and flow essentially up tower # 1 and along the skywire, decreasing to zero in magnitude. Then, starting again from zero, the travelling wave flows along the skywire, and is joined by an incoming wave from the adjacent skywire, and flows down the center tower. The structure behaves as three top loaded monopole antennas.

It is suggested that the stub is effective by virtue of its being placed near a location on the skywire where the current on the un-detuned line has a minimum. At such a point, the current magnitude is small so the circumferential H-field is small, but the current is changing rapidly so the linear charge density is high and the radial E-field is high. A useful definition of "impedance" is the ratio of radial E to circumferential H, and a current minimum is therefore a point of high E, low H and so high impedance. To disturb the resonant structure considerably, a low-impedance element should be connected at such a high impedance point. One such point is the current minimum on the skywire near each of the towers. A stub of length approximately a quarter wave presents a suitable low impedance element to connect at this point. At the open end of the stub, H is approximately zero because the current is zero, and so the impedance is high. However, approximately one quarter wave away from the open end, H is a maximum, and the radial E field is small because the current magnitude has a maximum and its derivative, proportional to the linear charge density, is zero.

Radial E is proportional to the linear charge density as well, and so radial E has a minimum. Thus at about a quarter wave from the open end, the stub presents a low impedance - small E over large H. This low impedance element is connected to a high-impedance point on the original structure, namely at the current minimum, and so alters the current distribution and destroys the resonance. Note that the location of the connection point for the stub in Fig. 6.6 corresponds closely with the location of the current minimum on the skywire in Fig. 6.4 .

6.3 Frequency Dependence with one Detuning Stub

Fig. 6.8 compares the max-to-min ratio using one detuning stub as described above, with that of Fig. 6.3 using no stub. It is seen that the power line is effectively detuned over the range shown in the figure, particularly near the stub's "design frequency" of 860 kHz. Above this frequency the max-to-min ratio rises sharply.

6.4 Frequency Dependence with Two Detuning Stubs

Lavrench(5) measured the azimuth pattern as a function of frequency for the case of two detuning stubs, as shown in Fig. 6.8 . The lengths were chosen to be one-quarter wavelength at 172 MHz and 150 MHz at 200 scale, and are 87.38 m and 101.09 m full scale, respectively. The gap between the open ends of the stubs corresponds to 0.3175 m full scale, and that value was used in the calculations. The separation "d" of the stub from the skywire was maintained at 17.4 m in the calculation. Fig. 6.10 shows the measured and computed max-to-min ratio of the pattern as a function of frequency. With the two stubs in place, the frequency dependence is quite flat and no resonance is evident. The computed curve is about three-quarters of a dB less than the measured curve. This discrepancy may be due to the extreme close spacing of the ends of the two stubs used to compute Fig. 6.8 . The wires used for the stubs had radii equal to the skywire radius, and two such large wires spaced so closely couple capacitively. A larger spacing may give improved results.

6.5 Conclusion

This section has demonstrated that the computational technique can successfully predict the azimuth pattern and frequency dependence of the three tower power line, when it is "detuned" with stub traps. Further development of the model could remove the discrepancy between the stub length in the computer model and in the measurement model, and could obtain better agreement in level between the frequency sweep computation and measurement in Fig. 6.10 .

7. Recommendations for Further Work

This report has advanced the work on the modelling of complex sites using Hornby, Ontario as an example, and has extended the scope of the computer analysis technique to include the problem of null-filling, and that of detuning by isolating towers and by using stub traps. Further work will include :

i) the addition of more towers at each end of the power lines in the Hornby model ;

ii) the investigation of the optimum location for the stub traps, and of the optimum length of the stub, on a model with nine towers instead of three ;

iii) the use of detuning stubs on a complex site such as Hornby ; and

iv) the effect of a finite conductivity ground on the azimuth pattern of a straight, evenly-spaced power line, using the "SOMNEC" computer code.

For the present, no further investigation of null-filling will be undertaken, nor will the problem of isolated towers be studied in any more depth.

REFERENCES

[1] C.W. Trueman and S.J. Kubina, "AM Re-Radiation Project", Final Technical Report, TN-EMC-80-03, March 1980.

[2] J.S. Belrose, reported in, "The Effects of Re-Radiation from Highrise Buildings, Transmission Lines, Towers and Other Structures Upon AM Broadcasting Directional Arrays", Interim Report No. 1, DOC Project No. 4-284-15010, October 26, 1977.

[3] J.S. Belrose, reported in, "The Effects of Re-Radiation from Highrise Buildings, Transmission Lines, Towers and Other Structures Upon AM Broadcasting Directional Arrays", Interim Report No. 4, DOC Project No. 4-284-15010, November 1, 1978.

[4] J.S. Belrose, reported in, "The Effects of Re-Radiation from Highrise Buildings, Transmission Lines, Towers and Other Structures Upon AM Broadcasting Directional Arrays", Interim Report No. 7, DOC Project No. 4-284-15010, October 10, 1979.

[5] W. Lavrench, private communication, September 28th, 1979.

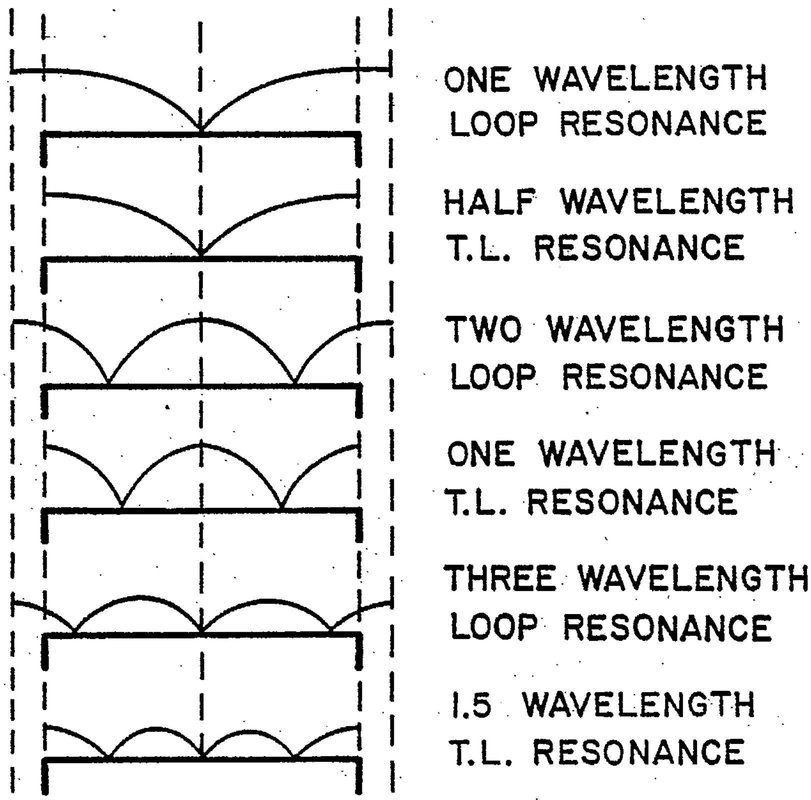


FIGURE 2.1

RF CURRENT DISTRIBUTION EXPECTED
FOR VARIOUS MODES OF RESONANCE

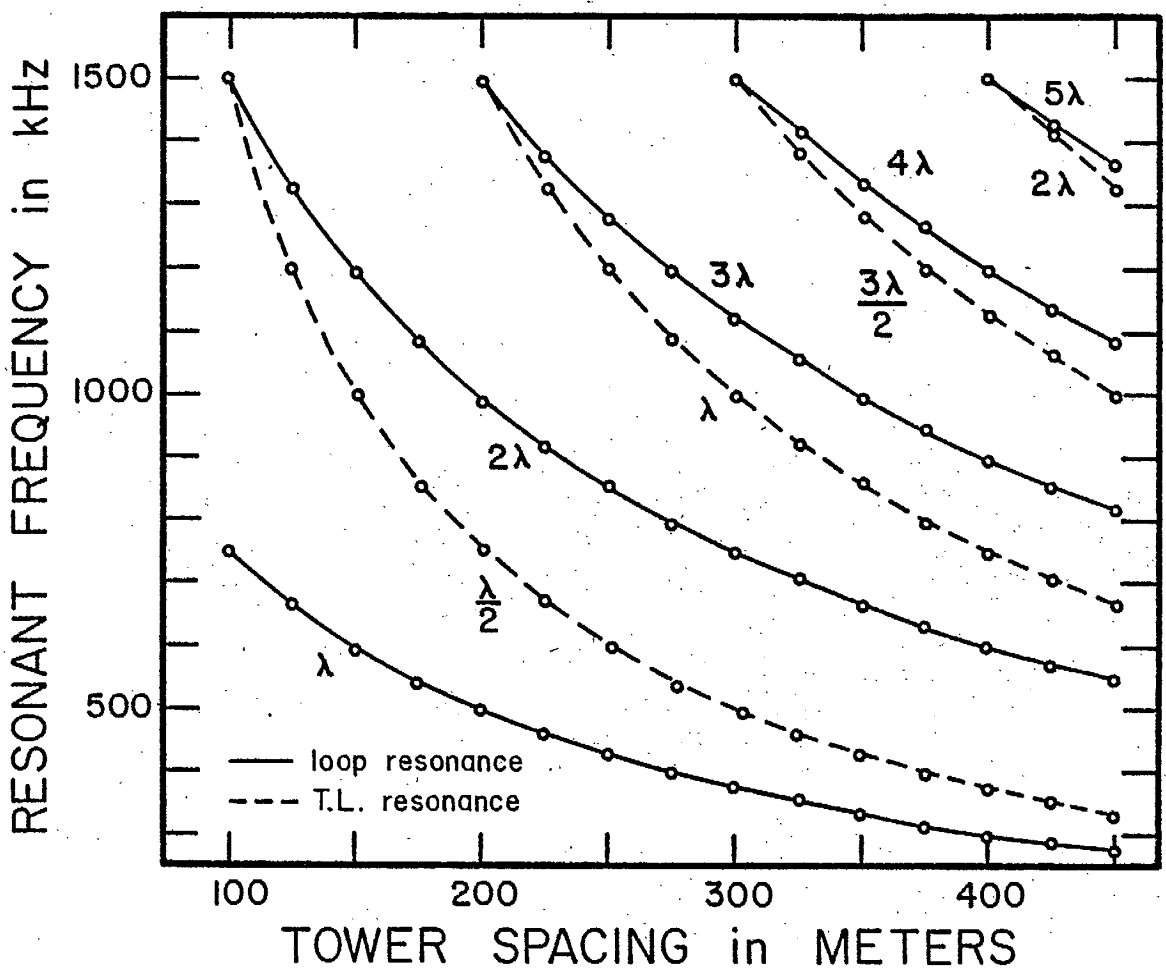


FIGURE 2.2

RESONANT FREQUENCY VS.
TOWER SPACING FOR 50.6 M TALL TOWERS

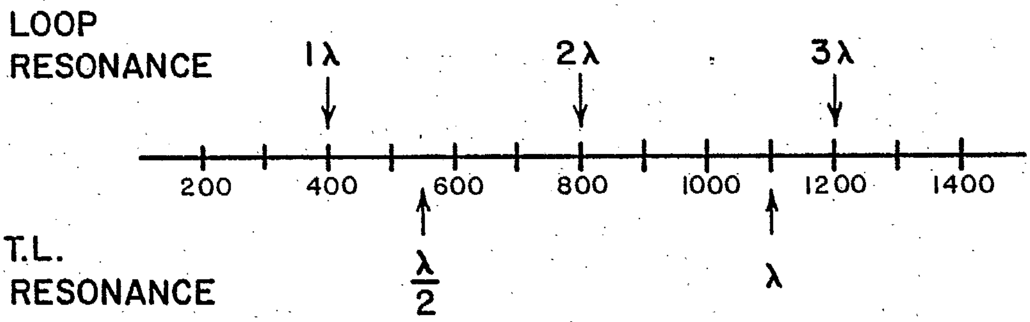


FIGURE 2.3

RESONANT FREQUENCIES FOR A TOWER SPACING OF 275 M WITH 50.6 M TALL TOWERS

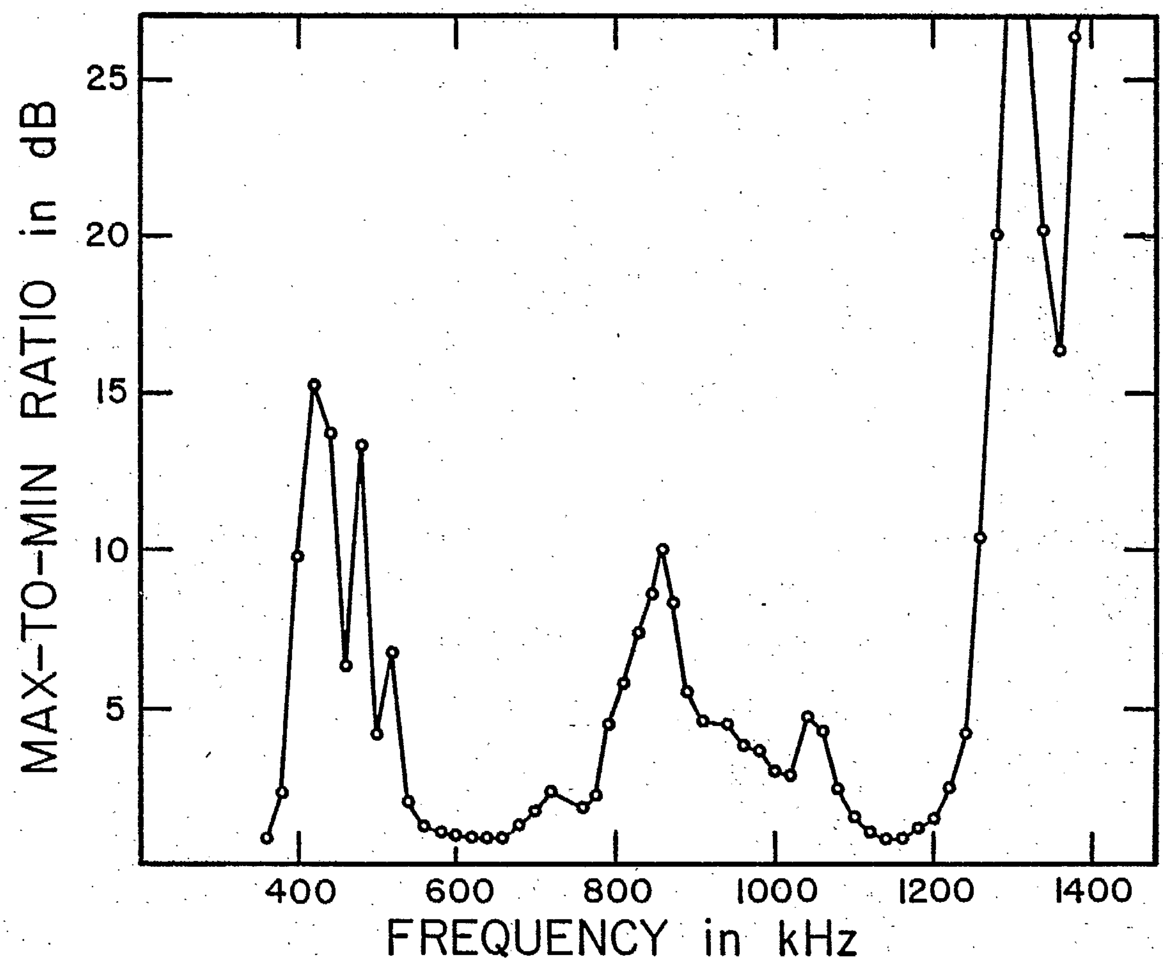


FIGURE 2.4

COMPUTED CURVE GIVING THE MAX-TO-MIN RATIO AS A FUNCTION OF FREQUENCY FOR NINE TOWERS SPACED 274.32 M APART

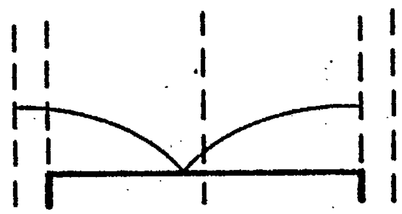


FIGURE 2.5

ONE-HALF WAVELENGTH HYBRID RESONANCE

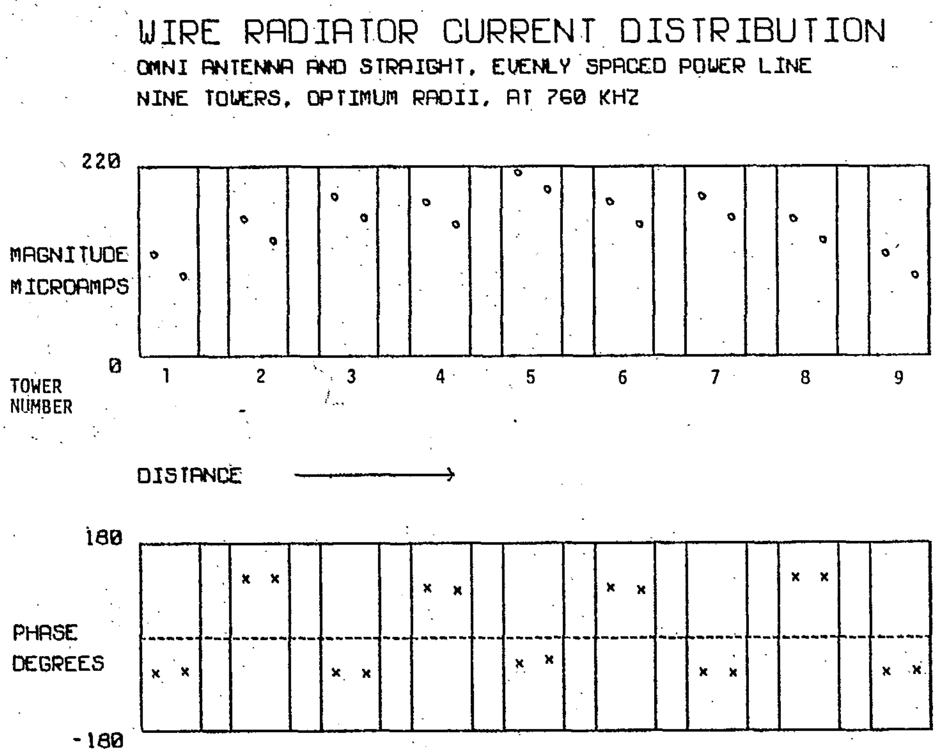


FIGURE 3.1 (A)

RF CURRENTS ON THE TOWERS, AT 760 KHZ

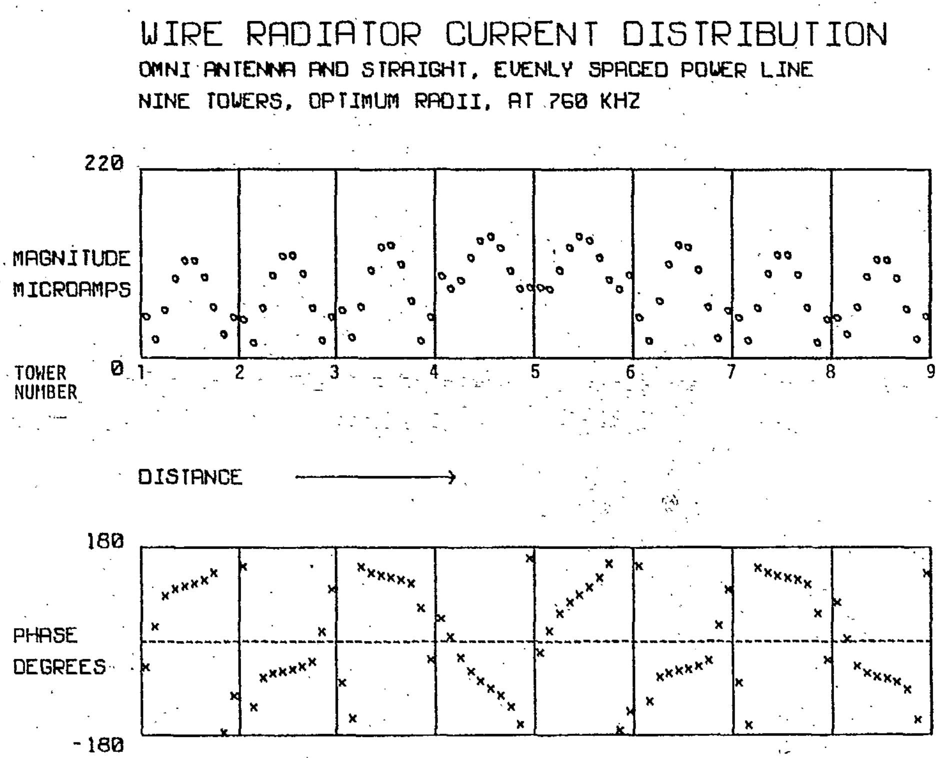


FIGURE 3.1 (B)

RF CURRENTS ON THE SKYWIRES, AT 760 KHZ

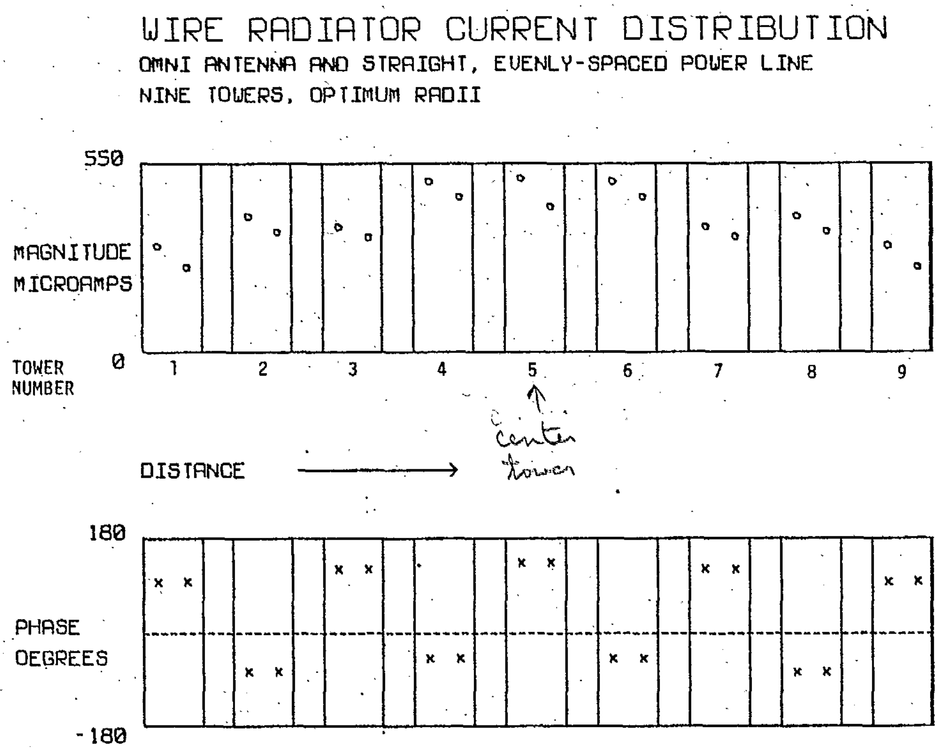


FIGURE 3.2 (A)

RF CURRENTS ON THE TOWERS AT 860 KHZ

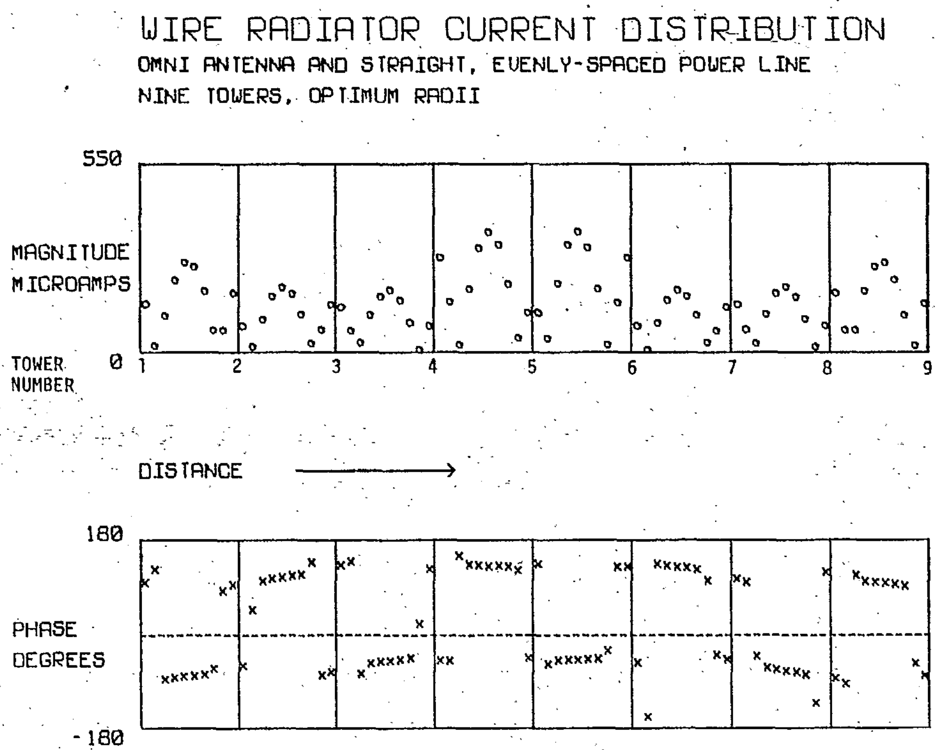


FIGURE 3.2 (B)

RF CURRENTS ON THE SKYWIRES AT 860 KHZ

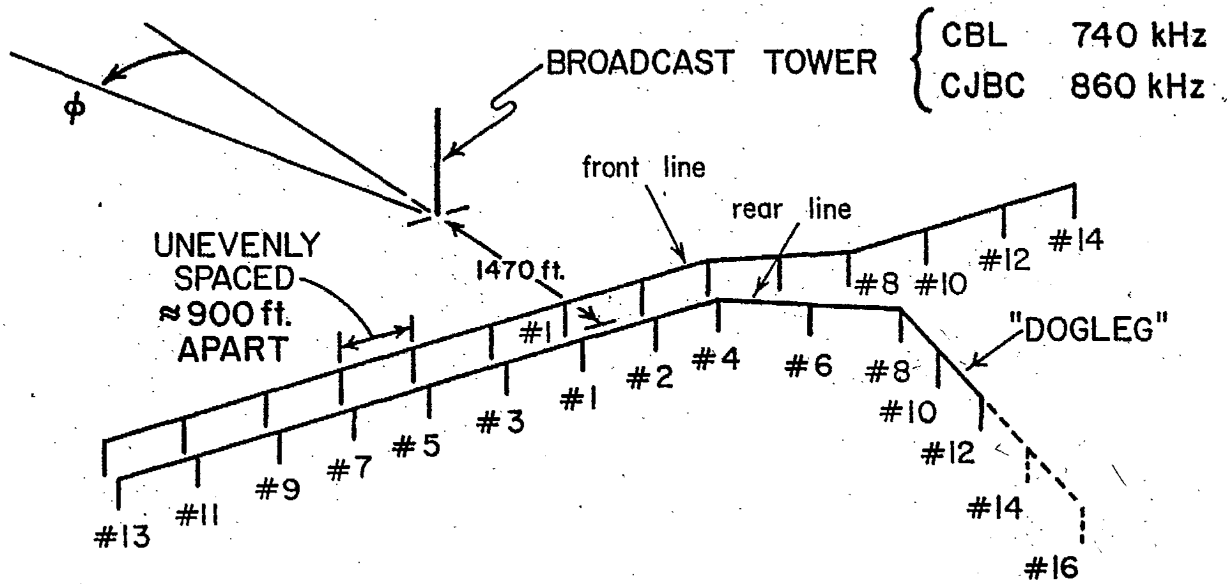


FIGURE 3.3

TOWER NUMBERING FOR THE HORNBY SITE MODEL

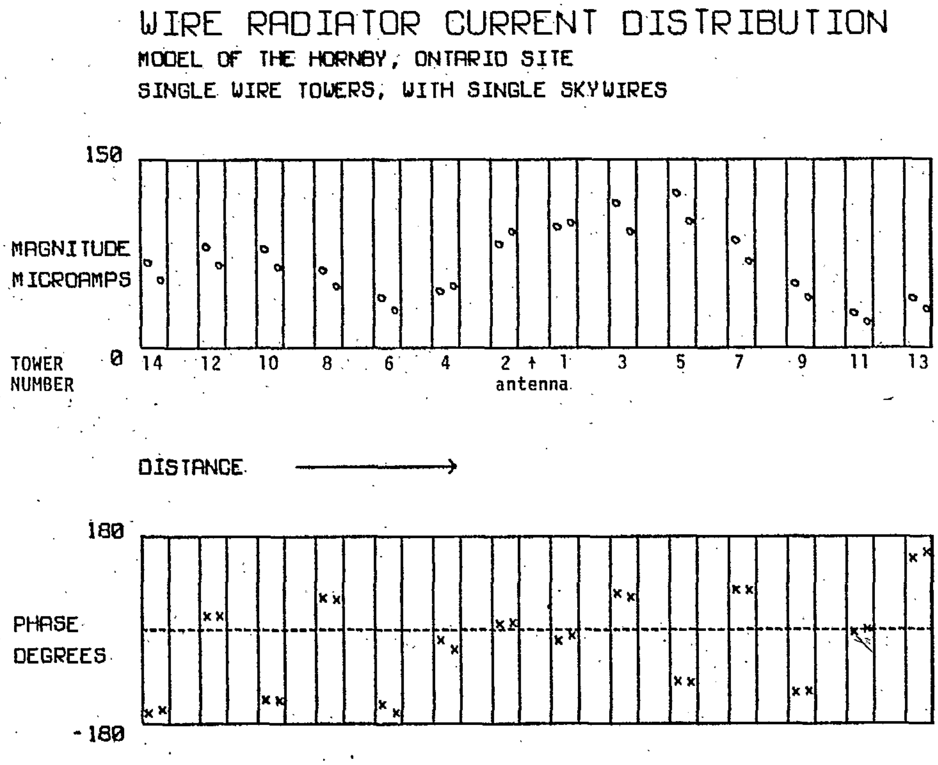


FIGURE 3.4 (A)

RF CURRENTS ON THE TOWERS OF THE FRONT LINE AT 740 KHZ

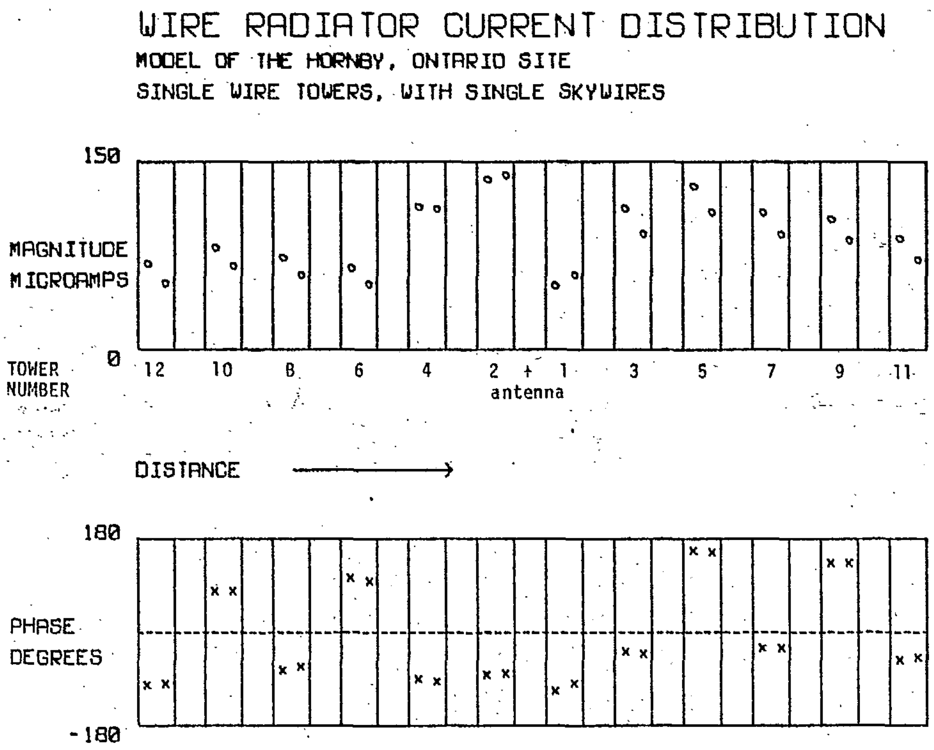


FIGURE 3.4 (B)

RF CURRENTS ON THE TOWERS OF THE REAR LINE AT 740 KHZ

WIRE RADIATOR CURRENT DISTRIBUTION
MODEL OF THE HORNBY, ONTARIO SITE
SINGLE WIRE TOWERS, WITH SINGLE SKYWIRES

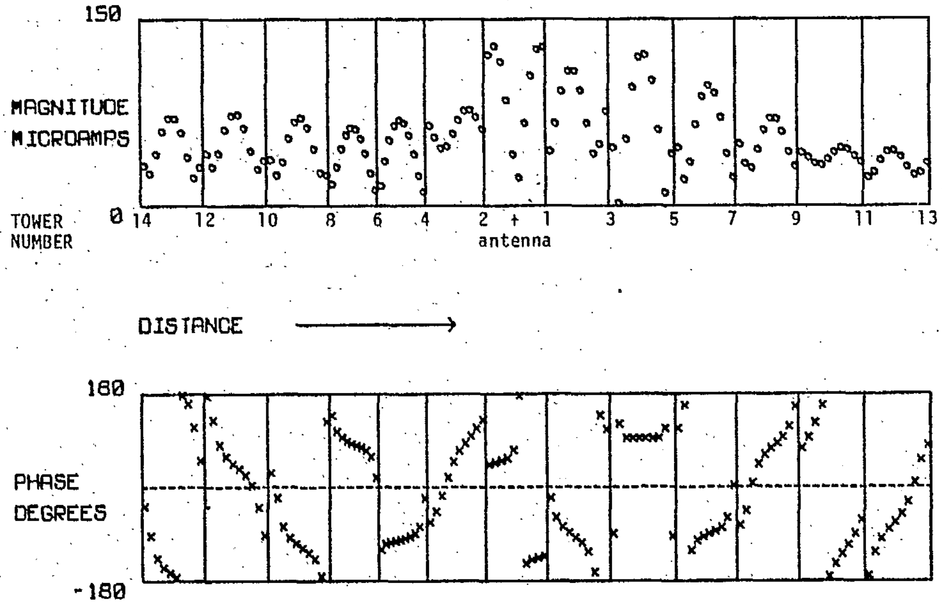


FIGURE 3.4 (C)

RF CURRENTS ON THE SKYWIRES OF THE FRONT LINE AT 740 KHZ

WIRE RADIATOR CURRENT DISTRIBUTION
MODEL OF THE HORNBY, ONTARIO SITE
SINGLE WIRE TOWERS, WITH SINGLE SKYWIRES

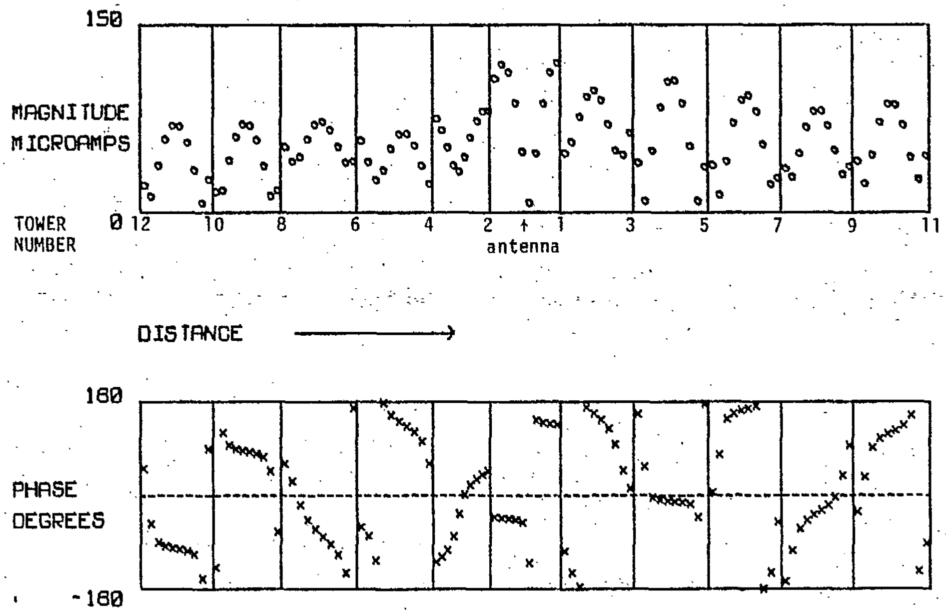


FIGURE 3.4 (D)

RF CURRENTS ON THE SKYWIRES OF THE REAR LINE AT 740 KHZ

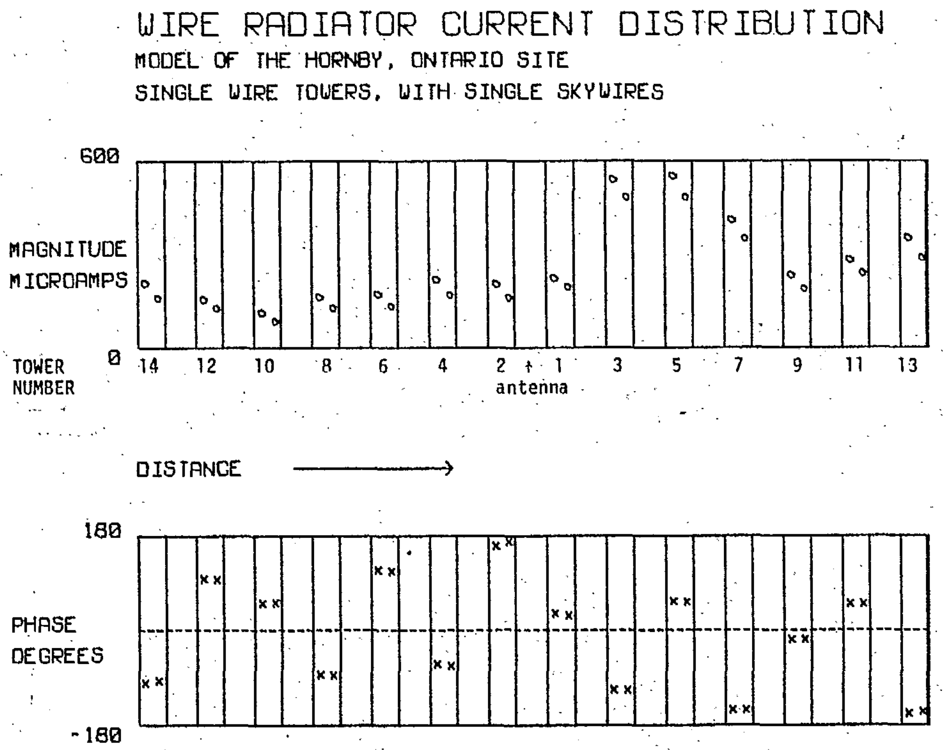


FIGURE 3.5 (A)

RF CURRENTS ON THE TOWERS OF THE FRONT LINE AT 860 KHZ

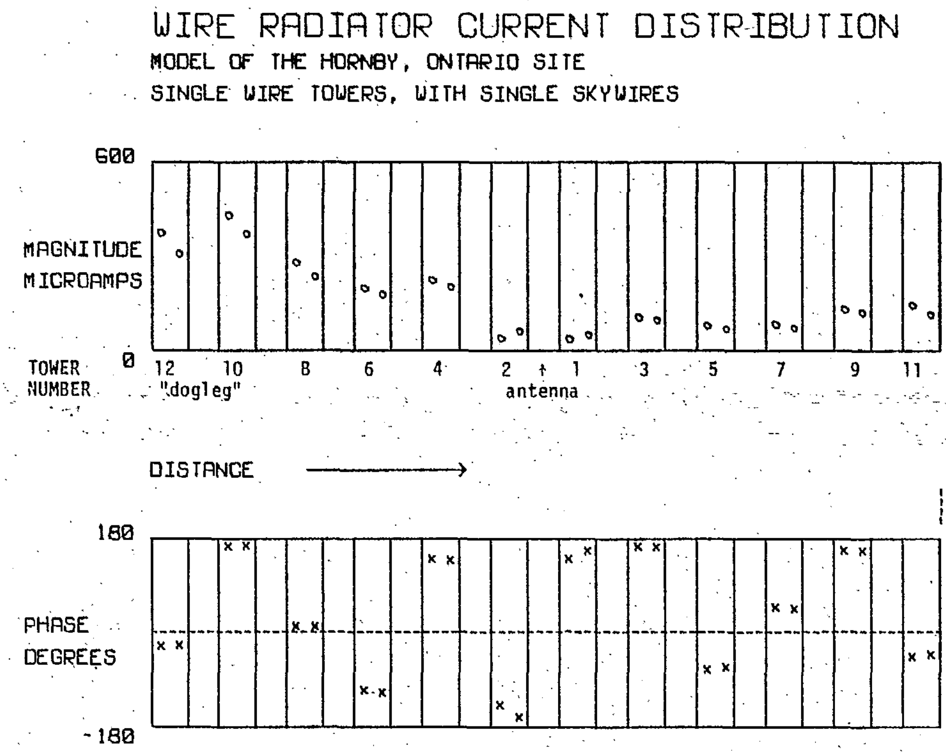


FIGURE 3.5 (B)

RF CURRENTS ON THE TOWERS OF THE REAR LINE AT 860 KHZ

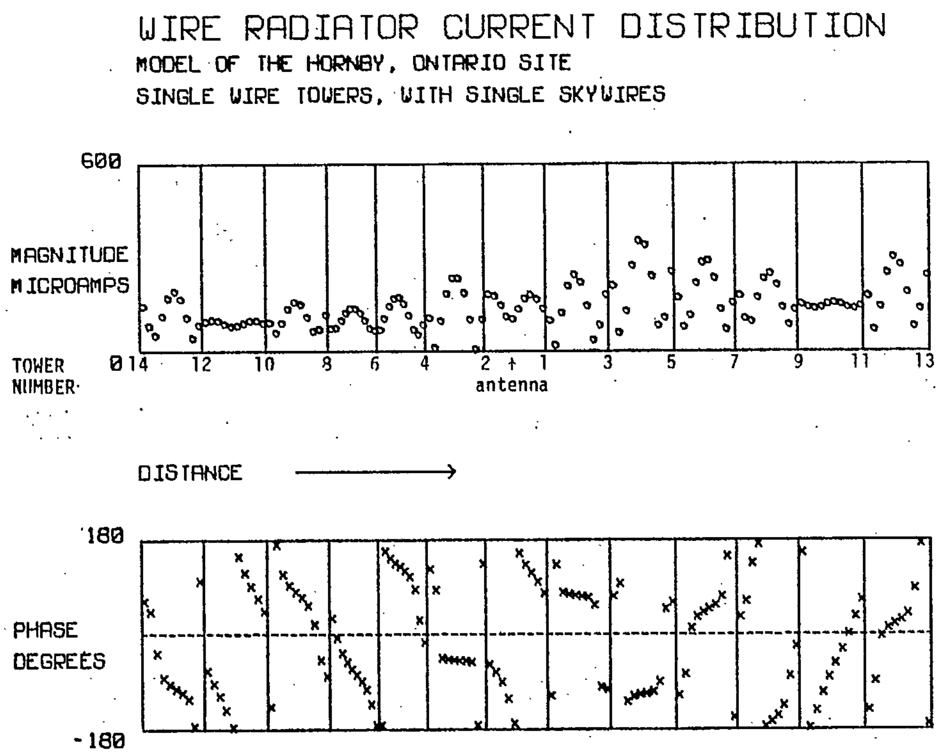


FIGURE 3.5 (C)

RF CURRENTS ON THE SKYWIRES OF THE FRONT LINE AT 860 KHZ

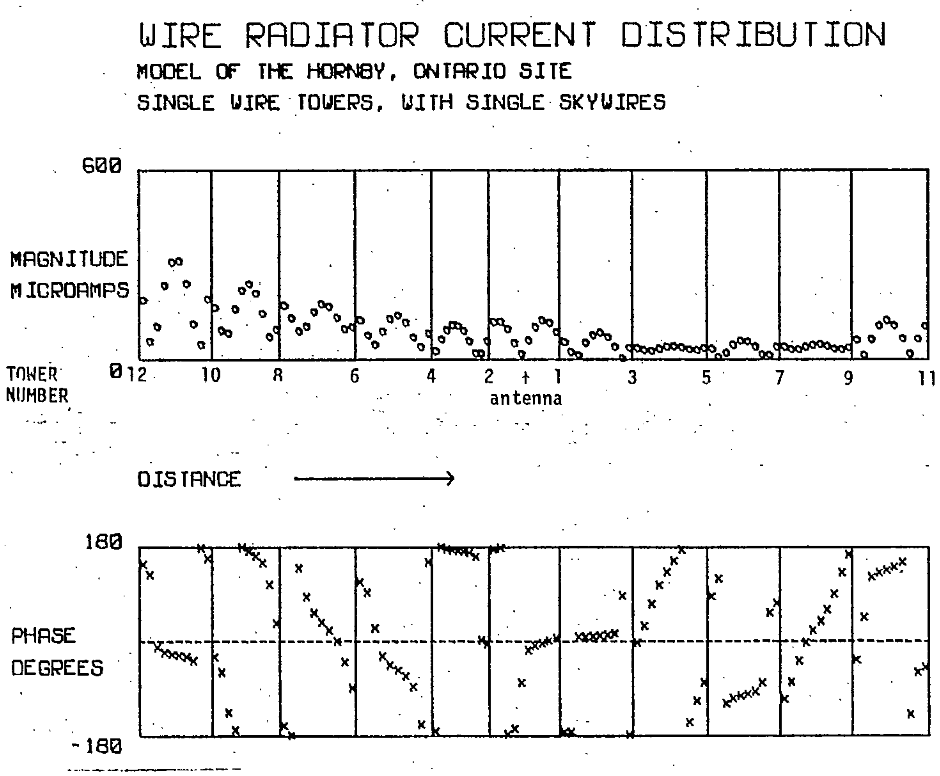


FIGURE 3.5 (D)

RF CURRENTS ON THE SKYWIRES OF THE REAR LINE AT 860 KHZ

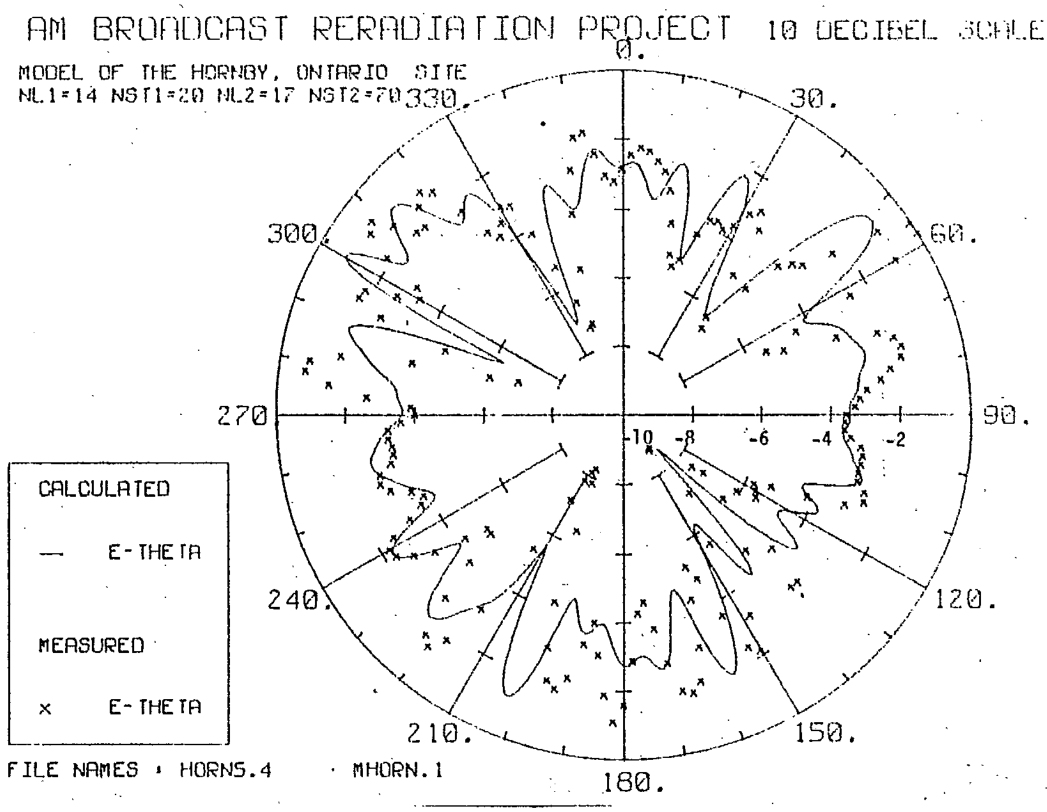


FIGURE 3.6

AZIMUTH PATTERN FOR THE HORNBY SITE
INCLUDING SEVEN TOWERS IN THE DOGLEG,
BEING #5 8,10,12,14,16,18 AND 20 IN FIG. 3.3

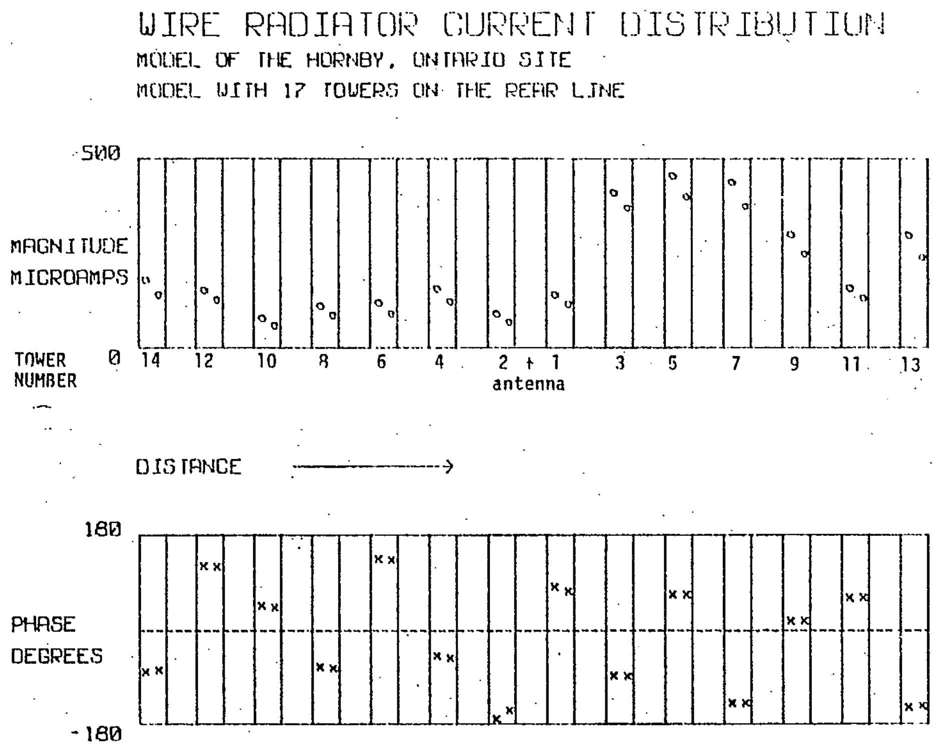


FIGURE 3.7 (A)

RF CURRENTS ON THE TOWERS OF THE FRONT LINE

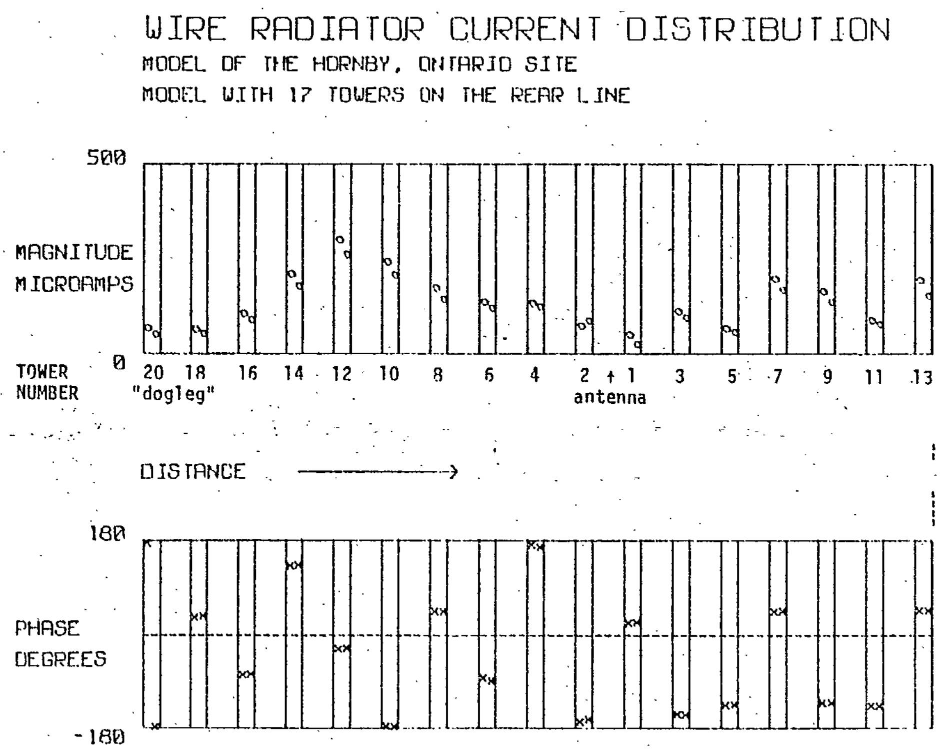


FIGURE 3.7 (B)

RF CURRENTS ON THE TOWERS OF THE REAR LINE

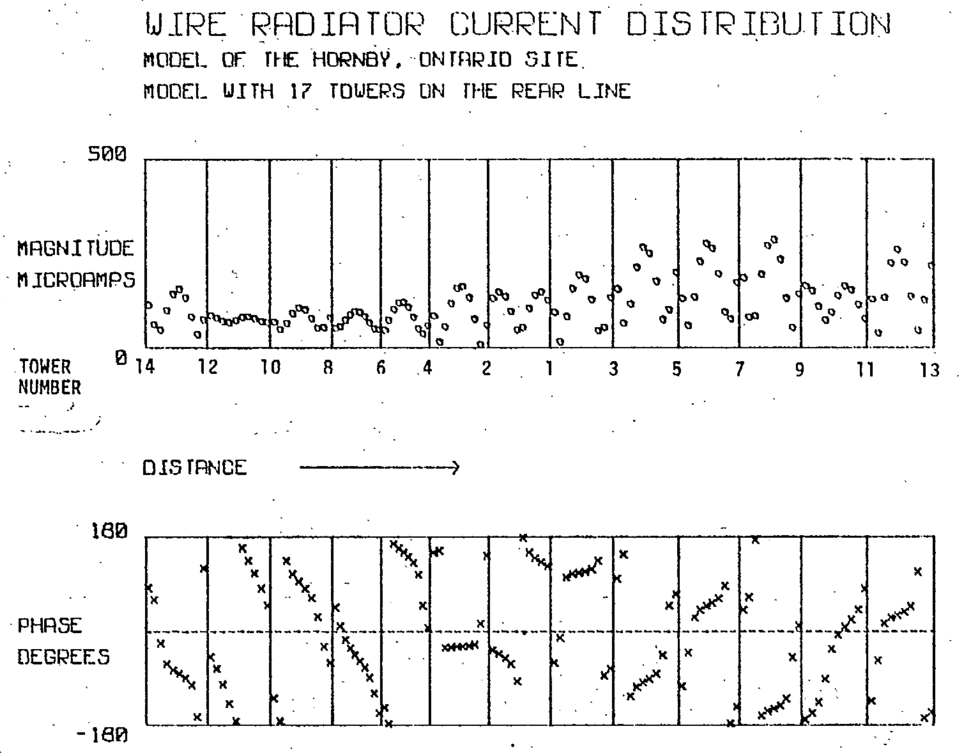


FIGURE 3.7 (C)

RF CURRENTS ON THE SKYWIRES OF THE FRONT LINE

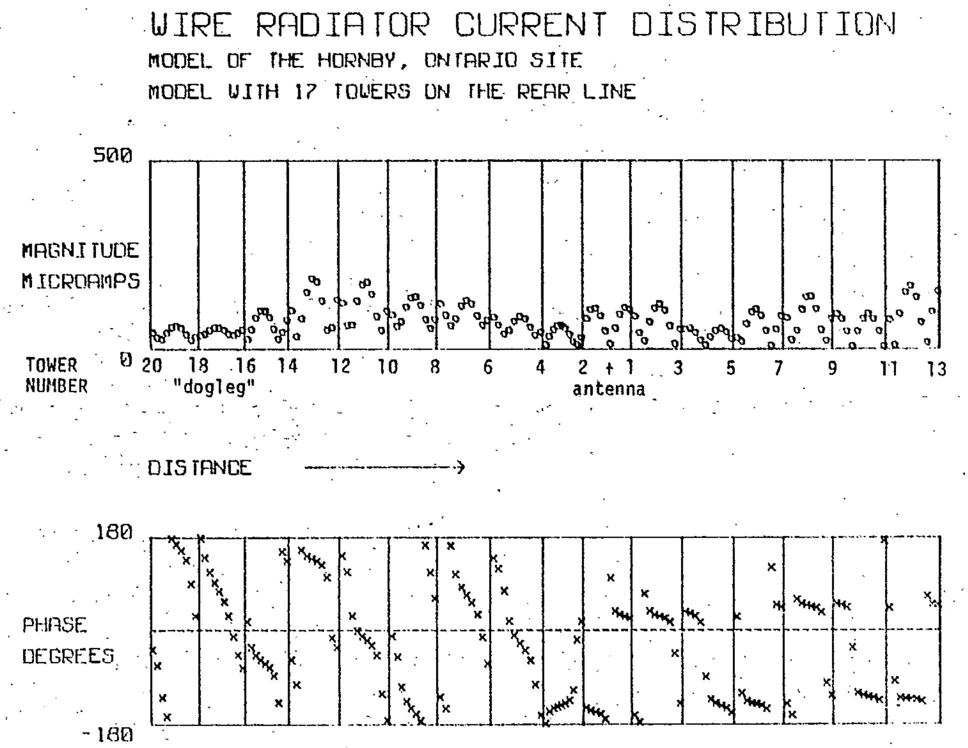


FIGURE 3.7 (D)

RF CURRENTS ON THE SKYWIRES OF THE REAR LINE

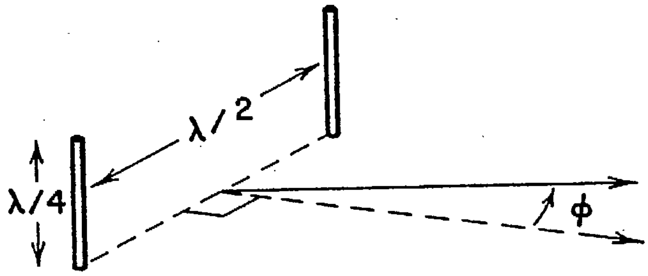


FIGURE 4.1

TWO ELEMENT DIRECTIONAL ARRAY

The towers are fed in phase, are 75 m tall, of radius 2 m, are located 150 m apart, and are operated at 1,000 kHz m in the computer model.

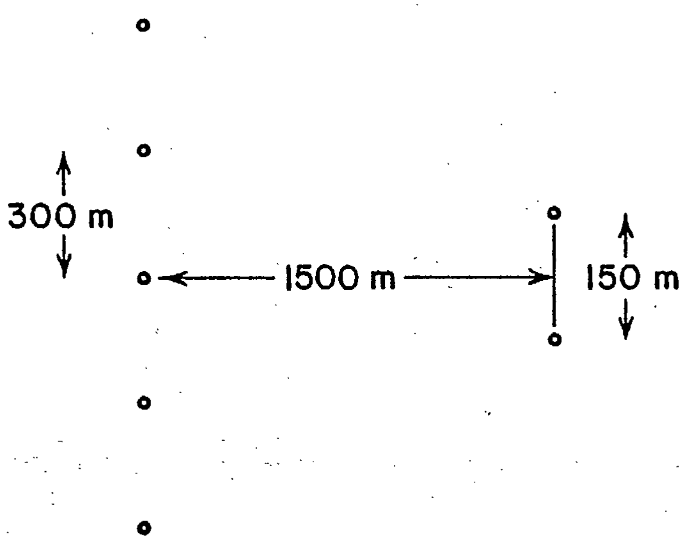


FIGURE 4.3

LOCATION OF THE FIVE TOWER POWER LINE RELATIVE TO THE ARRAY OF FIG. 3.1

The power line towers are 50.9 m (166 ft.) tall and of "equivalent radius" 3.51 m. The skywire radius was 0.71 m.

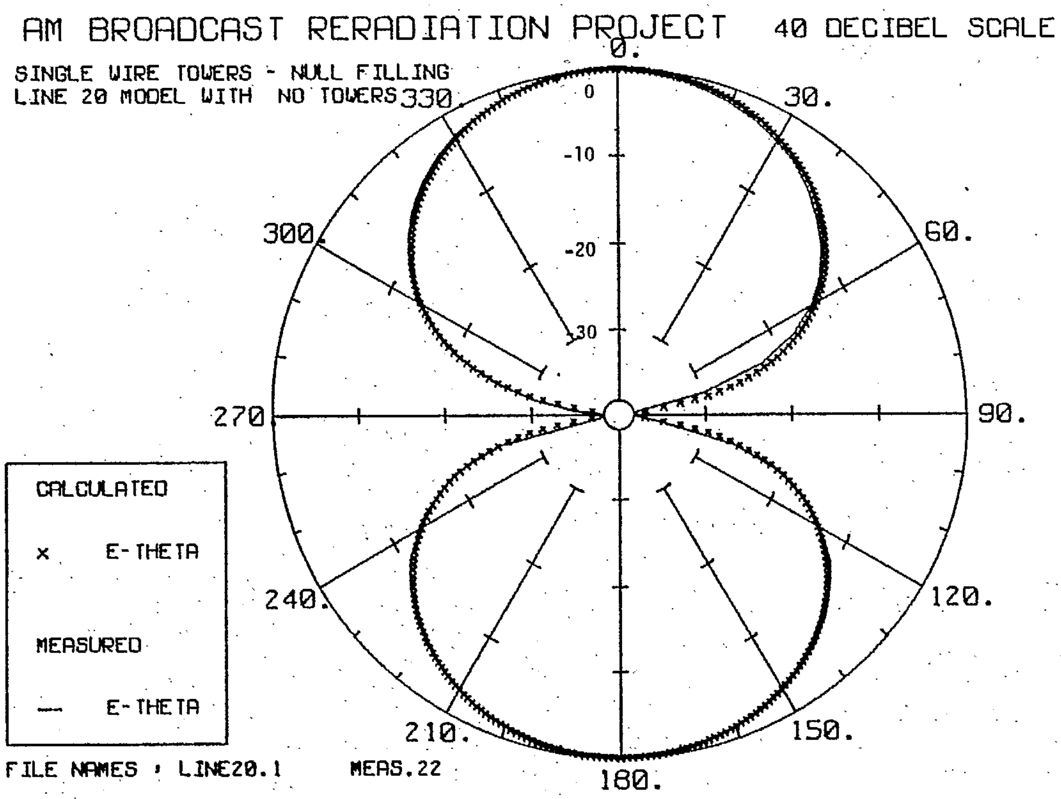


FIGURE 4.2

COMPARISON OF THE COMPUTED AND MEASURED PATTERN FOR THE DIRECTIONAL ARRAY

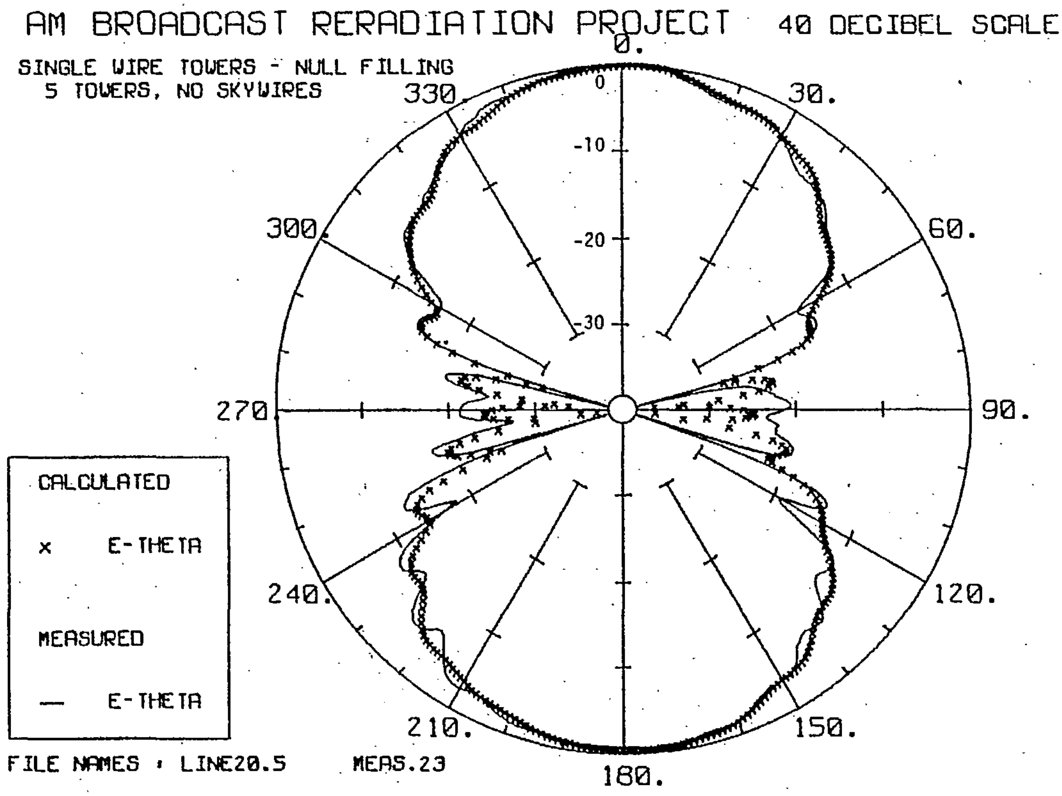


FIGURE 4.4

AZIMUTH PATTERN OF THE DIRECTIONAL ARRAY
IN THE PRESENCE OF THE POWER LINE TOWERS ONLY (NO SKYWIRES)

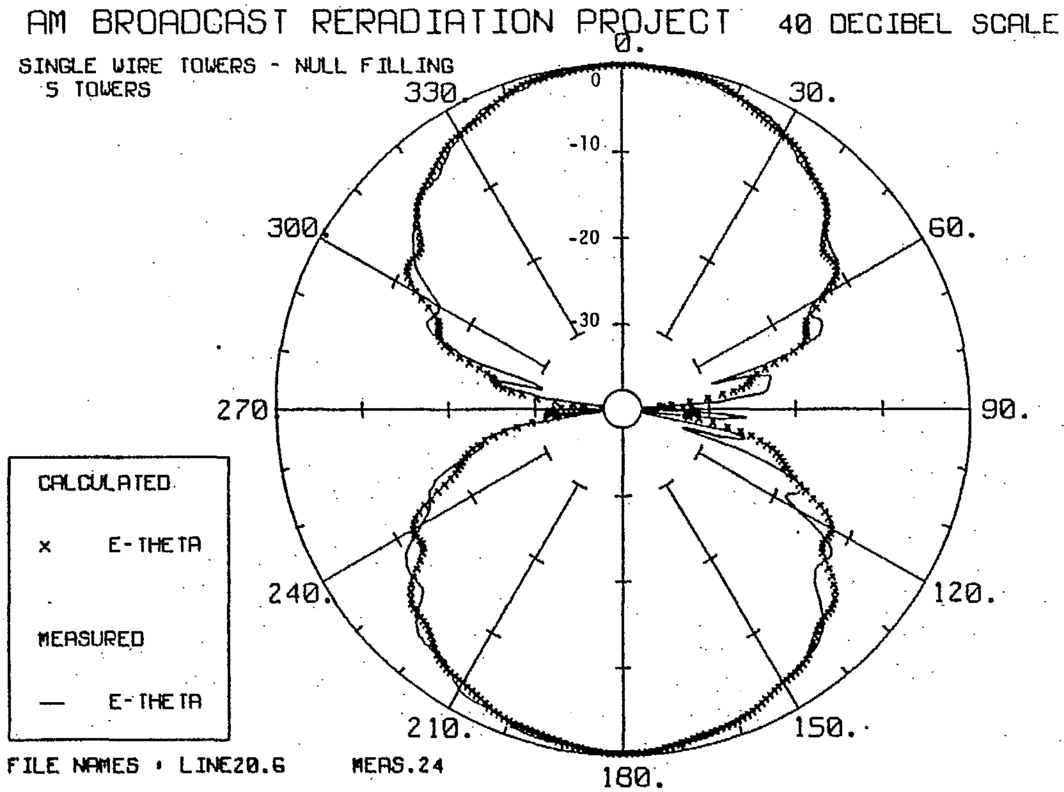


FIGURE 4.5

AZIMUTH PATTERN OF THE DIRECTIONAL ARRAY
WITH THE POWER LINE TOWERS
INTERCONNECTED BY SKYWIRES

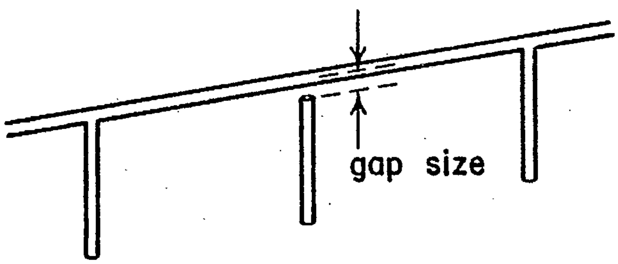


FIGURE 5.1

SIMPLE COMPUTER MODEL OF THE ISOLATED TOWER

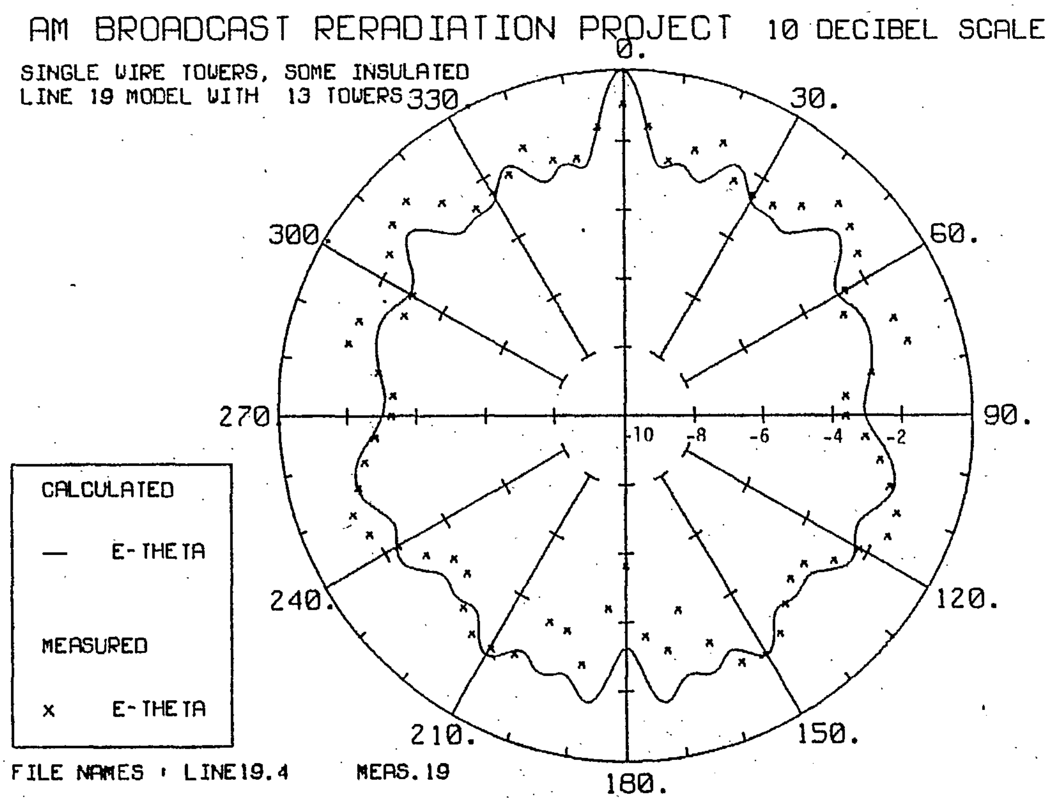


FIGURE 5.2

AZIMUTH PATTERN FOR THE GAP SIZE
EQUAL TO FOUR TIMES THE SKYWIRE RADIUS

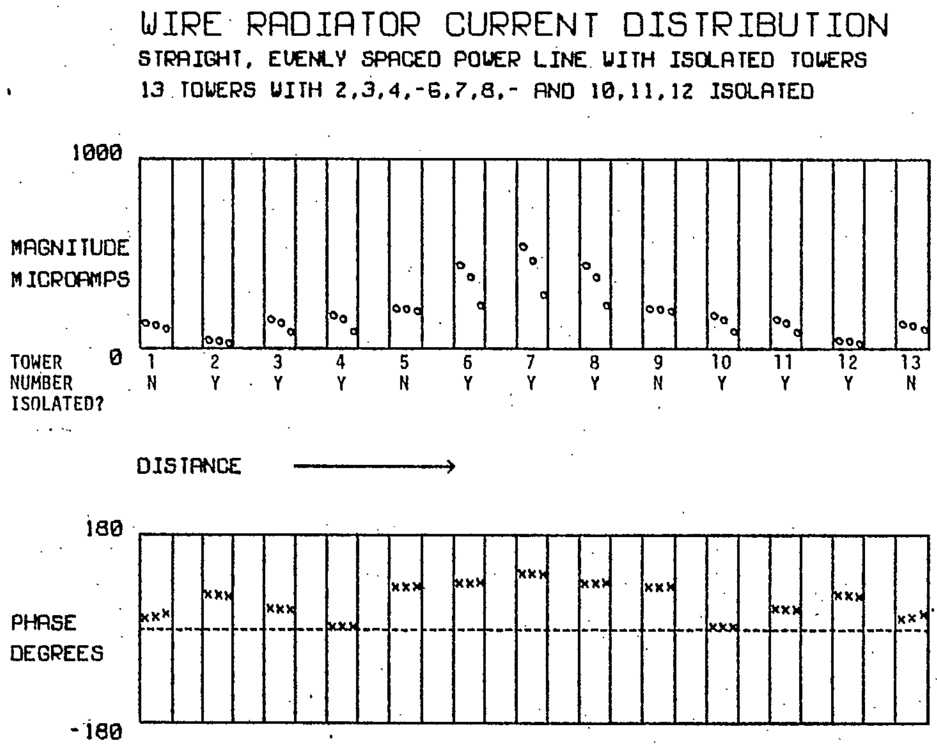


FIGURE 5.3 (A)

TOWER CURRENTS ON THE MODEL OF FIG. 4.1,
FOR THE GAP SIZE EQUAL TO FOUR TIMES THE SKYWIRE RADIUS

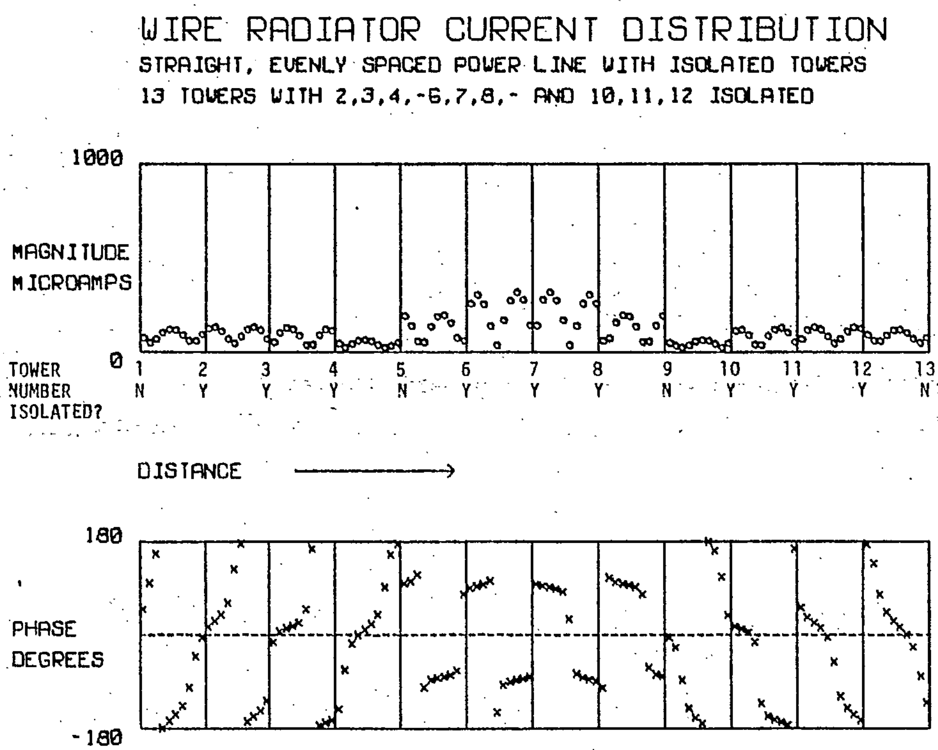


FIGURE 5.3 (B)

SKYWIRE CURRENTS

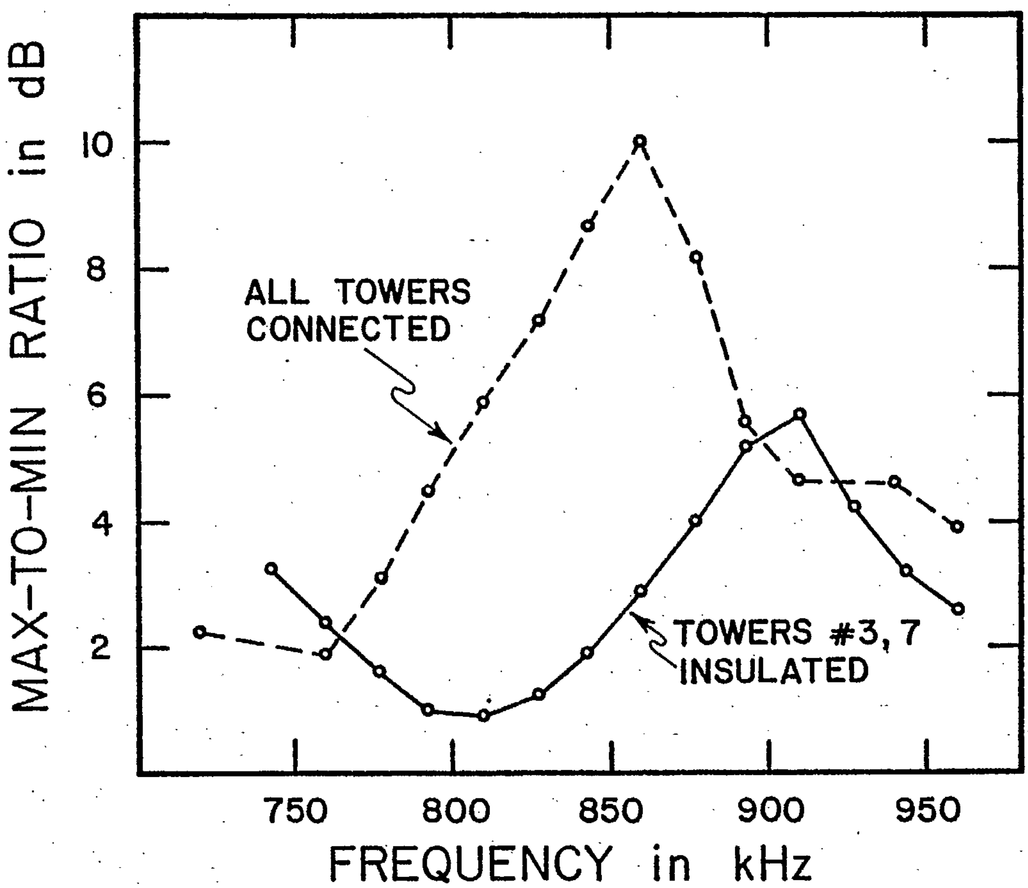


FIGURE 5.4

FREQUENCY DEPENDENCE OF THE MAX-TO-MIN RATIO
WITH SOME TOWERS ISOLATED

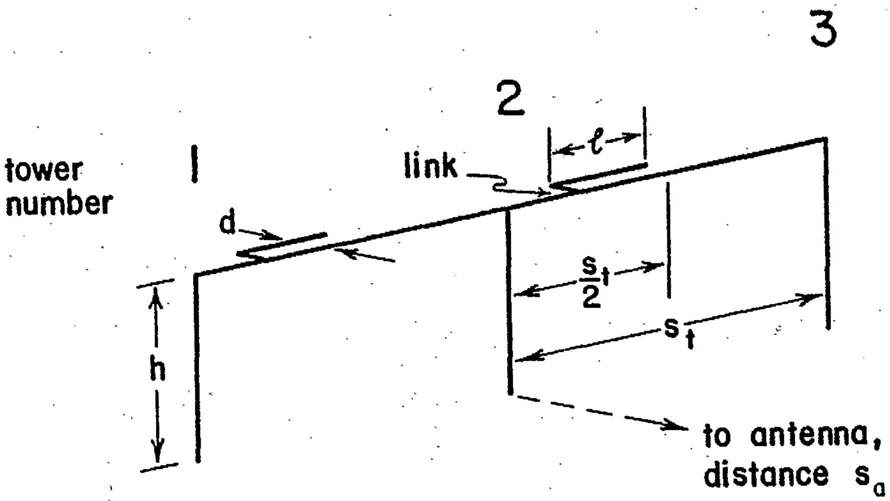


FIGURE 6.1

PARALLEL DETUNING STUBS

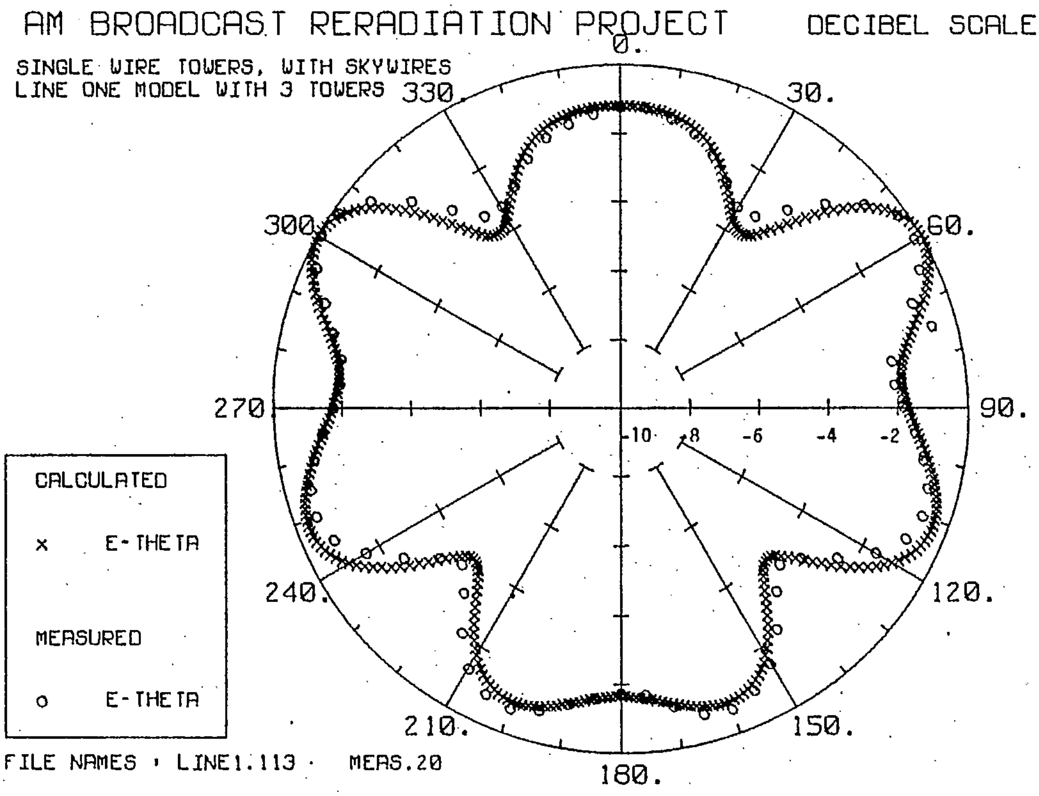


FIGURE 6.2

AZIMUTH PATTERN OF THE 3 TOWER POWER LINE
WITH NO DETUNING STUBS, AT 860 KHZ

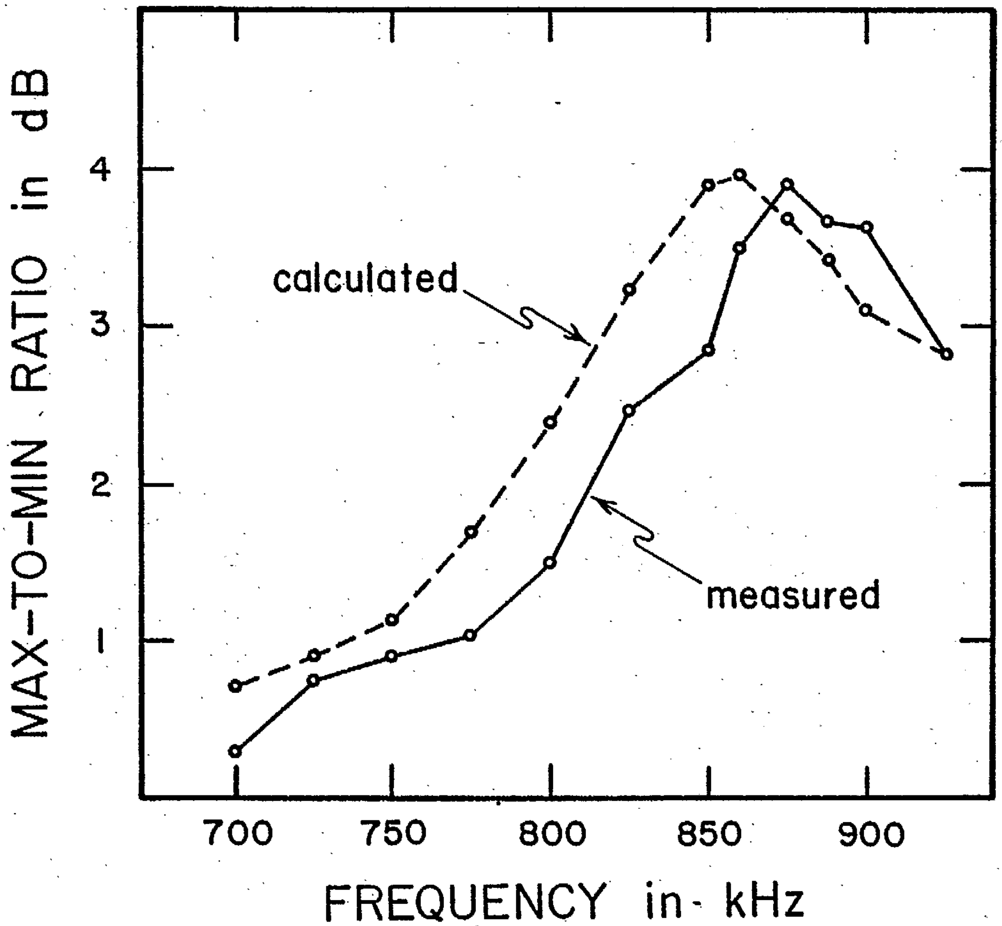


FIGURE 6.3

THE MAX-TO-MIN RATIO AS A FUNCTION OF FREQUENCY FOR THE POWER LINE WITH NO STUBS

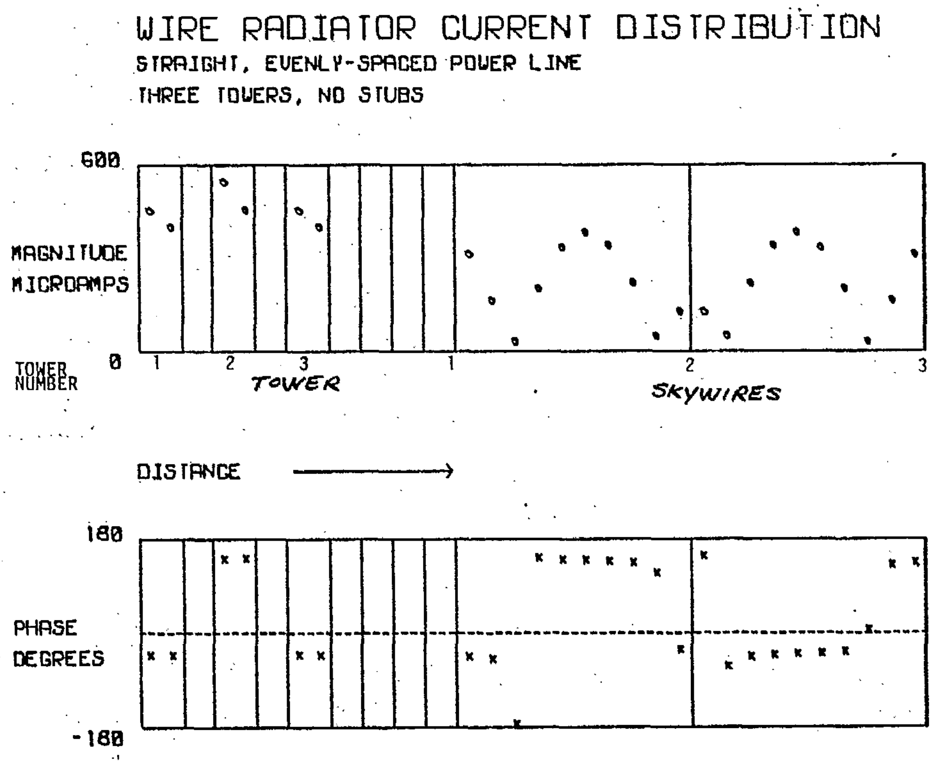


FIGURE 6.4

RF CURRENTS ON THE TOWERS AND SKYWIRES
OF THE THREE TOWER POWER LINE WITH NO DETUNING STUBS

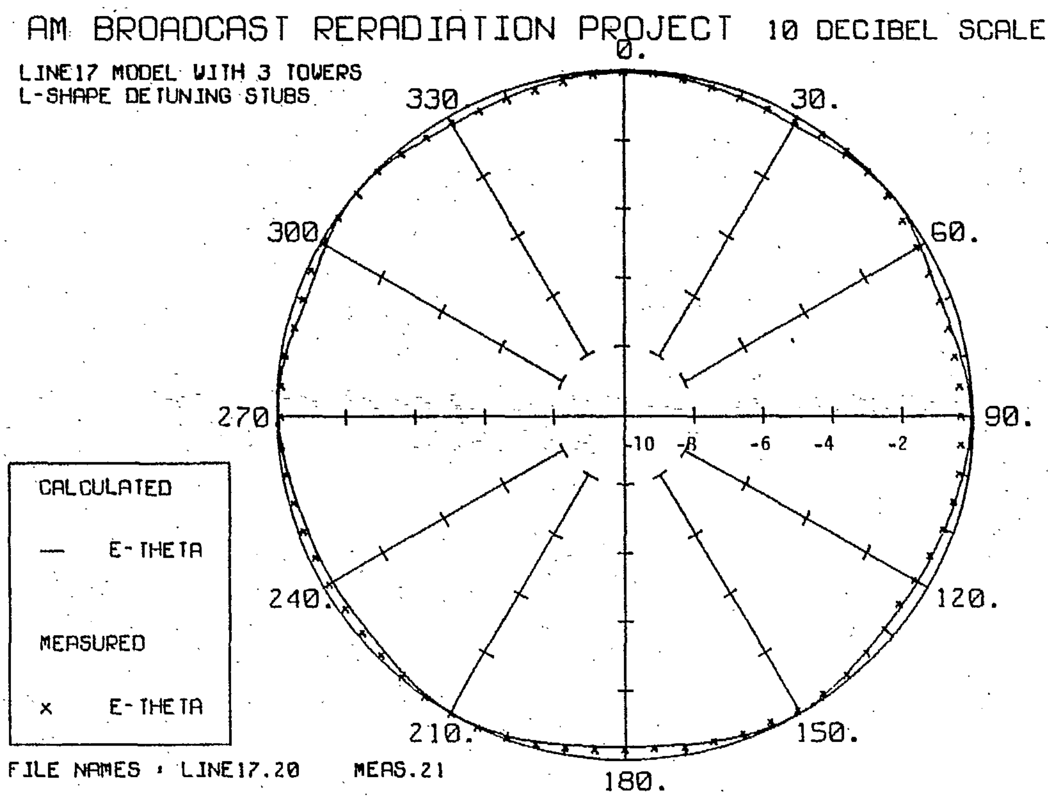


FIGURE 6.5

AZIMUTH PATTERN AT 860 KHZ USING ONE DETUNING STUB
ADJUSTED TO THAT FREQUENCY

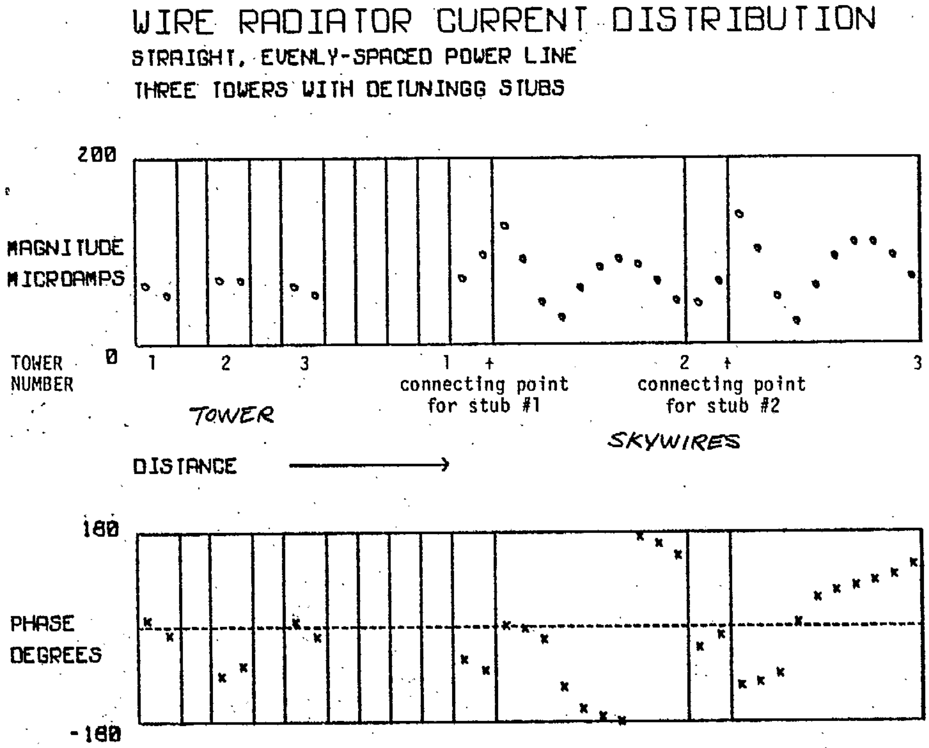


FIGURE 6.6 (A)

RF CURRENTS ON THE TOWERS AND SKYWIRES
AT 860 KHZ, WITH ONE DETUNING STUB

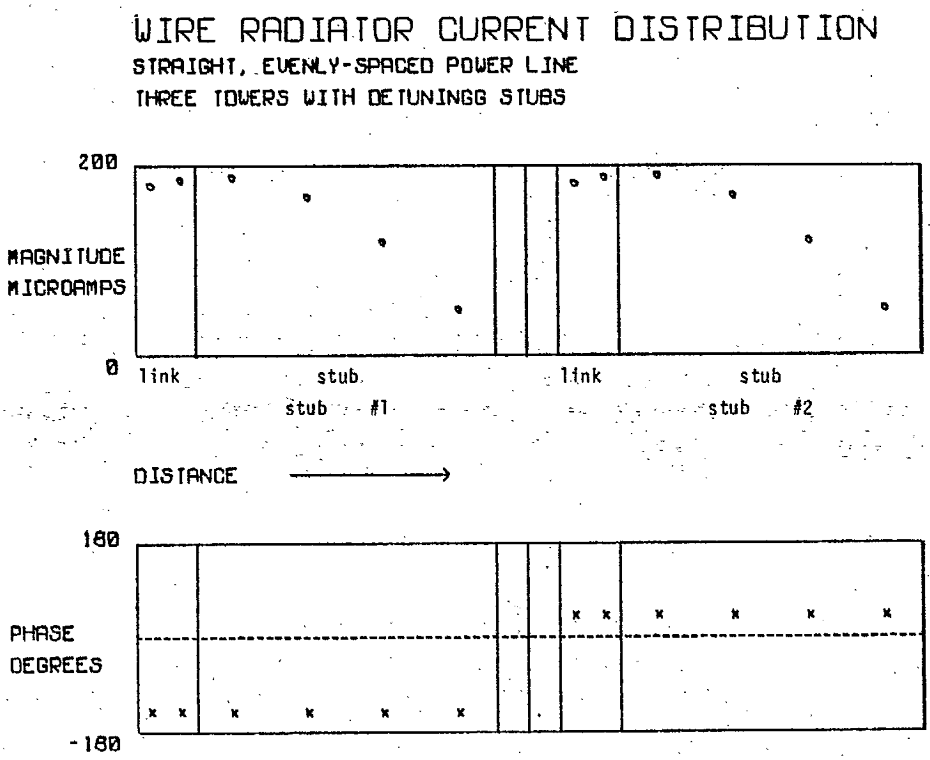


FIGURE 6.6 (B)

RF CURRENTS ON THE DETUNING STUBS

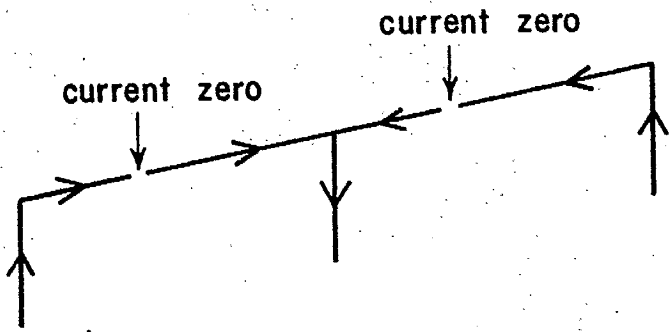


FIGURE 6.7

PATTERN OF CURRENT FLOW
ON THE TOWERS AND SKYWIRES,
WITH ONE DETUNING STUB

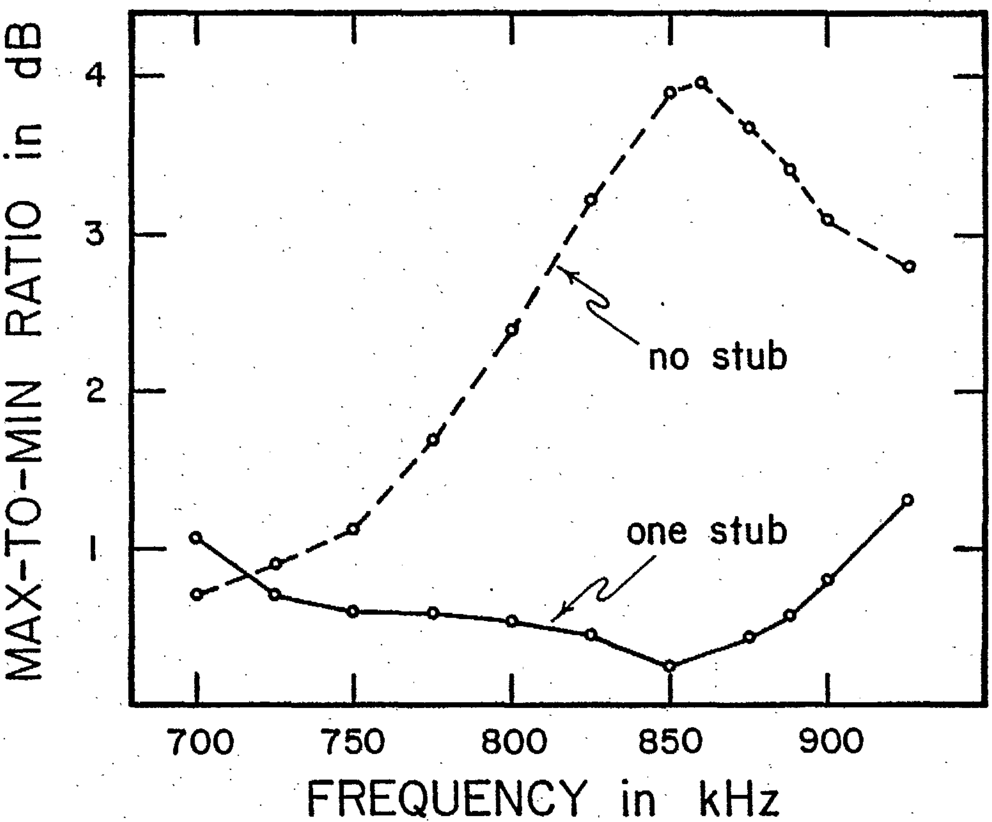


FIGURE 6.8

FREQUENCY DEPENDENCE
OF THE MAX-TO-MIN RATIO
WITH ONE STUB

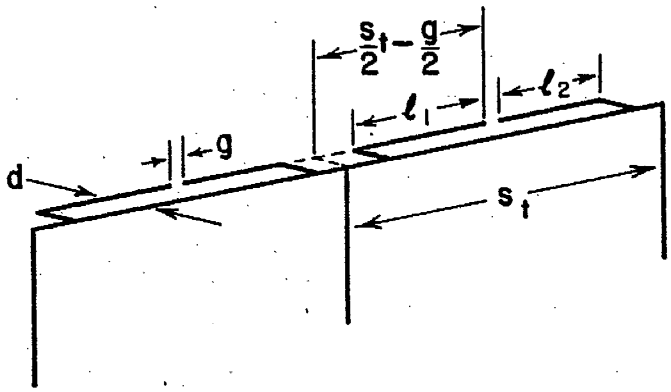


FIGURE 6.9

PAIR OF DETUNING STUBS

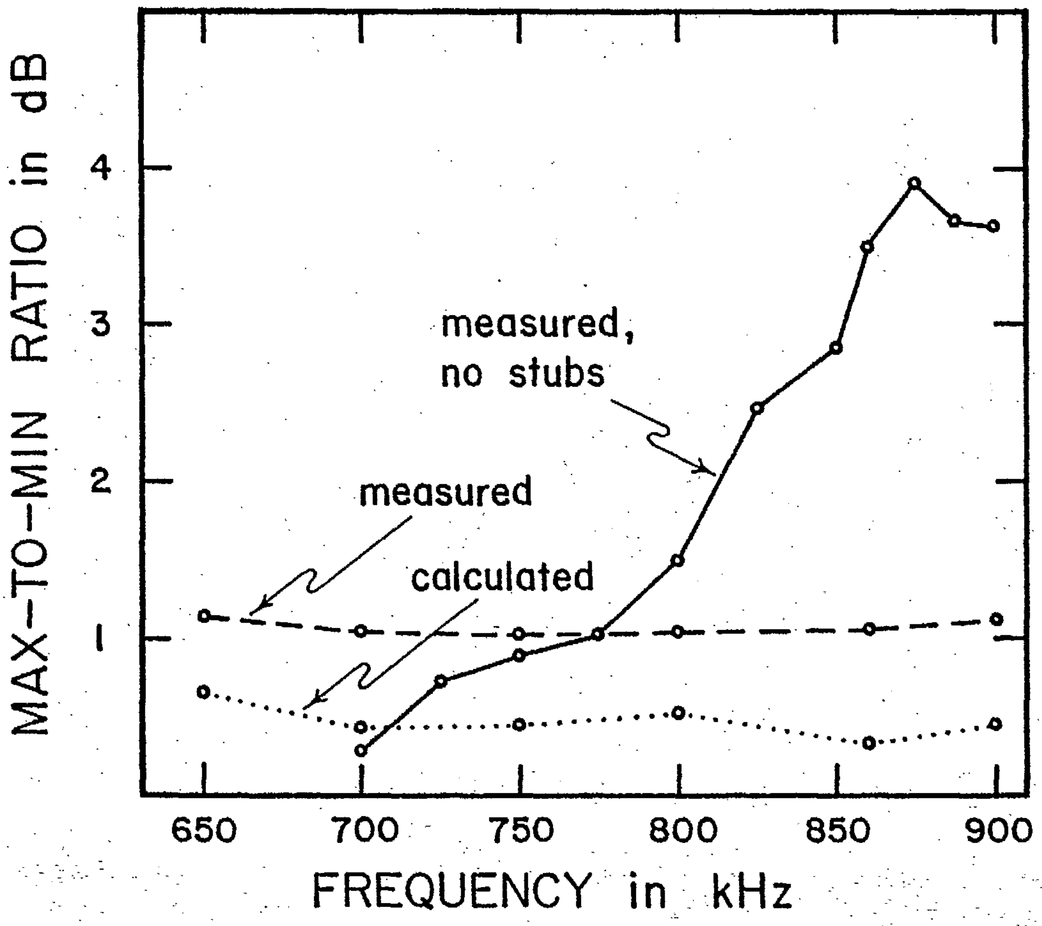


FIGURE 6.10

MAX-TO-MIN RATIO VS. FREQUENCY FOR THE PAIR OF DETUNING STUBS