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Technical Note No. TN-EMC-84-01
January 31, 1984

"The Radiation Pattern of CHFA, Edmonton near the As-Built North and Southeast Power Lines and Their Detuning By Isolating Towers"

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FACULTY OF ENGINEERING AND COMPUTER SCIENCE

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The Radiation Pattern of CHFA, Edmonton near the As-Built North and Southeast Power Lines and Their Detuning By Isolating Towers

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

ABSTRACT

This report contains an initial assessment of the reradiation from the as-built power lines near station CHFA, Edmonton, at 680 kHz, and of the detuning of the power lines by isolating towers from the skywire. The computer models in this report include about as many towers on the "north"(1202) and "southeast"(1209) power lines as were used for a previous assessment of reradiation from the proposed power lines, but here the as-built tower locations and heights are used. Thus each span has a different length, and so in the "as-built" computer model, each span has its own resonant frequency, whereas in the "proposed" computer model which used evenly-spaced towers of uniform height, all spans had the same resonant frequency. It is found that some spans in the computer model of the "as-built" power lines are strongly resonant when excited at 680 kHz by CHFA, and those spans carry large RF currents. Thus, as before, reradiation causes CHFA to radiate in excess of the protection limits imposed on the station. It is shown in this report that detuning the power lines by isolating towers from the skywire can be a highly effective technique, given that those few towers carrying strong RF currents can be identified for isolation. The resulting computed azimuth patterns satisfy the protection limitations. This report recommends that further work be done to remove some of the constraints of the initial assessment presented here, namely that more towers be included in the computer model of the power lines, and that the azimuth pattern of CHFA be found in the presence of both lines simultaneously, rather that in the presence of each individual power line.

The Radiation Pattern of CHFA, Edmonton near the As-Built North and Southeast Power Lines and Their Detuning by Isolating Towers

1. Introduction

Station CHFA in Edmonton must maintain a radiation pattern which is severely restricted for azimuth angles 165 to 236 degrees, and as shown in Fig. 1.This project deals with the prediction by computation of the radiation pattern of station CHFA at 680 kHz near Edmonton, radiating in the presence of the "north" or 1202 power line, and the "southeast" or 1209 line, as shown in the plan of the site in Fig. 2. The "detuning" of the two lines by isolating towers will be addressed in this report, with the object of determining which towers to isolate, and what results can be expected by this technique. The modelling methods used here are the same as those described in references (1) and (2), which report on earlier studies of the patterns of the CHFA antenna, and refs. (3), (4), (5) and (6), which deal with reradiation from power lines at AM broadcast frequencies. A recent measurement(8) of the pattern of CHFA in the presence of the power lines is shown in Fig. 1(b), and indicates that reradiation has raised the radiated field near 200 degrees azimuth to a level well above the maximum set by the protection requirement. Thus the power lines need to be "treated" or "detuned" to reduce reradiation.

2. Model of the Power Line

The broadcast array and power line models were developed in ref. (1). The pattern computed for the CHFA array shown in Fig. 1 was verified to be close to that calculated by the CBC. The power lines near CHFA are operated by Trans-Alta, and use type Z7S towers, which have been represented using the model shown in Fig. 3. This model was developed in conjunction with the isoperimetric inequalities and the tower geometry, as discussed in ref. (1). The tower representation is a "single wire tower" model of the type described in refs. (3) and (4). The radius of the tower stem was chosen as 4. m, and the tower was subdivided into 2 segments, for analysis by the NEC program. The equivalent skywire radius is 0.38 m, and the skywire from one tower to the next was represented with 10 segments. The accuracy of pattern predictions using this computer model for type Z7S towers has not been checked against scale model measurements. Such a validation is considered an essential step in establishing the reliability of a computer model, and so the results of the present study may not be as precise as could be achieved by computer modelling.

3. Choice of the Number of Towers

Fig. 2 shows a complex site with a total of 49 towers shown on the 1202 "north line", and 56 towers on the 1209 "southeast" line, although these lines actually extend beyond the drawing shown in Fig. 2. Tables 1 and 2 give the coordinates of the base of each tower relative to the center tower of the CHFA array. The data was derived from maps supplied by Trans-Alta(7). In the work of refs. (1) and (2), many fewer towers were represented. The question of how many towers to include in the computation must be answered by comparing results for increasing numbers of towers. This question has been left open for the present. An arbitrary choice has been made, in which about the same number of towers is included in the present models as in those of refs. (1) and (2). Thus Fig. 4 shows a 1202 "north" line model with a greatly reduced number of towers, in comparison with the proposed line of ref. (2). Towers #164 thru 176 from Fig. 2 have been included for a total of 13 towers. Similarly, Fig. 5 compares a 1209 "southeast" line model with a reduced number of towers with the proposed line of ref. (2), and includes towers # 156 to 178 for a total of 23 towers. Figs. 4 and 5 thus compare the "as-built" locations of the power line towers with the proposed locations made prior to construction, which were the basis for the pattern predictions in refs. (1) and (2). This provides an opportunity to compare the patterns of the CHFA array near the "proposed" power lines with those of the antenna near the "as-built" power lines.

The tower location and height data of Tables 1 and 2 can be analysed to estimate the resonant frequency of each span, as follows. If the distance between two adjacent towers or "span length" is d, and the tower heights are h_1 and h_2, then the geometrical loop length is

$$\ell = 2(h_1 + h_2 + d)$$

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

$$f_{g1} = \frac{c}{\ell}$$

and for two-wavelength loop resonance,

$$f_{g2} = \frac{2c}{\ell}$$

where c is the speed of light in free space. Because of capacitive coupling between the vertical tower wire and the horizontal skywire, the current tends to "cut off the corner" to some extent, which makes the electrical path length shorter than the geometrical path length, and hence the electrical resonance frequencies higher than f_{g1} and f_{g2}. The frequency difference can be estimated from the resonance studies of references (1), (2) and (3) for the site near Hornby, Ontario with evenly-spaced towers of uniform height. Thus for that site, the geometrical resonance frequencies are calculated as 400 and 800 kHz, while the electrical resonance frequencies were found by computation using the Numerical Electromagnetics Code, to be 430 and 860 kHz, respectively. Thus a reasonable estimate of the electrical resonance frequencies is

$$f_{en} = \frac{860}{800} f_{gn} = 1.08 f_{gn}$$

Thus the electrical resonance frequencies of a span are estimated as, for one-wavelength loop resonance,

$$f_{e1} = \frac{1.08\ c}{2(h_1 + h_2 + d)}$$

and for two-wavelength loop resonance,

$$f_{e2} = 2 f_{e1}$$

Tables 3 and 4 give the span lengths and electrical resonance frequencies for the north and southeast power lines. The two-wavelength loop resonance frequencies are generally comparable to CHFA's frequency of 680 kHz. Recall that the bandwidth of two-wavelength loop resonance is of the order of 100 kHz. In fact, Fig. 5 of ref.(3) indicates that the resonance effect tapers gradually above the frequency of resonance, and so it is reasonable to scan the tables for estimated resonance frequencies between about 630 and 750 kHz.

For the north line, Table 3 shows that the spans from tower 193, through 192, 191, 190, and 189 resonate close to 680 kHz, as do the spans 184-183-182, 179-178-177, 176-175-174,168-167, 166-165-164, 159-158, 153-152 and 151-150. In the reduced model of Fig. 4, towers 164 to 176 are represented, and so the spans 176-175-174, 168-167 and 166-165-164 are expected to be resonant. Whether these spans are excited to resonance depends on whether the magnitude of the electric field exciting the span is significant, and whether the excitation field has a significant "difference mode" component. The strength of the excitation field depends on whether the span lies in the pattern's maximum or in the minimum, and on how far away it is from the antenna, because the excitation field decreases according to the inverse-square law. "Common-mode" refers to in-phase excitation of adjacent towers, while "difference mode" refers to a 180 degree phase difference in the excitation from one tower to the next. Two-wavelength loop resonance can only be excited by a difference-mode field.

For the southeast power line, Table 4 shows that spans 198-197-196-195-194 are resonant close to CHFA's frequency, as are spans 192-191, 188-187, 184-183-182, 180-179-178, 176-175, 167-166, 165-164, 161-160, 158-157, 156-155, 154-153-152-151, 150-149, 148-147-146 and 145-144. In the reduced power line model of Fig. 5, towers 156 to 178 are included, and so spans 157-158, 160-161, 164-165, 166-167, and 175-176 may be resonant. But low-numbered towers lie in CHFA's minimum and are not significantly excited.

The choice of the number of towers to be represented in the computer model of a power line should consider this data for the resonant frequency of each span. It will be of interest in further work to extend the models of Figs. 4 and 5 and compare the azimuth patterns and RF current distributions with those reported here.

4. Patterns with the Individual Power Lines

The CHFA array radiates in the presence of both the "north" and the "southeast" power lines, and the radiation pattern should be analysed in the presence of both. For the present, however, the radiation pattern will be analysed in the presence of each power line individually, so that the effect of each on the antenna's pattern can be assessed. A later report will deal with the two power lines present simultaneously.

Fig. 6(a) shows the pattern of the CHFA array in the presence of the as-built segment of the "north" power line modelled in Fig. 4. There is a large amount of reradiation into the restricted arc of the pattern from azimuth 165 to 236 degrees. Fig. 6(b) shows the structure of the minimum and compares the radiation pattern in the minimum with the protection requirement and with the CBC's measured field strength(8). The measurement and computation both show a broad lobe of radiation from about 185 to 215 degrees azimuth, significantly in excess of the protection requirement. It is shown below that the southeast power line does not contribute to this lobe. Fig. 7(a) compares the pattern of CHFA plus the as-built line with CHFA plus the proposed power line, which was obtained in ref. (2). Evidently the as-built power line gives rise to a broader reradiated lobe at 210 degrees azimuth than did the proposed power line. Fig. 7(b) compares the field strength in the minimum for CHFA plus the as-built power line with CHFA plus the proposed power line. The as-built pattern more strongly exceeds the protection requirement and matches the measured field strength of Fig. 6(b) better than would the computation with the "proposed" configuration, lending confidence to the computer model's results. The reader should be cautioned that increasing the number of towers in the model of Fig. 4 may result in a somewhat different radiation pattern.

Fig. 8(a) shows the radiation pattern of the CHFA array plus the as-built segment of the "southeast" power line shown in Fig. 5. Superposing Fig. 8(a) and Fig. 1 shows reradiation into the restricted area for 210 to 236 degrees, as well as some individual narrow lobes near 165 and 203 degrees. Fig. 8(b) compares the field strength in the minimum with CBC's measurement and with the protection requirement. Comparing Figs. 6(b) and 8(b), it is evidently the "north" power line which is primarily responsible for the broad lobe in the measured result. The field strength of CHFA plus the as-built "southeast" power line nearly meets the protection requirement, and only exceeds it by a few millivolts per meter from about 220 to 236 degrees. Figs. 9(a) and (b) compare the pattern of the CHFA array near the as-built line with the computation of reference (1) for the proposed power line. The as-built line reradiates much less than did the proposed power line. Once again, adding towers to the power line model of Fig. 5 may change the resulting radiation pattern.

5. RF Current Distribution

Fig. 10 shows the RF currents induced by the CHFA array on the towers of the segment of the "north" power line modelled in Fig. 4. The strength of the largest current is 85 milliamps relative to a current of 1 amp on the base of the center tower of the CHFA array. Two data points are plotted for each tower of the power line. The left hand data point gives the value of the current one-quarter the tower height above the ground, and the right hand data point specifies the value at three-quarters the tower height. The figure refers to tower numbers as "tags". It is seen that towers number 43, 47, 59, 61, 63, 65 and 67 carry significant RF currents. Thus by isolating some of these towers, it may be possible to reduce the reradiation into the protected arc. The estimates of Table 3 of the resonant frequency of each span of the power line can be compared with the current distribution on the towers in Fig. 10. It is expected that resonant spans may carry significant currents. Table 3 indicates that the spans from tower 176 to 175 to 174 resonate at about 640 kHz, and Fig. 10 shows relatively large currents on towers 176 and 174. The phase of the currents on towers 175 and 174 differs by about 180 degrees, as expected for two-wavelength loop resonance, and so that is the resonance mode present on the span. Table 3 shows the spans from towers 174 to 168 as non-resonant, and indeed Fig. 10 shows small currents on those towers. The spans from tower 168 through 167, 166, 165 to tower 164 are resonant near 680 kHz, and particularly the span from tower 168 to 167 has an estimated resonant frequency of666 kHz, very close to CHFA's 680 kHz. Fig. 10 shows large RF currents flowing on tower 168 and 167, with the 180 degree phase difference expected of two-wavelength loop resonance. This 180 degree phase change from tower to tower is seen on all towers through number 164, and so these spans are all two-wavelength loop resonant to a greater or lesser extent. Since span 168 to 167 resonates so close to 680 kHz, it carries the largest RF current.

Fig. 11 shows the RF currents flowing on the towers of the southeastern power line. The strongest current is 37 milliamps relative to 1 amp at the base of the center tower of the CHFA array. Towers 175 and 176 carry strong RF currents. Progressing from tower 169 to 156 goes deep into the "null" of the CHFA pattern and these towers are not strongly excited by the antenna. From Table 4, the span from tower 176 to 175 is resonant at 644 kHz and Fig. 11 shows by far the largest RF current on those towers, with a nearly perfect 180 degree phase shift between the current on the two towers, indicative of two-wavelength loop resonance. The spans from towers 175, through 174, 173, 172, 171 and 170 are all resonant a little above 680 kHz, and all carry significant RF current, with the expected 180 degree tower to tower phase shift. The subsequent towers on the power line lie deep in the minimum of CHFA's pattern so are very weakly excited and carry small currents.

The estimated resonance frequencies of Tables 3 and 4 are thus a useful guide to those spans which will carry strong RF currents. It will be shown that "detuning" these spans by isolating towers from the skywire is an effective technique for the CHFA site.

6. Detuning by Isolating Towers

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

The isolated tower was modelled as shown in Fig. 12. A short "segment" of length 2 m was inserted into the top of the tower, of mean radius between the tower and skywire radii. This segment was then loaded with a high series resistance in parallel with the 27 pF insulator capacitance.

The question of which towers to isolate to obtain the largest reduction in the radiation into the protected arc is a difficult one. An isolated tower does not carry zero RF current.

It behaves as a free-standing tower, top-loaded by its crossarms, and coupled capacitively to the nearby skywire passing overhead, and so it can carry a substantial RF current. Also, if a certain tower in a power line carries a strong RF current, then isolating that tower breaks up two resonant loops in the power line and so strongly affects the currents flowing on the two adjacent towers, and to a lesser extent on other nearby towers. A loop of two span lengths is created by isolating a tower, and such a loop can itself be resonant and increase the current on the towers which are part of the two-span loop. Thus isolating a tower changes its RF current and that on nearby towers in a complex fashion.

Thus no general approach has been proposed for optimizing the choice of towers to isolate from the skywire. This study is an initial exploration of the problem. For the present, those towers carrying strong RF currents will be identified and isolated from the skywire, and the resulting radiation pattern and RF current distribution on the towers will be examined. This will prove to be an effective technique.

7. Detuning the Power Lines

The distribution of RF currents on the towers of the north (1202) power line in Fig. 10 suggests that towers 174, 168, 167, 166 and 165 be isolated from the skywire in order to detune the power line. However, it has been assumed that no more than two towers in a row should be isolated, hence only towers 174, 168, 167 and 165 were isolated from the skywire, but not 166 even though its current is strong. The resulting radiation pattern is shown in Fig. 13. In comparison to Fig. 6(a) it is seen that the power line has been effectively detuned. Comparing with Fig. 1 the small lobes in Fig. 11 can been seen to exceed CHFA's two small back lobes by a few decibels. Fig. 13(b) compares the "detuned" pattern with that of Fig. 6, in the minimum. The protection requirement is met by the "detuned" pattern.

Fig. 14 shows the RF currents flowing on the towers of the detuned power line. The isolated towers have been indicated with a capital I in the figure. Isolating towers here evidently effectively breaks up resonant loops. Thus the current on the isolated towers is small. Also, the current on towers 169, 166 and 164, which were part of closed, resonant loops with adjacent towers, is small as well because the loops have been open-circuited. Thus isolating towers is an effective technique for detuning the north line, provided that those towers carrying strong RF currents can be identified.

The as-built southeast power line reradiates weakly into CHFA's minimum and the resulting field strength only exceeds the protection requirement by a small amount, as shown in Fig. 9(b). However, the strong RF currents flowing on towers 176 and 175 in Fig. 11 suggest that some improvement may be possible by isolating towers. Accordingly, these two towers were isolated, and also towers 173 and 172, which form part of resonant loops and carry relatively larger currents than the other towers. Tower 174 was left connected in conformance with the rule that not more than two towers in a row be isolated. The resulting azimuth pattern is shown in Fig. 15 and has very little radiation into the minimum. Fig. 16(b) shows that the field strength in the minimum meets the protection requirement by a good margin.

Fig. 16 shows the RF currents on the towers of the "detuned" southeast power line, with the isolated towers marked with an "I". The currents on towers 176 and 175 have been reduced greatly compared with those seen in Fig. 11. The current on tower 174 is also greatly reduced, even though it was not isolated. This is because isolating towers 175 and 173 has broken up the resonant spans 175 to 174, and 174 to 173, which gave rise to the large current on tower number 174. The current on tower 171 is not reduced in value because it is part of a resonant loop with tower 170, and this loop has not been open-circuited by isolating a tower. The measure of isolating only four towers is adequate to meet the protection requirements, and further towers need not be disconnected.

8. Conclusion

This report has investigated the difference between the radiation pattern of station CHFA operating near the "as-built" north and southeast power lines and the pattern of the station operating near the "proposed" power line designs, and has provided an initial indication that detuning by isolating towers may be successful for this site.

Comparing the azimuth patterns of CHFA near the as-built power lines with the patterns near the proposed power lines, Figs. 7(b) and 9(b), leads to the general conclusion that a substantial change in the reradiation from the power lines is seen. The fundamental reason for this is the fact that the proposed power line design of references (1) and (2) uses for the most part evenly-spaced towers of uniform height, and so all the spans are either resonant or non-resonant together, while the as-built power lines use non-uniform tower spacing and varying height. Thus the as-built line has some spans near resonance and others far from resonance, and those near resonance carry large RF currents which dominate the pattern. Thus in assessing the degree to which a proposed power line will give rise to reradiation, it would be useful to know the variability associated with the tower spacing and height, perhaps stated in terms of statistical mean and standard deviation figures. The assessment would be made using several computer runs with evenly spaced towers with several typical spacings for the site.

The specific results obtained show that for the as-built "north" power line, the reradiation is generally similar but much stronger than for the proposed line. But for the as-built southeast power line, the reradiation is less and the protection requirement is almost satisfied.

The method of detuning by isolating towers was used in this report to achieve a substantial improvement in the pattern of CHFA near each power line, as shown in Figs. 13(b) and 15(b). The procedure used was to determine which towers on the power line model actually carry strong RF currents, and to isolate those towers. It was not necessary to isolate all such towers. A scheme of two isolated, one connected, two isolated is sucessful in suppressing two-wavelength loop resonance mode currents on all the towers. In the full scale, on-site, direct measurement of the tower currents may be necessary, or it may be possible to use a directional loop antenna with a field strength meter to identify towers with strong RF currents by measuring their immediate near fields.

9. Recommendations for Further Work

This study has presented an initial assessment of the amount of reradiation from the as-built "north" and "southeast" power lines near CHFA, and of the detuning of the lines by isolating towers. The work was based on a model which represents a limited number of towers on each power line, and which treats CHFA near each of the two power lines as a separate problem. The primary recommendation for further work is that these simplifications be removed.

There is at present no way to assess a priori the number of spans to include in a power line model. For this study, about the same number of spans were included as in the work of references (1) and (2). In general, an estimate of the resonant frequency of each span should be the basis for the choice. Thus, for example, in Table 3, on the "north" line the span for tower 177 to 178 is expected to be resonant and should be included, as is the span for tower 158 to 159. On the southeast line, the span for tower 179 through 182 may be resonant. It is recommended that additional "runs" be made, extending the power line model to include these spans, and that the results be compared with those in this report. The electric field excitation of a span decreases according to the inverse square law, so spans "far enough away" will not be strongly excited even if resonant. The question of an adequate number of towers involves including all resonant spans which are close enough to make a significant contribution to the reradiated field.

The CHFA array radiates in the presence of both transmission lines, and it is recommended that the computer model be "run" with both lines present simultaneously. This increases the cost of the analysis very greatly. Power lines which are far apart will not interact significantly and a separate analysis for each power line will be a good indicator, because vector-addition could then be used to find the field of the antenna in the presence of both lines as the sum of the field in the presence of each individual line. But long runs of parallel power lines can interact significantly and so the simple vector-addition approach will fail. It is recommended that the results of an analysis with both lines simultaneously be compared with the vector-sum of the fields with the individual lines. For CHFA, interaction between the power line segments of Figs. 4 and 5 is likely to be small, but if additional towers are included to obtain a more complete representation of the site of Fig. 2, then the parallel power lines may be found to interact significantly.

The initial assessment of reradiation from the as-built power lines and of detuning by isolation of towers must be extended in further work to remove its simplifications and show that the promising results obtained thus far can be duplicated with a more complete model of the site.

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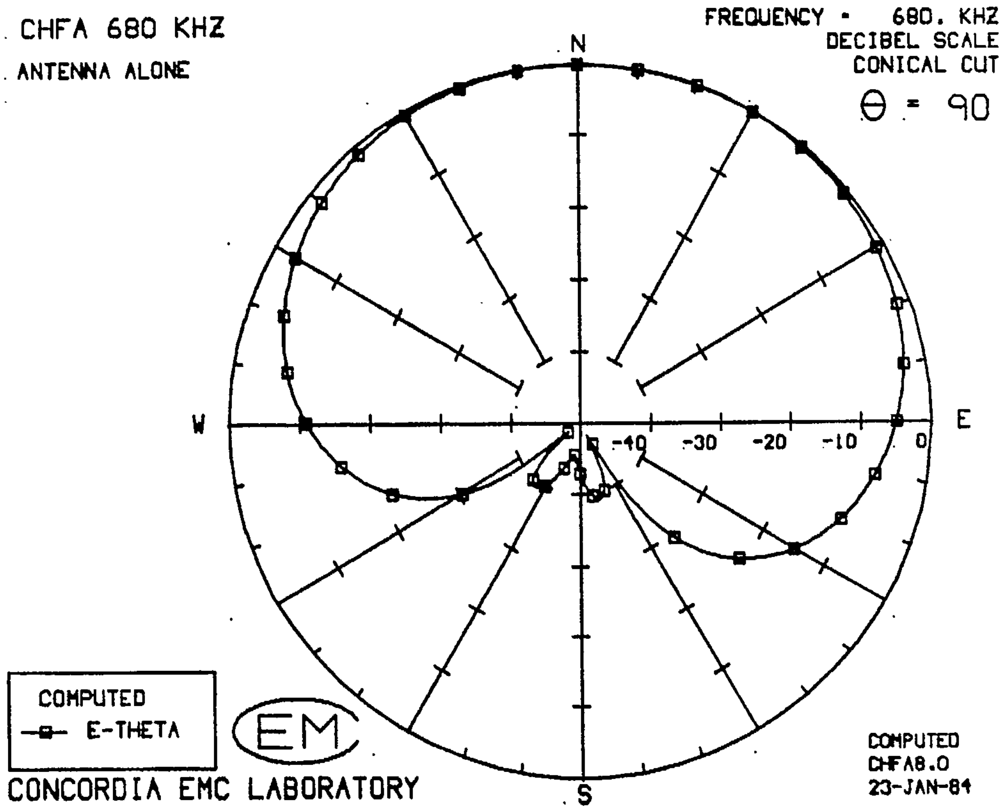

Figure 1(a) The computed azimuth pattern of station CHFA at 680 kHz. The station must maintain a stringent protection requirement from azimuth 167 to azimuth 236 degrees.

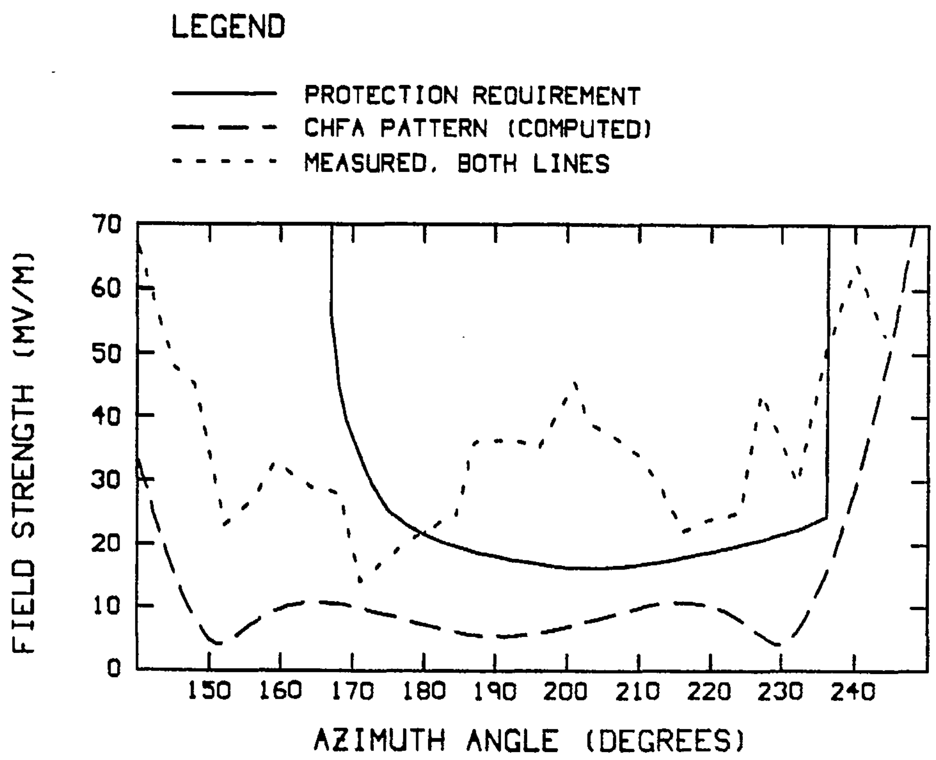

Figure 1(b) The protection requirement from azimuth 167 to 236 degrees is met by the pattern that the CHFA array is designed to deliver, but is not met in a recent measurement of the field strength of the antenna operating in the presence of two power lines.

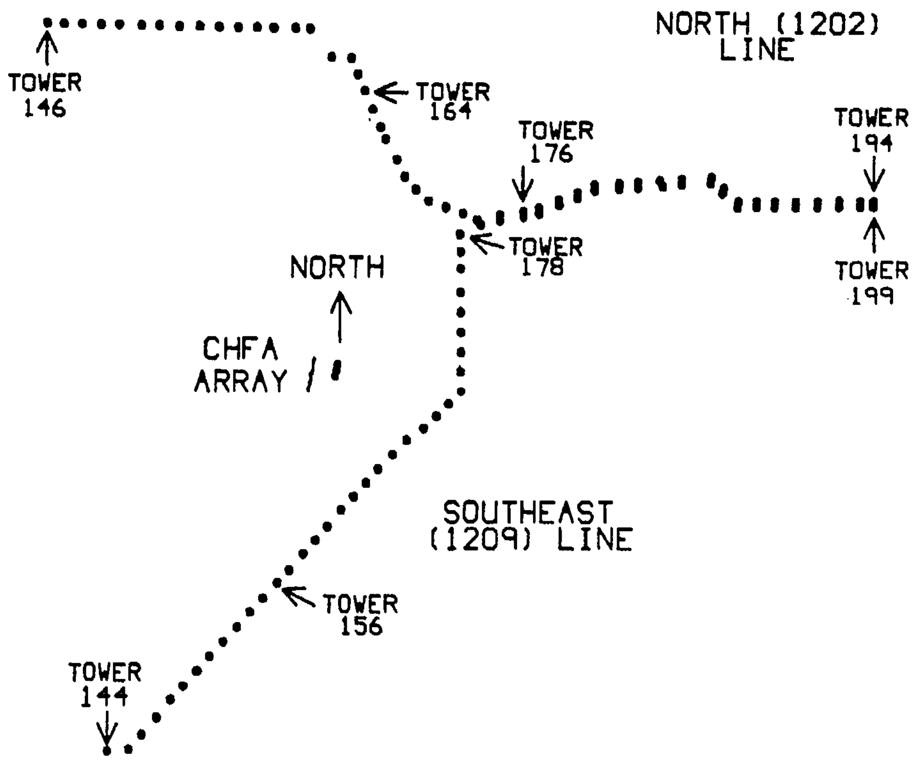

Figure 2 Plan view of the CHFA array and the two nearby high voltage power lines. The closest towers to CHFA on the north line are about 3.5 km away, and the closest towers on the southeast line are about 1.8 km distant.

TOWER NUMBER	NORTH M	WEST M	HEIGHT M	DISTANCE FROM THE ORIGIN(M)
194	3047.09	-9922.19	38.6	10380.
193	3046.10	-9676.19	36.0	10144.
192	3044.51	-9282.19	35.7	9769.
191	3042.88	-8876.19	32.6	9383.
190	3041.32	-8489.20	35.8	9018.
189	3039.80	-8110.20	35.8	8661.
188	3038.48	-7782.20	35.6	8354.
187	3037.08	-7436.21	32.4	8033.
186	3266.84	-7165.58	36.0	7875.
185	3462.94	-6934.60	32.4	7751.
184	3426.63	-6380.79	38.6	7243.
183	3400.39	-5980.65	38.6	6880.
182	3374.02	-5578.51	38.6	6519.
181	3351.52	-5235.25	39.0	6216.
180	3321.42	-4776.23	35.6	5818.
179	3199.74	-4471.64	39.0	5499.
178	3062.47	-4128.04	33.0	5140.
177	2911.11	-3749.16	32.2	4747.
176	2860.66	-3465.61	36.0	4494.
175	2784.11	-3035.37	35.4	4119.
174	2708.78	-2612.02	35.8	3763.
173	2814.83	-2322.85	35.8	3650.
172	2931.21	-2005.52	35.8	3552.
171	3042.77	-1701.33	29.8	3486.
170	3236.39	-1459.23	32.6	3550.
169	3466.31	-1252.79	32.6	3686.
168	3766.64	-1099.92	34.8	3924.
167	4134.70	-912.56	38.6	4234.
166	4350.99	-818.15	35.5	4427.
165	4674.51	-676.93	35.8	4723.
164	5026.45	-523.30	31.1	5054.
163	5334.39	-388.88	32.7	5349.
162	5623.08	-262.86	32.6	5629.
161	5643.85	96.54	34.4	5645.
160	6165.52	504.10	33.4	6186.
159	6171.12	768.04	33.0	6219.
158	6179.81	1176.95	39.0	6291.
157	6186.39	1486.88	32.8	6363.
156	6193.76	1833.80	31.0	6460.
155	6201.30	2188.72	32.8	6576.
154	6208.85	2544.64	33.0	6710.
153	6216.60	2909.56	32.8	6864.
152	6224.50	3281.48	35.8	7037.
151	6231.75	3609.40	35.7	7202.
150	6241.87	4028.28	35.9	7429.
149	6249.93	4362.18	32.0	7622.
148	6258.48	4716.08	33.0	7836.
147	6266.71	5056.98	31.4	8053.
146	6273.41	5367.90	32.6	8257.

Table 1 Tower base coordinates, tower heights, and distances from the origin for the "north" (1202) power line. The origin is the center tower of the CHFA array.

TOWER NUMBER	NORTH M	WEST M	HEIGHT M	DISTANCE FROM THE ORIGIN(M)
199	2949.40	-9921.58	38.6	10351.
198	2948.41	-9675.58	35.8	10115.
197	2946.83	-9281.58	36.0	9738.
196	2945.19	-8875.58	32.8	9351.
195	2943.64	-8488.59	36.0	8984.
194	2942.11	-8109.59	35.4	8627.
193	2940.79	-7781.59	35.8	8319.
192	2939.35	-7423.60	32.8	7984.
191	3176.87	-7143.82	36.0	7818.
190	3364.56	-6922.75	32.6	7697.
189	3329.03	-6380.91	35.4	7197.
188	3306.53	-6037.65	38.8	6884.
187	3276.43	-5578.64	38.8	6470.
186	3253.92	-5235.37	38.8	6164.
185	3224.09	-4780.35	35.8	5766.
184	3105.37	-4483.19	36.0	5454.
183	2968.11	-4139.59	32.8	5094.
182	2815.26	-3756.99	34.8	4695.
181	2764.11	-3469.51	39.0	4436.
180	2687.56	-3039.26	39.0	4057.
179	2623.09	-2676.95	39.0	3748.
178	2452.21	-2274.75	31.0	3345.
177	2140.21	-2276.26	37.6	3124.
176	1839.21	-2277.50	35.6	2927.
175	1408.22	-2279.28	35.8	2679.
174	1045.22	-2280.78	32.2	2509.
173	687.22	-2282.25	32.8	2383.
172	329.23	-2283.24	35.9	2307.
171	-27.77	-2283.24	34.8	2283.
170	-390.77	-2283.24	32.4	2316.
169	-619.54	-2056.20	32.2	2148.
168	-848.79	-1828.67	32.8	2016.
167	-1078.05	-1601.14	34.6	1930.
166	-1289.33	-1279.89	33.0	1817.
165	-1548.91	-1030.45	36.0	1860.
164	-1815.70	-774.09	33.0	1974.

Table 2 Tower base coordinates, tower heights, and distances from the origin for the "southest" (1209) power line. The origin is the center tower of the CHFA array.
(continued on next page)

163	-2056.53	-542.67	35.2	2127.
162	-2296.65	-311.94	33.0	2318.
161	-2536.04	-81.91	32.2	2537.
160	-2825.93	178.98	37.0	2832.
159	-3068.25	397.06	36.7	3094.
158	-3310.57	615.13	35.8	3367.
157	-3608.63	883.38	33.5	3715.
156	-3850.21	1100.79	32.6	4004.
155	-4139.36	1361.01	32.6	4357.
154	-4408.44	1603.17	32.6	4691.
153	-4681.23	1848.67	32.6	5033.
152	-4963.69	2102.87	32.6	5391.
151	-5237.23	2349.04	32.6	5740.
150	-5502.62	2587.82	32.6	6081.
149	-5781.40	2838.63	32.6	6441.
148	-6036.17	3067.85	32.6	6771.
147	-6374.19	3332.01	32.6	7193.
146	-6685.43	3611.03	32.6	7598.
145	-6954.98	3852.66	32.6	7951.
144	-6976.14	4257.44	32.6	8173.

Table 2 (continued)

SPAN TOWER TO TOWER		SPAN LENGTH M	PATH LENGTH M	ONE-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)	TWO-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)
194	193	246.0	641.2	505.	1010.
193	192	394.0	931.4	348.	695.
192	191	406.0	948.6	341.	683.
191	190	387.0	910.8	355.	711.
190	189	379.0	901.2	359.	719.
189	188	328.0	798.8	405.	811.
188	187	346.0	828.0	391.	782.
187	186	355.0	846.8	382.	765.
186	185	303.0	742.8	436.	872.
185	184	555.0	1252.0	259.	517.
184	183	401.0	956.4	339.	677.
183	182	403.0	960.4	337.	674.
182	181	344.0	843.2	384.	768.
181	180	460.0	1069.2	303.	606.
180	179	328.0	805.2	402.	804.
179	178	370.0	884.0	366.	733.
178	177	408.0	946.4	342.	684.
177	176	288.0	712.4	454.	909.
176	175	437.0	1016.8	318.	637.
175	174	430.0	1002.4	323.	646.
174	173	308.0	759.2	426.	853.
173	172	338.0	819.2	395.	790.
172	171	324.0	779.2	416.	831.
171	170	310.0	744.8	435.	869.
170	169	309.0	748.4	433.	865.
169	168	337.0	808.8	400.	801.
168	167	413.0	972.8	333.	666.
167	166	236.0	620.2	522.	1044.
166	165	353.0	848.6	382.	763.

Table 3 Span length, geometrical path length, and estimates of the electrical resonant frequencies of each span for the north (1202) power line. (continued on next page)

165	164	384.0	901.8	359.	718.
164	163	336.0	799.6	405.	810.
163	162	315.0	760.6	426.	851.
162	161	360.0	854.0	379.	758.
161	160	662.0	1459.6	222.	444.
160	159	264.0	660.8	490.	980.
159	158	409.0	962.0	337.	673.
158	157	310.0	763.6	424.	848.
157	156	347.0	821.6	394.	788.
156	155	355.0	837.6	387.	773.
155	154	356.0	843.6	384.	768.
154	153	365.0	861.6	376.	752.
153	152	372.0	881.2	367.	735.
152	151	328.0	799.0	405.	810.
151	150	419.0	981.2	330.	660.
150	149	334.0	803.8	403.	806.
149	148	354.0	838.0	386.	773.
148	147	341.0	810.8	399.	799.
147	146	311.0	750.0	432.	863.

Table 3 (continued)

SPAN TOWER	TO TOWER	SPAN LENGTH M	PATH LENGTH M	ONE-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)	TWO-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)
199	198	243.0	640.8	505.	1011.
198	197	394.0	931.6	348.	695.
197	196	406.0	949.6	341.	682.
196	195	387.0	911.6	355.	710.
195	194	379.0	900.8	359.	719.
194	193	328.0	798.4	406.	811.
193	192	358.0	853.2	379.	759.
192	191	367.0	871.6	371.	743.
191	190	290.0	717.2	451.	903.
190	189	543.0	1222.0	265.	530.
189	188	344.0	836.4	387.	774.
188	187	460.0	1075.2	301.	602.
187	186	344.0	843.2	384.	768.
186	185	456.0	1061.2	305.	610.
185	184	320.0	783.6	413.	826.
184	183	370.0	877.6	369.	738.
183	182	412.0	959.2	338.	675.
182	181	292.0	731.6	443.	885.
181	180	437.0	1030.0	314.	629.
180	179	368.0	892.0	363.	726.
179	178	437.0	1014.0	319.	639.
178	177	312.0	761.2	425.	851.
177	176	301.0	748.4	433.	865.
176	175	431.0	1004.8	322.	644.
175	174	363.0	862.0	376.	751.
174	173	358.0	846.0	383.	765.
173	172	358.0	853.4	379.	759.

Table 4 Span length, geometrical path length, and estimates of the electrical resonant frequencies of each span for the southeast (1209) power line. (continued on next page)

172	171	357.0	855.4	379.	757.
171	170	363.0	860.4	376.	753.
170	169	322.3	773.8	418.	837.
169	168	323.0	776.0	417.	835.
168	167	323.0	780.8	415.	829.
167	166	384.5	904.2	358.	716.
166	165	360.0	858.0	377.	755.
165	164	370.0	878.0	369.	738.
164	163	334.0	804.4	403.	805.
163	162	333.0	802.4	404.	807.
162	161	332.0	794.4	408.	815.
161	160	390.0	918.4	353.	705.
160	159	326.0	799.4	405.	810.
159	158	326.0	797.0	406.	813.
158	157	401.0	940.6	344.	688.
157	156	325.0	782.2	414.	828.
156	155	389.0	908.4	356.	713.
155	154	362.0	854.4	379.	758.
154	153	367.0	864.4	375.	749.
153	152	380.0	890.4	364.	727.
152	151	368.0	866.4	374.	747.
151	150	357.0	844.4	383.	767.
150	149	375.0	880.4	368.	736.
149	148	342.7	815.8	397.	794.
148	147	429.0	988.4	328.	655.
147	146	418.0	966.4	335.	670.
146	145	362.0	854.4	379.	758.
145	144	405.3	941.1	344.	688.

Table 4 (continued)

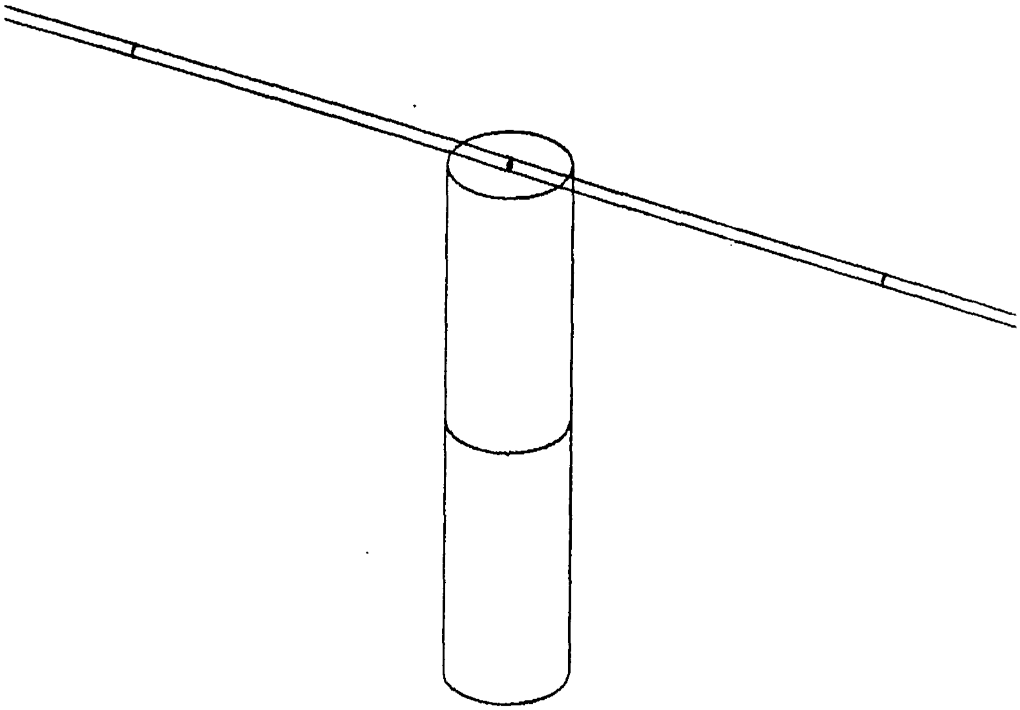

Figure 3 The model of the type Z7S tower of Reference (1) represents the tower with a wire 8 m in diameter, with a single overhead skywire 0.76 m in diameter.

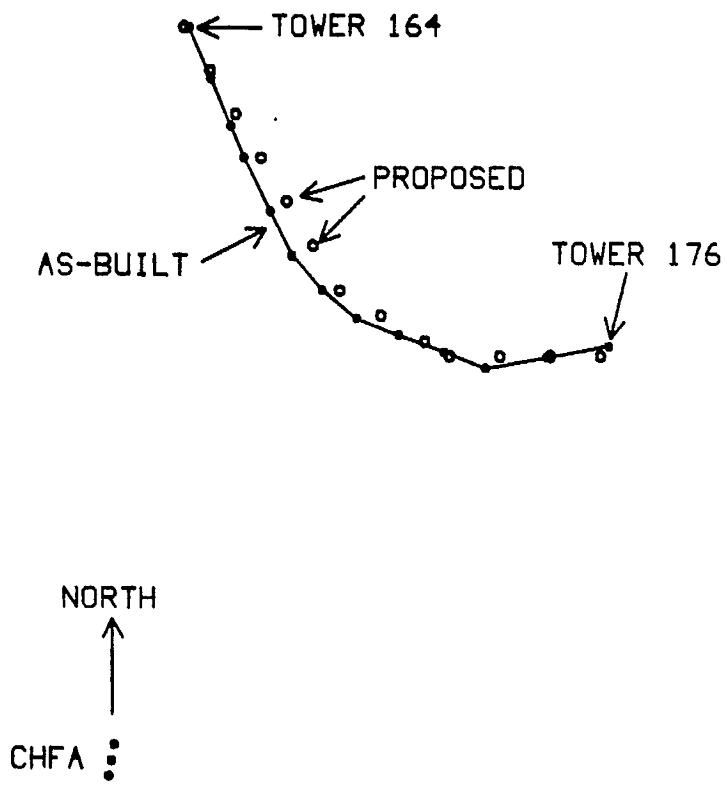

Figure 4 The computer model of the "north" power line used in the present study includes as-built towers 164 to 176, and is compared in this figure with the tower locations of the towers of the proposed power line, used in Reference (2).

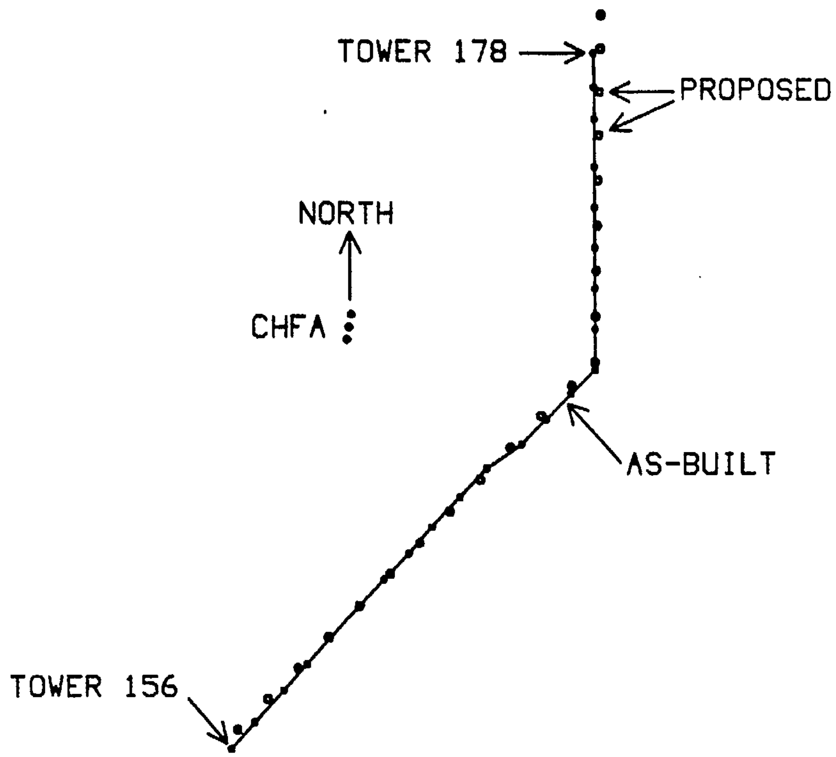

Figure 5 The computer model of the "southeast" power line used in the present study includes as-built towers 156 to 178, and is compared in this figure with the tower locations of the proposed power line, used in Reference (1).

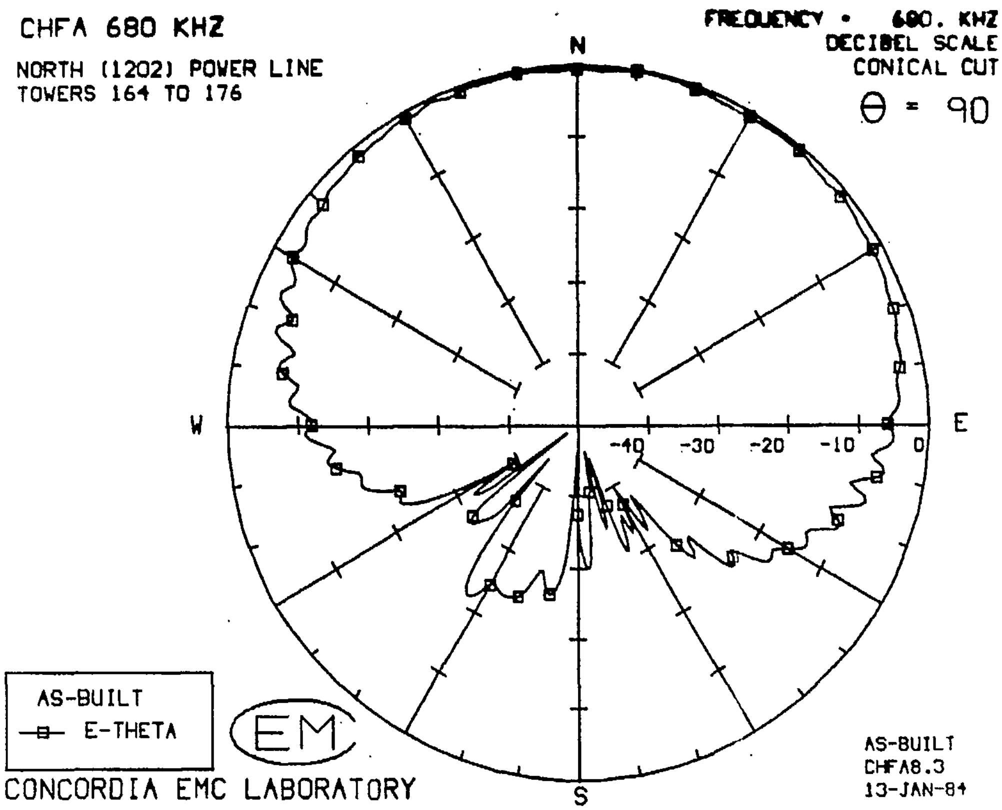

Figure 6(a) Computed azimuth pattern for CHFA radiating in the presence of the segment of the "north" power line of Figure 4.

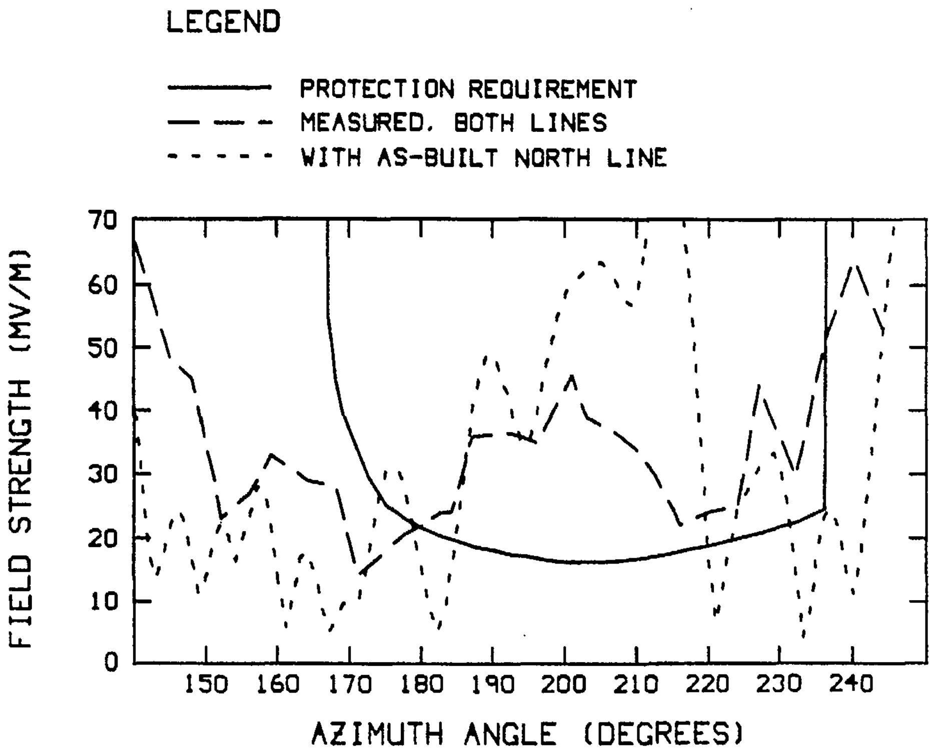

Figure 6(b) Comparison of the computed field strength for CHFA plus the "north" power line, with the CBC's measured field strength.

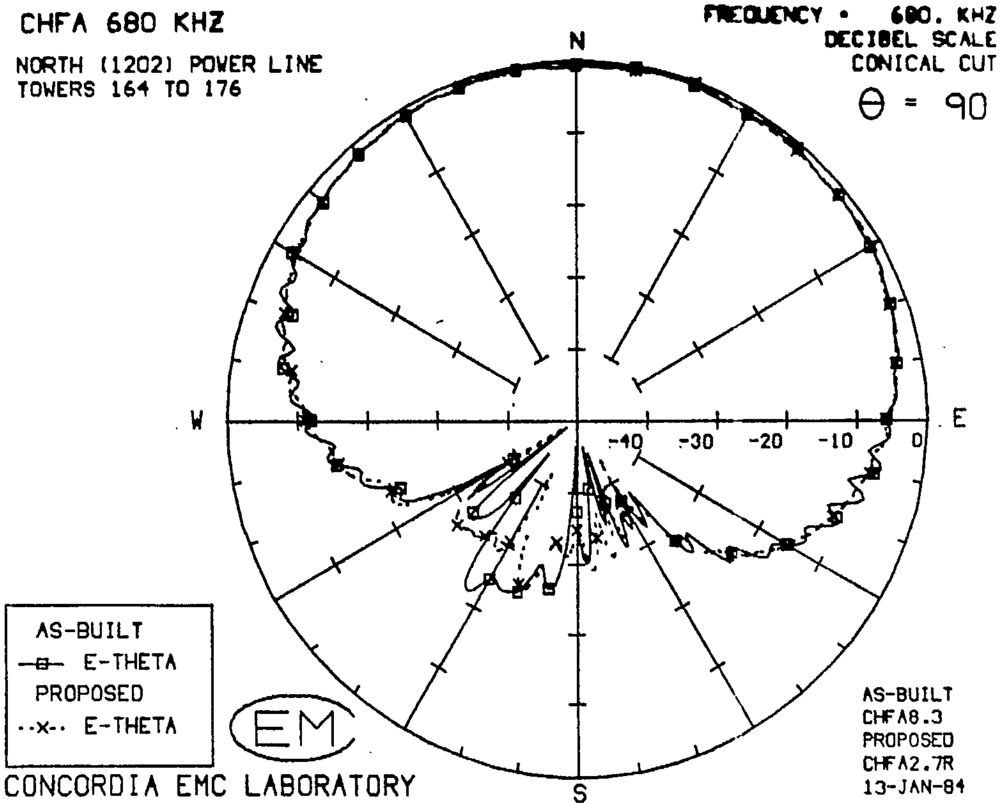

Figure 7(a) Comparison of the azimuth pattern of CHFA plus the as-built "north" power line with that of CHFA plus the proposed power line.

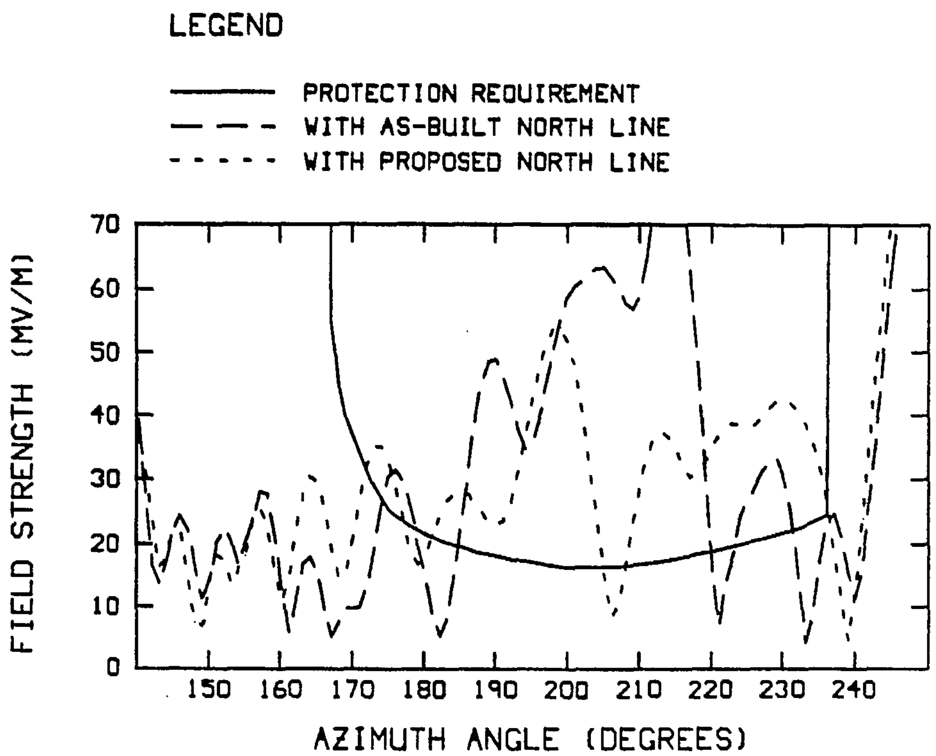

Figure 7(b) The "proposed" and "as-built" patterns are compared in the minimum.

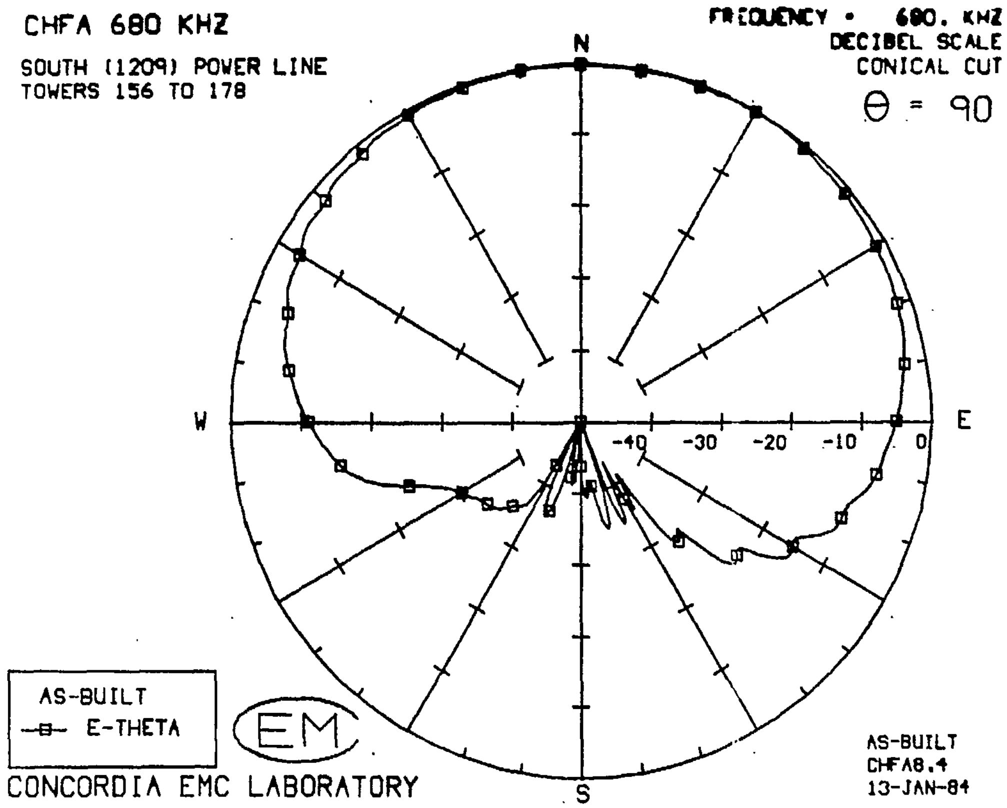

Figure 8(a) Computed azimuth pattern for CHFA radiating in the presence of the segment of the "southeast" power line of Figure 5.

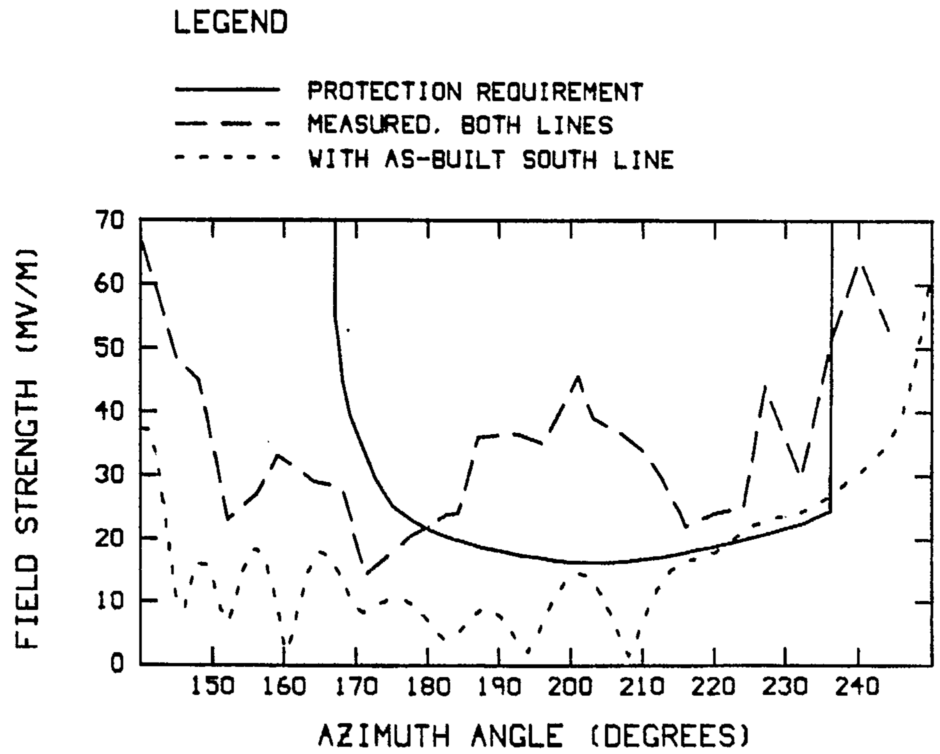

Figure 8(b) Comparison of the computed field strength for CHFA plus the "southeast" power line with the CBC's measured field strength.

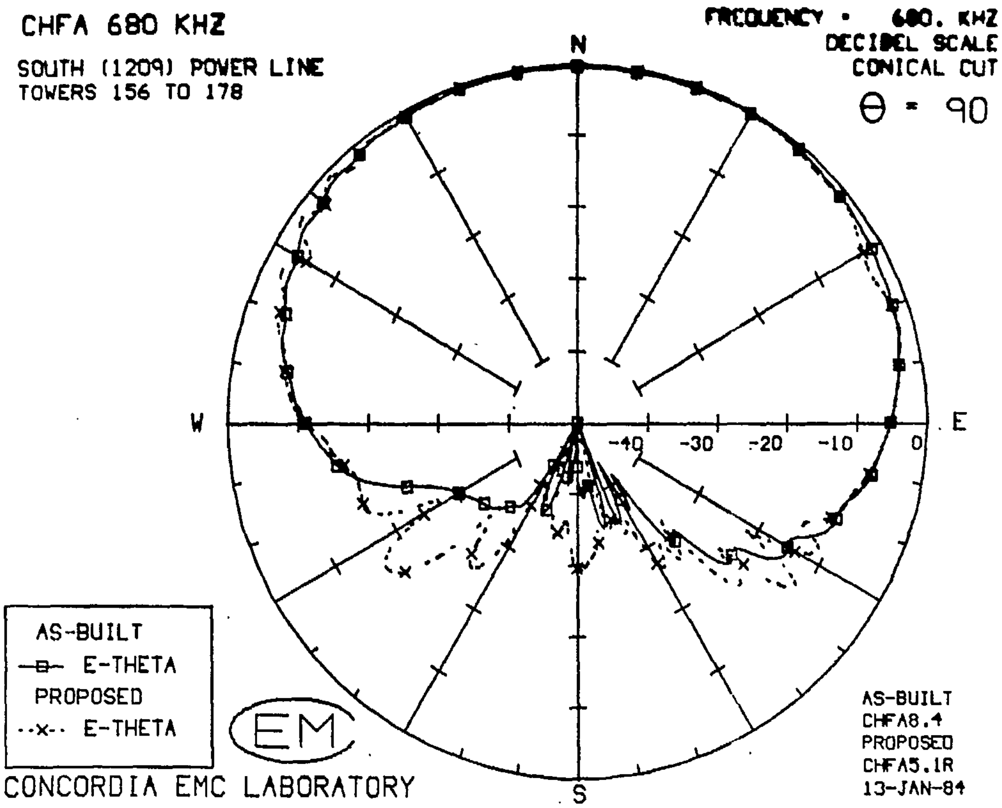

Figure 9(a) Comparison of the azimuth pattern of CHFA plus the as-built "southeast" power line with that of CHFA plus the proposed power line.

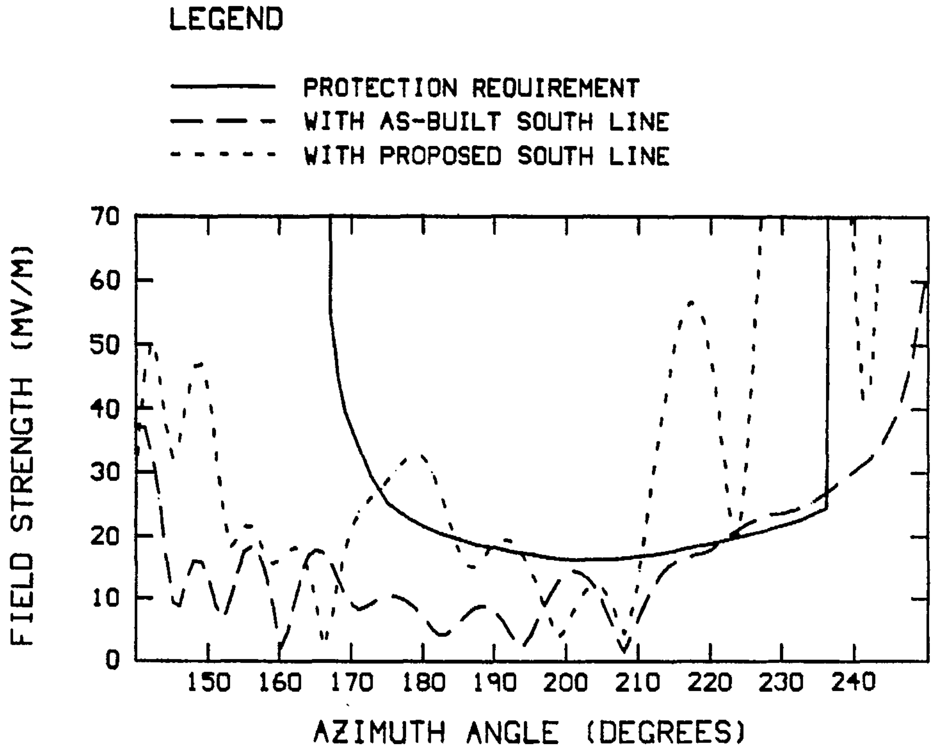

Figure 9(b) The "proposed" and "as-built" patterns are compared in the minimum.

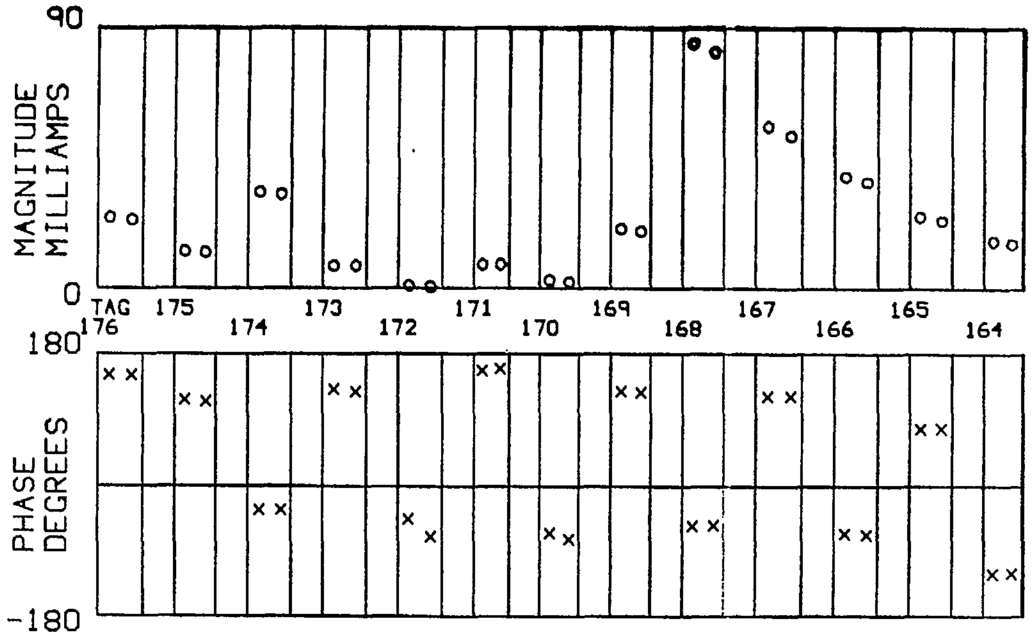

Figure 10 The RF currents flowing on the towers of the "north" power line of Figure 4.

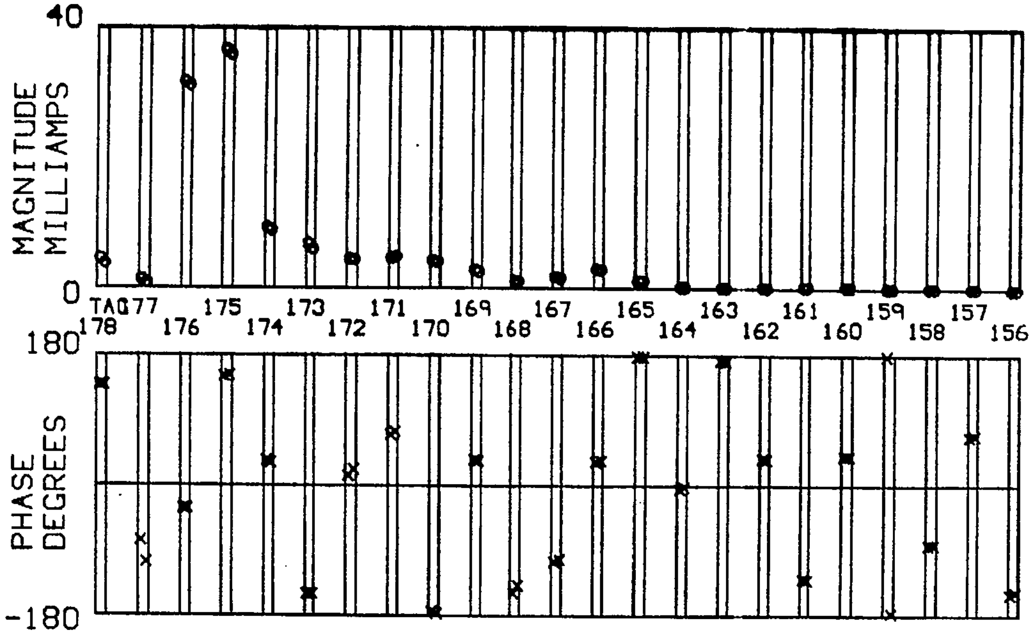

Figure 11 The RF currents flowing on the towers of the "southeast" power line of Figure 5.

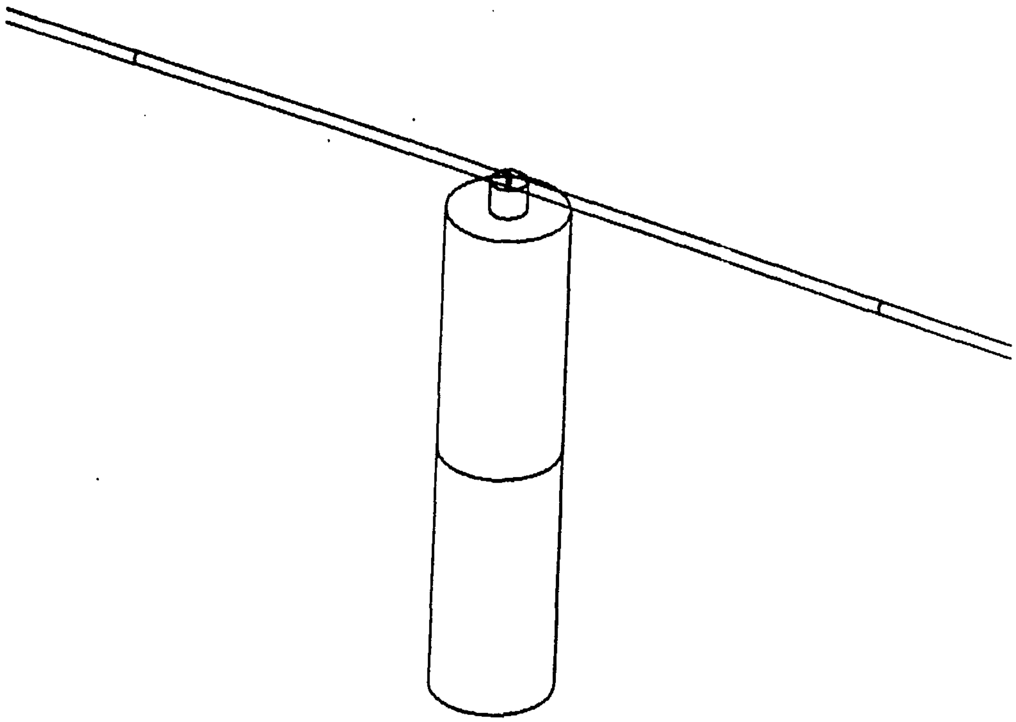

Figure 12 Modification to the model of Figure 3 to include a short segment at the top of the tower, which is "open circuited" with a large series resistor in order to "isolate" the tower from the power line.

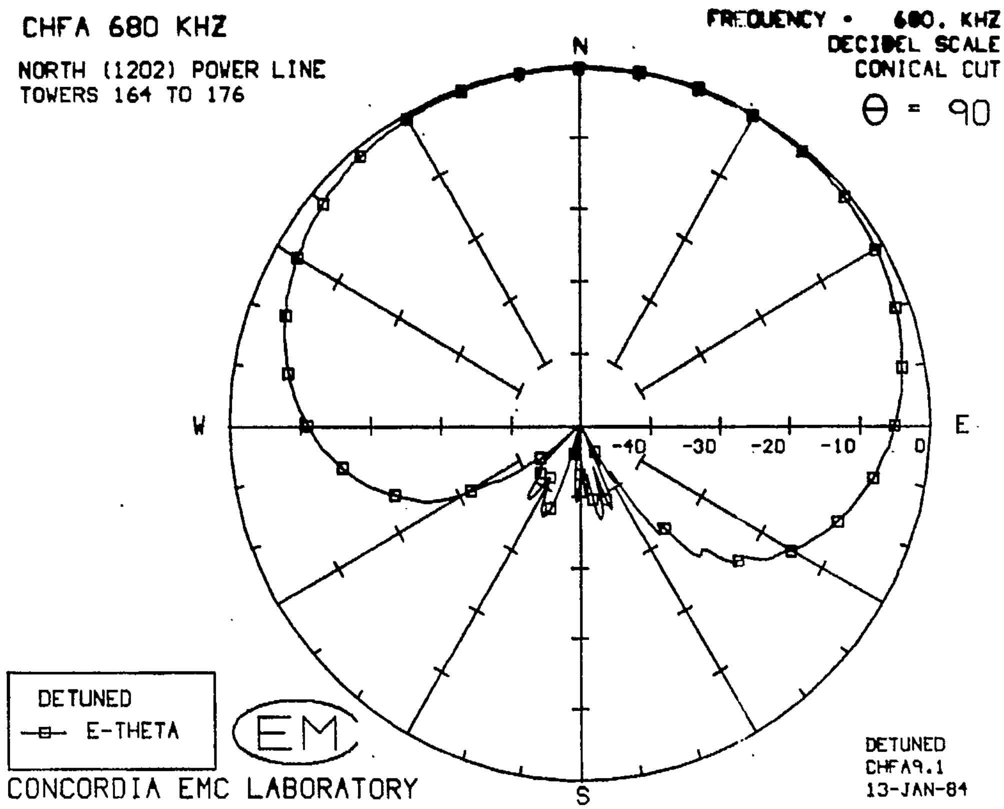

Figure 13(a) Azimuth pattern of CHFA near the "north" power line, which has been "detuned" by isolating towers number 174, 168, 167, and 165.

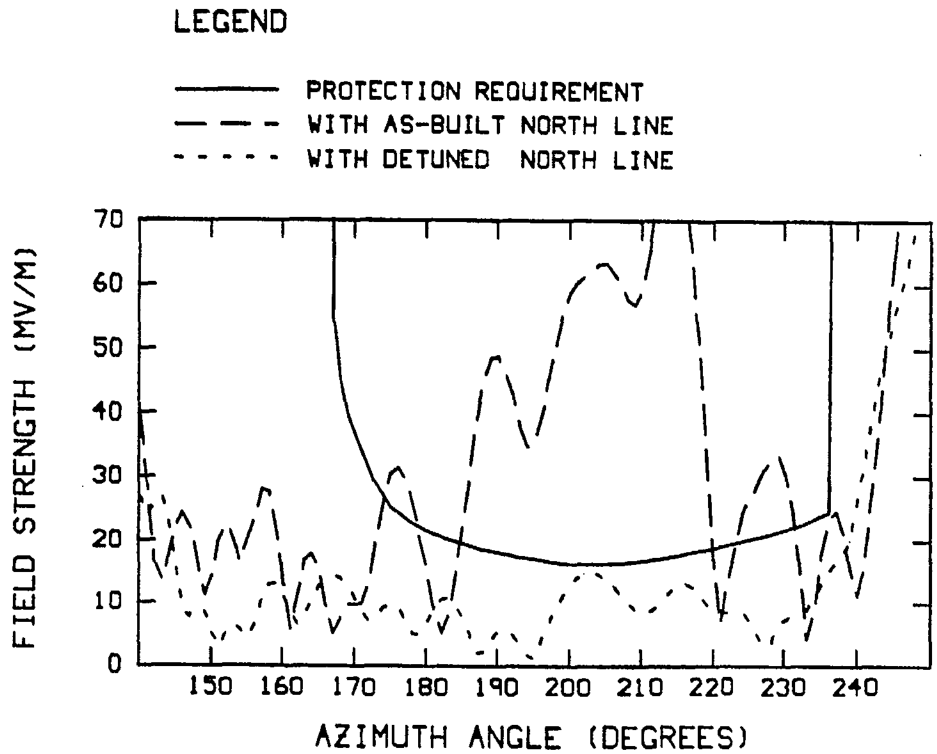

Figure 13(b) The "detuned" pattern meets the protection requirement.

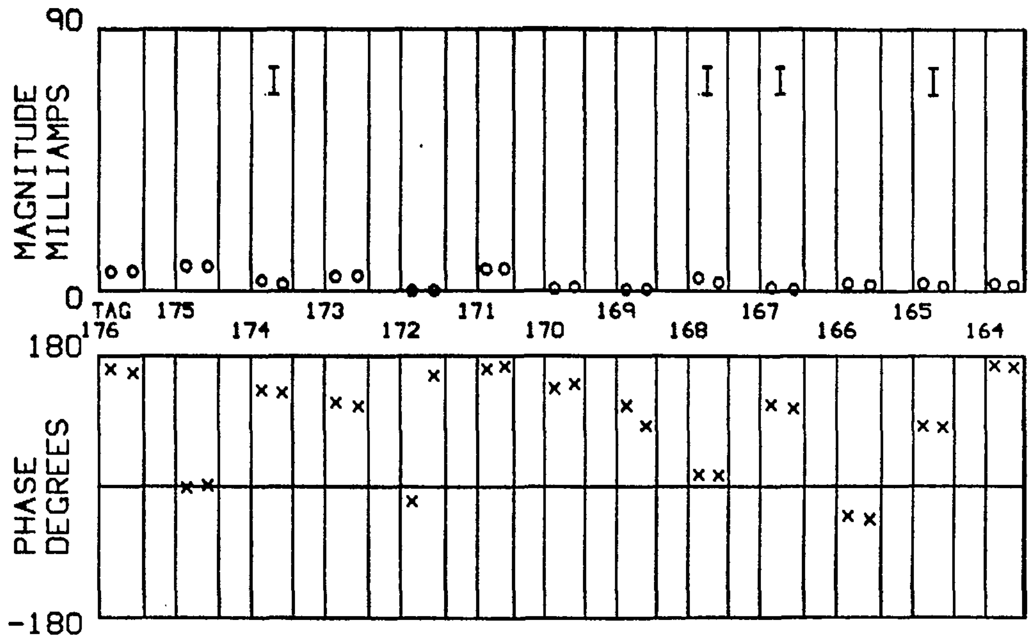

Figure 14 The RF currents flowing on the towers of the "detuned" north line. Towers marked with an "I" are isolated from the skywire.

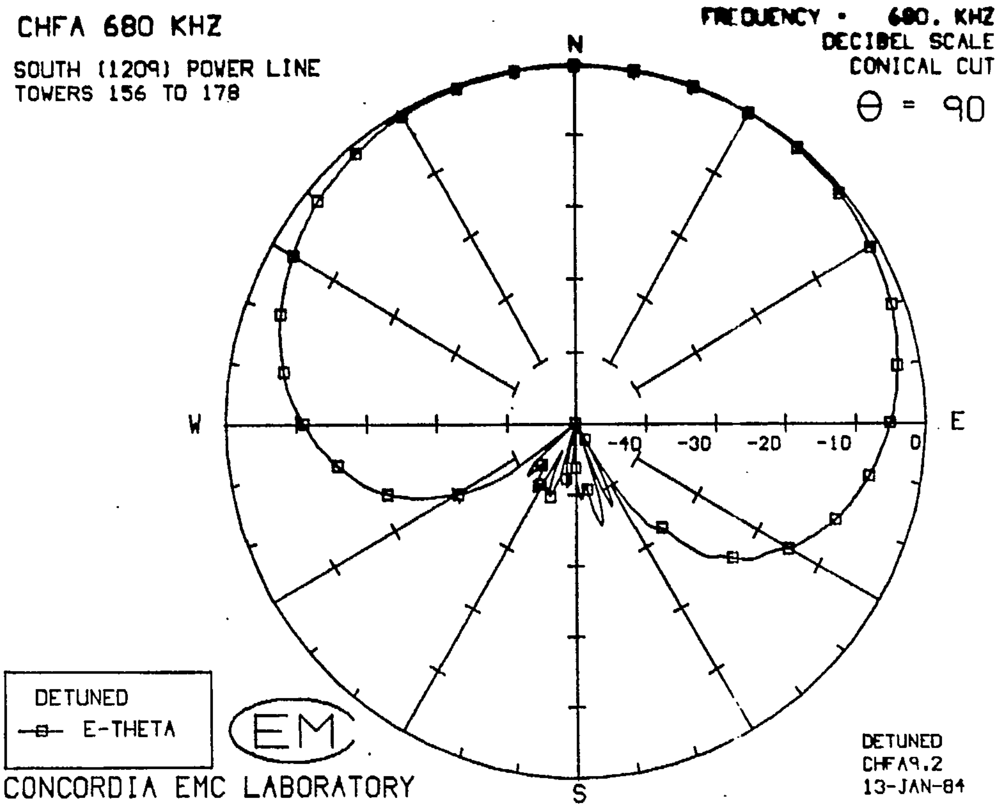

Figure 15(a) Azimuth pattern of CHFA near the "southeast" power line, which has been "detuned" by isolating towers number 176, 175, 173, and 172 from the skywire.

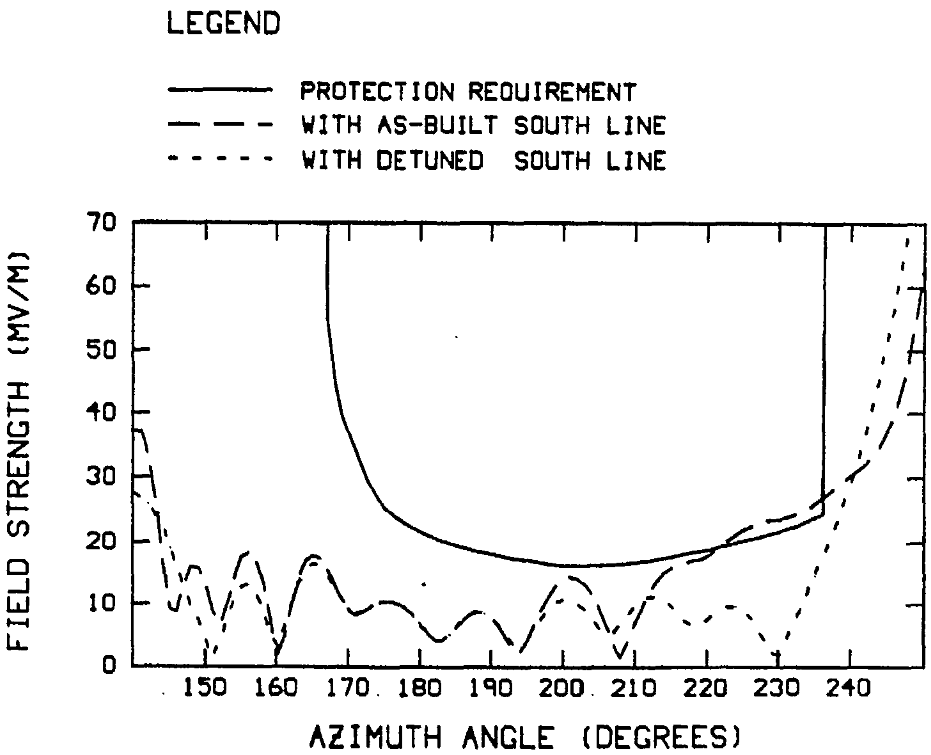

Figure 15(b) The "detuned" pattern meets the protection requirement.

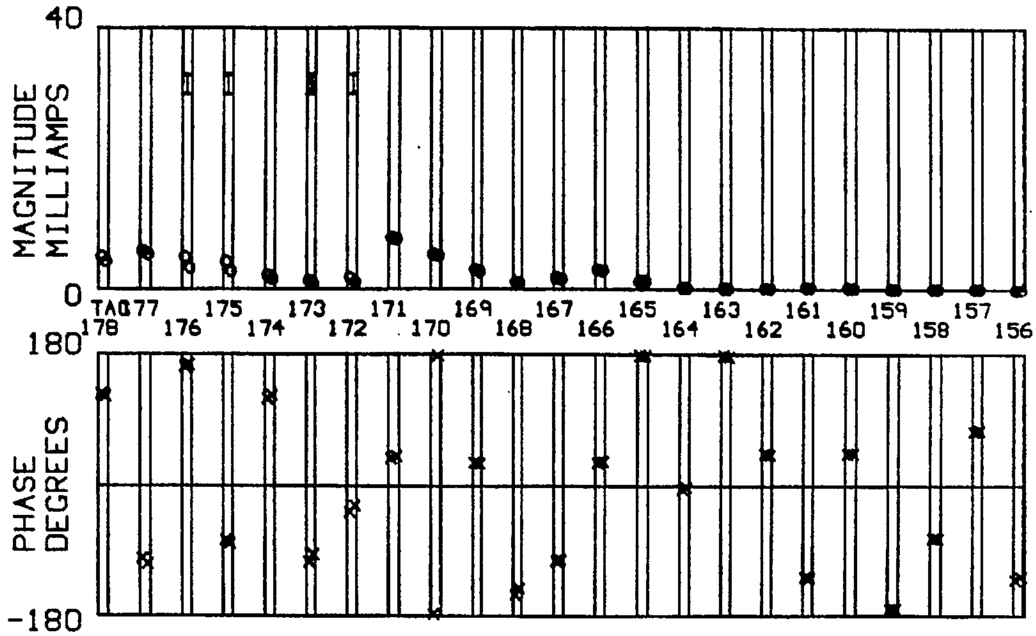

Figure 16 The RF currents flowing on the towers of the "detuned" southeast line. Towers marked with an "I" are isolated from the skywire.

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