CONCORDIA UNIVERSITY

Technical Note No. TN-EMC-84-03
May 31, 1984.

"Analysis and Procedures for
Detuning the Power Lines near CHFA, Edmonton
By Isolating Towers"

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Contract No. OST83-00290

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EXECUTIVE SUMMARY

This report extends the computer modelling study in Ref. 1 of station CHFA operating near the north and southeast power lines.

1. Longer sections of each power line are modelled. CHFA operating near the north line is found to radiate greatly in excess of the protection requirement. CHFA operating near the southeast line exceeds protection by a small amount only.

2. Substantial RF currents on towers not modelled in Ref. 1 are found for both power lines. Thus additional towers over and above those specified in Ref. 1 will have to be isolated from the skywire.

3. A "resonance chart" is drawn, giving an estimate of the resonant frequency of each "double-span" obtained by isolating one tower, and of each "triple-span" obtained by isolating two adjacent towers.

4. The method of "suppression of resonances" is developed. Towers are specified for isolation on the north and the southeast power line.

5. The set of towers to be isolated are classified according to the anticipated effect on the radiation pattern, into "Group 1" for towers carrying very large RF currents, "Group 2" for towers carrying significant RF currents, and "Group 3" for those carrying little RF current.

6. It is recommended that a measurement be made of the relative value of the tower base current before any towers are isolated. This will serve as a reference for evaluating the success of tower isolation.

7. It is recommended that Group 1 towers be isolated initially, followed by a measurement of the tower base current currents to verify that they are uniformly small, and of the field, at certain specified angles in the pattern minimum. Group 2 towers are then isolated followed by tower base current and field strength verification. The isolation of Group 3 towers is optional.

8. A procedure is suggested for selecting towers for isolation, and carrying out tower isolation "in the field", based on measured tower base currents.

The implementation of the detuning measures recommended here should result in a greatly reduced field strength in the minimum of CHFA's azimuth pattern.

Analysis and Procedures for Detuning the Power Lines near CHFA, Edmonton By Isolating Towers

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

ABSTRACT

This report uses computer modelling to study the reradiation from the north power line and southeast power line near station CHFA, Edmonton at 680 kHz, and to study the detuning of the power lines by isolating towers from the skywires. In Ref. 1, the north line was modelled from tower 164 to 176, and the southeast line from tower 156 to 178, and it was shown that CHFA operating near each section of power line radiates in excess of its protection requirement. It was shown that these short sections of power line can be detuned by isolating four towers on each. This report studies longer sections of each line, from tower 149 to 185 for the north line and from tower 156 to 178 for the southeast line. CHFA operating near the longer north line model exceeds its protection requirement by more than 50 millivolts/metre at some azimuth angles, but CHFA near the longer southeast line model exceeds protection only by a modest amount. It is found that there are substantial RF currents on some of the towers not modelled in Ref. 1, and so additional detuning will be required.

A systematic procedure called "suppression of resonances" is developed for detuning by isolating towers from the skywire. The resonance modes of a "double-span" created by isolating one tower, and of a "triple-span" obtained by isolating two adjacent towers, are identified and estimates of the resonant frequencies are made. A "resonance chart" is constructed giving the estimated resonant frequency of all possible double-spans and triple-spans on the power line. Towers are then selected for isolation such that all resonant single-span loops are broken open, and at the same time no resonant double-spans or triple-spans are created. A set of towers are specified for isolation for the north and the southeast line. The tower base currents computed with all towers connected to the skywire are used to classify the set of towers chosen for isolation according to the anticipated effect on the radiation pattern. Thus "Group 1" towers carry the strongest currents, "Group 2" towers carry significant currents and "Group 3" towers carry little

RF current.

The implementation of tower isolation "in the field" is considered. In order to have a controlled, systematic procedure, it is recommended that a measurement be made of the base current on all the towers of each power line, before any are disconnected. Then the "Group 1" towers should be isolated on the north line, followed by re-measurement of the base currents on those towers to verify that they are uniformly small. The field strength in the pattern minimum should be checked for improvement. Then "Group 2" towers are to be isolated, followed by tower base current and field strength measurements. The procedure is then repeated for the southeast power line. The isolation of Group 3 towers is optional.

A procedure is suggested for selecting towers for isolation based on the resonant frequency estimates of the "resonance chart" and on a field measurement of the tower base currents, without the aid of computer modelling.

The report concludes with a review of the simplifications inherent in the computer model, and suggests topics for further investigation.

CHAPTER ONE

INTRODUCTION

This report investigates some of the questions raised in the report, "The Radiation Pattern of CHFA, Edmonton near the As-Built North and Southeast Power Lines, and Their Detuning by Isolating Towers"(Ref. 1). In that initial study, the pattern of the CHFA array operating near each of the "as-built" power lines was compared with the station's pattern operating near each power line of the design "proposed" by the hydro utility. The "proposed" and "as-built" designs are quite different at MF frequencies because the "proposed" lines use evenly spaced towers, and so all spans are either resonant or non-resonant together, whereas the "as-built" lines use a variable tower spacing, and so some spans are strongly resonant while most are too short to be resonant. Each of the power lines was modelled in Ref. 1 using a small number of towers, representing a relatively short section of the power line located near the CHFA array. It was found that certain individual spans are strongly resonant and that reradiation from these spans into the minimum of CHFA's azimuth pattern exceeded the maximum field strength specified by the "protection requirement" which CHFA must meet. In this report longer sections of each power line are modelled and the conclusion of Ref. (1) is re-examined. Factors involved in exciting a span to resonance are discussed. The question of "how many towers need to be modelled" is raised. The answer lies in estimating the resonant frequencies of each span of the power line.

Ref. (1) also contains an initial study of the "detuning" of the power lines by isolating towers from the skywire. The criterion used to select towers to be isolated is examined in the present report, and a rational choice is made based on the estimated resonant frequencies of the power lines. It was shown that isolating four towers on the north line was enough to restore the pattern of CHFA operating in the presence of towers 164 to 176 of that line, where the tower numbers are shown in Fig. 2.1. Similarly it was shown that isolating four towers on the southeast line resulted in an acceptable pattern when towers 156 to 178 were included in the model of that line. In this report a longer section of each power line is modelled. It is shown in Chapter 2 that more towers than were specified in

Ref. (1) will have to be isolated to detune the longer sections of power line.

The question of which towers to isolate is studied in this report. Ref. (1) simply chose those towers carrying strong currents, and this choice is re-examined. Chapter 3 reviews the resonant behaviour expected of a power line, including resonance modes involving two and three spans, and provides an estimate of the frequency at which each resonance mode is expected. The bandwidth of power line resonance is estimated. A "resonance chart" is given, which depicts the power line and its resonant frequencies schematically for quick reference.

The thrust of this report is to provide a systematic procedure for choosing towers for isolation. Chapter 4 examines "bulk isolation", in which a large number of towers are isolated in a regular fashion, such as isolating every second tower, or two out of each three towers. Such an "arbitrary" procedure inevitably leads to the creation of resonant paths involving two spans or three spans, and these are shown to respond strongly to the excitation of the broadcast antenna. A "selective isolation" technique is presented, in which the "resonance chart" is used to choose towers for isolation such that all resonant single-span loops are broken, without creating any resonant double- or triple-span loops. This method of "suppression of resonances" is shown to yield a greatly improved radiation pattern for CHFA operating in the presence of each of the two power lines. It is used to specify a set of towers for isolation to detune the north line, and a set for detuning the southeast line. Further, the towers are grouped according to their importance in improving the azimuth pattern, into those carrying large RF currents, those carrying significant RF currents, and those which carry little RF current in the computer model.

A procedure is suggested for carrying out the isolation of towers "in the field". It is recommended that the base current on each power line tower be measured with all towers connected to the skywire, which serves as a reference case. Then the towers carrying "large" RF currents are to be isolated, followed by a measurement of the tower base currents to verify that a reduction has been achieved, and of the field strength at selected azimuth angles to check the effect on the reradiated field. Then the set of towers carrying "significant" RF currents should be isolated, followed by a similar check of tower base currents and of azimuth pattern field strength. In this way a systematic improvement in the radiation pattern can be achieved.

The conclusion of the report stresses that a precise comparison between computed tower currents and measured tower currents on a real power line "in the field" has not been undertaken thus far, and recommends such a comparison. It is anticipated that such a comparison would establish general agreement, but that some differences would be evident. The simplifications in the computer model which give rise to such differences are reviewed. The final conclusion reviews the procedure of "suppression of resonances" and suggests that it could be applied "in the field" with the aid of a set of measured tower base currents, without recourse to computer modelling.

In the following Chapter, the question of how many towers to include is addressed. The next Chapter reviews power line resonance modes and provides estimates of the resonant frequencies. Then the method of "suppression of resonances" is presented and used to select towers for isolation for the north and the southeast power lines.

CHAPTER TWO

LONGER POWER LINE MODELS

In this Chapter the radiation pattern of the CHFA array is computed when it operates in the presence of longer sections of the two power lines than were represented in the models of Ref. (1). There, it was shown that CHFA operating in the presence of a section of the north line from tower 164 to tower 176 results in a field strength in the minimum substantially in excess of the protection requirement, whereas CHFA operating in the presence of a section of the southeast line from tower 156 to tower 178 results in a field strength only a small amount in excess of protection. Fig. 2.1 shows a plan of the site. In the following, considerably longer portions of the two power lines are modelled. The result is that some new resonant spans are included and somewhat different radiation patterns are found, but the overall conclusion remains the same as that stated above, namely that the north line reradiates a great deal but the southeast line only reradiates a small field.

2.1 North Line

Fig. 2.2 shows the radiation pattern and the current distribution when towers number 164 to 176 are included on the north line, and is reproduced from Ref. (1). The tower currents are given in Fig. 2.2(c) and are large on towers # 176, 174, 169, 168, 167, 166, 165 and 164. The relative phase of the currents on towers 175-174-173, 169-168-167-166, and 165-164 is 180 degrees different from tower to tower, and suggests that those spans may be in two-wavelength loop resonance. The current distribution on the skywires, given in Fig. 2.2(d), shows the magnitude curve expected of two-wavelength loop resonance on the spans from tower 176 to 175, 175 to 174 and 168 to 167, which has a maximum at the center of the span and a null adjacent to each tower. The phase distribution on these spans is that of two-wavelength loop resonance, being constant with distance, except for sharp 180 degree phase changes coincident with the nulls in the magnitude of the current. The estimated resonant frequencies for these spans are given in Ref. (1), Table 2 (which is reproduced below as Table 3.1) and are 637, 646 and 666 kHz, respectively, and are all close to CHFA's 680 kHz. The question of how different a span's resonant frequency can be from 680 kHz and still result in large, resonant RF currents on the span, concerns the bandwidth of resonance, and is discussed in Chapter 3. In general if CHFA's frequency lies outside the bandwidth of resonance for a given span, then a small induced RF current is expected, but if CHFA lies within the bandwidth of resonance, then a large response may be present, depending on the magnitude of the excitation and its relative phase at the two towers. This is discussed further below. Also, in Chapter 3 it is shown that the resonance mode on the spans from tower 176 to 175 and 175 to 174 may be a "double-span" mode.

Fig. 2.3 shows the radiation pattern and the RF current distribution on the towers and skywires of a longer section of the north power line, including towers 149 to 185. The field strength in the minimum shown in Fig. 2.3(b) varies more rapidly with angle than that of Fig. 2.2(b), and there is stronger reradiation between 185 and 190 degrees, and between 220 and 230 degrees. The protection requirement is still exceeded by a large amount. The RF current distribution on the towers given in Fig. 2.3(c) shows that a strongly resonant span has been added from tower 151 to tower 150. The current distribution on the towers and skywires from tower 164 to tower 176 is substantially the same in Fig. 2.3(c) and (d) and in Fig. 2.2(c) and (d), and so the current does not change much when this section is embedded into a longer power line model by adding towers at each end. The currents on a given span appear to exert only a local influence, affecting the currents on the two or perhaps four adjacent spans, but not having much affect on spans further away.

The current distribution on the skywires of Fig. 2.3(d) shows the presence of two-wavelength loop resonance on certain spans. In addition to the resonant spans on the section from tower 164 to 176, the spans from tower 184 to 183, and from tower 178 to 177 show the amplitude distribution of two wavelength loop resonance although the phase only weakly indicates the expected response. The spans from tower 159 to 158 and especially from tower 151 to 150 show two-wavelength loop resonance both in magnitude and phase. The resonant frequencies of these four spans are estimated in Table 3.1 to be 678, 685, 674 and 660 kHz, all close to CHFA's 680 kHz. Thus the estimated resonant freqencies of the stongly responding spans all lie close to CHFA's frequency.

It is notable in Fig. 2.3 that some spans not expected to be resonant carry significant RF currents. Thus the spans from tower 169 to 168 and from tower 167 to 166 are resonant at 801 and 522 kHz, quite different from 680 kHz, yet both spans carry large currents. These spans are excited by direct coupling to the strongly resonant span from tower 168 to 167. If the resonace of this adjacent span is detuned, then the currents on the spans 169 to 168 and 167 to 166 disappear.

Thus adding towers to the section of the power line represented in the computer model results in substantially the same currents on the original section, and some additional resonant spans on the new section. These resonant spans result in a somewhat different radiation pattern, but the overall result still holds. The north line causes CHFA to substantially exceed its protection requirement.

2.2 Southeast Power Line

Fig. 2.4 shows the radiation pattern and the RF currents induced on the southeast power line when towers 156 to 178 are included in the model, and is reproduced from Ref. (1). The protection requirement is violated by a small amount from 220 to 236 degrees. The RF currents induced on the towers, shown in Fig. 2.4(c), are less than half of those on the north line, even though the southeast line is closer to the CHFA array. Only the span from tower 176 to 175 carries a very substantial RF current. The skywire currents are plotted in Fig. 2.4(c). The estimate of the frequency of two-wavelength loop resonance of Ref. (1), Table 4 (reproduced below in Table 3.4) indicates that spans 176-175, 167-166, 161-160 and 158-157 are resonant at 645, 717, 706 and 689 kHz, respectively. Only the span from tower 176 to tower 175 shows strong two-wavelength loop resonance. The plan of the power line, Fig. 2.1, shows that towers numbered 170 and lower lie south of east of the antenna, where the field strength decreases rapidly with azimuth angle. Thus due east the field strength is about 5 dB down from the maximum, and 30 degrees south of east, roughly at tower # 167, the field strength is 15 dB down. This is reflected in the induced RF current, which decreases progressively from tower 174 towards tower 156. For this reason, the power line model was not extended southwest beyond tower 156.

Fig. 2.5 shows the field strength and RF currents induced on an extended model of the southeast power line, where towers 179 to 190 have been added so that the model represents towers 156 to 190. The field strength in the minimum differs from Fig. 2.4(b) in that an excursion in excess of the protection requirement is seen at 188 degrees, while the field between 220 and 236 degrees has been reduced by a small amount, and for the most part satisfies protection. The currents on towers 156 to 178 are substantially the same as in Fig. 2.5. There are large currents on the added section of power line, on towers 183, 182, 181 and 179. The table of estimated resonant frequencies, Table 3.4, indicates that spans 183-182, 181-180, 180-179 and 179-178 are resonant at 676, 629, 726 and 639 kHz. Fig. 2.5(d) shows the skywire currents and shows the magnitude distribution expected of two-wavelength loop resonance on the spans from tower 183 to 182, 181 to 180 and 180 to 179. The phase distribution does not show strong resonance. All spans except 183-182 are resonant near the limits of the bandwidth, and that span carries by far the largest current.

Thus the added section of power line includes some resonant spans, and these result in a somewhat different radiation pattern, but the conclusion remains the same. The southeast power line causes small excursions above the protection requirement but the problem is minor.

2.3 Excitation, Resonance and Response

The strength of the RF current induced on a span depends on the strength of the excitation field, on the relative phase of the excitation field at the two towers terminating the span, and on whether the frequency of operation of the broadcast antenna lies within the bandwidth of a resonance mode of the span, and how close the resonant frequency is to the operating frequency. This section examines these factors.

If a span is resonant at f_s and the broadcast antenna operates at f_o , then how close must f_s and f_o be in order that a significant RF current could be induced on the span ? The bandwidth of single-span resonance can be estimated from Fig. 5.5 of Ref. (2), which plots the max-to-min ratio of the pattern of an onmidirectional broadcast antenna which is operated 448 m from the center tower of a straight, evenly spaced power line with 13 towers, tower spacing 274 m and tower height 51 m. The "bandwidth" is defined as the frequency range over which the power line causes more than 5 dB peak-to-peak distortion of the "omni" pattern. For one-wavelength loop resonance, the bandwidth extends from about 380 to about 500 kHz, with the largest distortion of the pattern at about 430 kHz. For two-wavelength loop resonance, the bandwidth extends from about 800 to about 930 kHz, with the largest pattern distortion occuring at 860 kHz. Thus the bandwidth of single-span resonance is roughly 120 kHz, extending from roughly 60 kHz below to 60 kHz above the resonant frequency. The 5 dB figure was "arbitrarily" chosen and the resulting 120 kHz bandwidth figure gives a "rule of thumb" estimate. It may be necessary to refine this estimate in specific situations.

The strength of the broadcast antenna's field, or "excitation field", decreases as inverse distance in the far field, and faster in the antenna's near field. All else being equal, a span which is further away is more weakly excited and so responds more weakly. The "all else" includes the span length and tower heights, and hence proximity to a resonant frequency. Also, it includes the orientation of the span, which is shown in the following to be a significant factor. The strength of the antenna's field is also a function of the azimuth angle at which the span is located in the radiation pattern. Thus the section of the southeast line closest to the antenna is roughly twice as close as the closest section of the north line, and so is about 6 dB more strongly excited. But the closest section of the southeast line lies east of the antenna where the field is 5 dB down from the maximum, and so most of the 6 dB difference is counteracted by the shape of the antenna pattern.

To gain insight into the influence of the orientation of the span on the response of the span, recall that the two-wavelength resonance mode requires an anti-symmetric excitation, which is different by 180 degrees in phase at the two towers. Thus Belrose(Ref. 4) has remarked that if a span is oriented perpendicular to the radial line from the antenna, it cannot be excited to two-wavelength loop resonance. The excitation field can be factored into a common-mode component C which is in-phase at the two towers, and a difference-mode component D which is 180 degrees out of phase. In Fig. 2.6, let the field at the two towers be given by

$$E_1 = E_o e^{-jkr_1} \quad \ldots 2.1$$

and

$$E_2 = E_o e^{-jkr_2} \quad \ldots 2.2$$

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

$$C + D = E_1 \quad \ldots 2.3$$

and at tower # 2

$$C - D = E_2 \quad \ldots 2.4$$

which can be solved to obtain

$$C = \frac{E_1 + E_2}{2} \qquad \text{...2.5}$$

and

$$D = \frac{E_1 - E_2}{2} \qquad \text{...2.6}$$

The distances r_1 and r_2 can be compared to the distance r from the antenna to the center of the span, by assuming that both r_1 and r_2 are large compared to the length of the span, s. From Fig. 2.7,

$$r_1 = r - \frac{s}{2}\cos\theta \qquad \text{...2.7}$$

and

$$r_2 = r + \frac{s}{2}\cos\theta \qquad \text{...2.8}$$

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

$$C = E_0\, e^{-jkr} \cos\left(\frac{ks}{2}\cos\theta\right) \qquad \text{...2.9}$$

and

$$D = j E_0\, e^{-jkr} \sin\left(\frac{ks}{2}\cos\theta\right) \qquad \text{...2.10}$$

Evidently for θ =90 degrees, the excitation is pure common-mode and so two-wavelength loop resonance is not excited. For a typical span with 32.6 m tall towers, the span length must be about 411 m for two-wavelength loop resonance at 680 kHz, and such a span is most favorably oriented roughly at θ =60 degrees to the radial, where D is largest and C is smallest.

The impact of orientation for the two lines can be summarized as follows. In general, when a span makes an angle near θ =60 degrees to the radial from the broadcast antenna, it is "favorably" oriented, but when it is roughly parallel to the radial(θ =0), or roughly perpendicular to it(θ =90), it is "unfavorably" oriented and most of the excitation field is in the common mode component, and two-wavelength loop resonance will not be strongly excited. For a 411 m span, the difference mode field D is 6 dB or more down from its largest value if the span is oriented at less than 25 degrees or more than 80 degrees to the radial. Referring to Fig. 2.1, most of the spans lie within the 25 to 80 degree range, and so most see less than 6 dB of excitation loss due to orientation. Spans oriented between 35 and 75 degrees to the radial see less than a 3 dB loss in the excitation due to orientation.

Two strongly resonant spans can be compared to assess the impact of the various factors. The span from tower 168 to tower 167 on the north line is about 4080 m from the broadcast antenna, is located at 14 degrees azimuth in the radiation pattern and so is just about exactly in the maximum of CHFA's pattern, makes an angle of 41 degrees to the radial for D equal to about 80 percent of its largest value, and is resonant at 666 kHz. Span 176 to 175 on the southeast line is about 2800 m from the antenna at 54 degrees azimuth in the pattern, where the field is down about 0.7 dB from its largest value, makes an angle of about 54 degrees to the radial for D about 98 percent of its largest value, and is resonant at 645 kHz. To compare loss of excitation due to distance, inverse distance variation is assumed, and so span 168 to 167 on the north line sees 4.7 dB less excitation than span 176 to 175. Span 168 to 167 sees 0.7 dB more than span 176 to 175, due to azimuth position, for a net difference of 4.0 dB. Due to orientation, span 176 to 175 is more favorably oriented, and the difference is $20 \log(.98/.80) = 1.8$ dB, for a net difference of 5.8 dB more difference-mode excitation for span 176 to 175 on the southeast line compared to span 168 to 167 on the north. This would suggest that the span on the southeast line should respond more strongly, but recall that the resonant frequency of the span on the north line, 666 kHz, is much closer to 680 kHz than that on the southeast line, 645 kHz. In fact, the results shown in Figs. 2.2 and 2.4 indicate that span 176 to 175 carries a much larger RF current, of about 85 mA compared to 36 mA for span 168 to 167, a difference of 7.5 dB. Thus analysis of excitation could be misleading. The "transfer function" between the excitation of a single span embedded in a power line, and the resulting RF current on the span is not at present available in a simple form. Thus even if a span is much further away and less favorably oriented than some other span, it can carry the stronger current if it is closer to resonance.

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

2.4 Conclusion

This Chapter has demonstrated that the north line causes the protection requirement to be substantially exceeded, whereas the southeast line causes only small excursions above the protection requirement. The dependence of this conclusion on the length of the section of power line included in the computer model has been investigated, and it was found that adding towers to the section of power line represented added some resonant spans and changed the field strength in the minimum somewhat, but did not change the overall result.

The current distributions calculated on the two power line models indicate the usefulness of the resonant frequency estimate of Ref. (1), reproduced in Tables 3.1 and 3.4. Thus where a span is estimated in the Tables to be resonant within half of the 120 kHz bandwidth of resonance of CHFA's frequency, a strong response is often seen. If a span is not estimated to be resonant, then a weak response is generally found, with the exception of non-resonant spans directly adjacent to strongly resonant spans, where there is a direct coupling. The factors involved in exciting a resonant span have been discussed, with the conclusion that even if a span is resonant it will not necessarily be strongly excited, because of distance from the antenna, location in the azimuth pattern, and orientation, and so a strong RF current will not necessarily be found.

The question of how many towers need to be included in the computer model in order to assess whether protection is met is a difficult one. If a computer model representing the 10 or 15 spans closest to the antenna indicates a large excursion above protection, as is the case for the north line, then it can be stated with confidence that protection will be exceeded with a longer power line model. However, if a model representing the 10 or 15 closest towers shows that protection is met, or is marginal as in the case of the southeast line, then it is difficult to guarantee the same result as towers are added to the line. The case of the southeast line suggests that the same result would hold for longer power line models provided that there are not a great many strongly resonant spans.

If it were desired to model a very large number towers, say 100 or more, in order to be sure of including all spans that are close enough to the broadcast antenna to be significantly excited, then the presently available computer resources would be inadequate and a more approximate solution would have to be constructed. One possible approach is to take advantage of the fact that a span appears to exert only a local influence on its neighbours, and so the current distribution on a certain group of towers is not substantially changed when some other group of towers not adjacent, is included or deleted from the model. Thus the power line could be modelled in five "runs" of groups of twenty or twenty-five towers to determine the RF current distribution on each span, then a composite current distribution for the whole line could be built up. The groups might be chosen to overlap and the currents on the end spans in each run could be discarded. The composite current distribution could be integrated to give the far field pattern in the presence of the whole power line. This would be an expensive, time-consuming procedure, but opens the door to modelling very large groups of power line towers.

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

CHAPTER THREE

MULTI-SPAN RESONANCE MODES

This section examines the resonant behaviour of the power line when some towers have been disconnected from the skywire. It is seen that disconnecting one tower creates a "double-span" loop which may be resonant at the frequency of the broadcast antenna, and similarly disconnecting two successive towers creates a possibly resonant "triple-span". The resonance modes for such "multi-span" loops are described. A method for estimating the resonant frequencies is given, based on previous experience with two-wavelength loop resonance for single spans.

3.1 Resonance Modes With Isolated Towers

A "single span" consists of two towers interconnected by a skywire, and creates a loop of geometrical length equal to the distance from the base of one tower, up the tower, along the skywire to the next tower, and back down to ground, plus the corresponding return path on the images of the towers and skywires in ground. The loop is resonant at those frequencies which make its electrical length is equal to integer multiples of the wavelength. The electrical length is somewhat shorter than the geometrical length, which is accounted for below in estimating the frequencies of resonance. The current distributions associated with single span resonance are given in Fig. 3.1, and are those reported in Ref. (3). One-wavelength loop resonance gives rise to a current maximum at the base of each tower, and a minimum at the skywire center. The phase of the current changes abruptly by 180 degrees in crossing the minimum in the current. The figure is drawn with the same wavelength for each resonance mode, and it is seen that two-wavelength loop resonance requires a longer span length to accomodate two half-wavelengths of the current distribution. Two-wavelength loop resonance is characterized by a maximum in the RF current at the center of the span and a sharp null with its associated 180 degree phase reversal near each of the towers. The arrows in the figure show the actual direction of current flow, and show that the phase of the current differs by 180 degrees at the towers for two-wavelength loop resonance. Thus this mode of resonance can only be excited by the "difference" mode component of the incident field. Both the amplitude distribution and the phase reversals are looked for to identify a resonance mode on the skywire as two-wavelength loop resonance. Thus in Fig. 2.4(d), the skywire from tower 168 to tower 167 shows the characteristic nulls near the towers and maximum at the span center, and the phase shows 180 degree reversals at the nulls, and so the span is in two-wavelength loop resonance.

Figs. 3.2 and 3.3 show the resonance modes expected for double-span and triple-span resonances. A double-span is created by isolating one tower from the skywire, and consists of the two towers adjacent, plus the skywire from one of these towers to the isolated tower, and from there to the other adjacent tower. This path length is filled up with half-wavelength long cycles of the current distribution and is resonant when an integer number of these half-waves "fit" perfectly. For the span lengths encountered on the power lines near CHFA, the three-wavelength loop resonance mode is encountered near 680 kHz for short spans, and for longer spans the four-wavelength mode is found. The "bulk isolation" tests described in the next section demonstrate the existance of such resonances. Note that the three-wavelength mode is excited by the "common mode" component of the incident field, while the four-wavelength mode is excited by the "difference mode" field.

It is interesting to note that the four-wavelength double-span mode can exist on the power line with all towers connected. Thus on the skywire-plus-image transmission line, when the current has a maximum, the voltage has a corresponding minimum, and a tower connected across the transmission line at a voltage minimum will have little effect on the four-wavelength resonance mode. On the north line the double-span from tower # 176 to # 174 is estimated below to be four-wavelength resonant near 680 kHz, and looking at the skywire current distribution in Fig. 2.3(d), it is seen that the curve is similar to the idealization of Fig. 3.2, and that the phase has the necessary 180 degree reversals at the nulls in the current. Also, the estimated two-wavelength single-span resonant frequencies for the two spans are 637 and 646 kHz, which are somewhat low for a strong two-wavelength resonance to exist. It is shown in Sect. 5.1 that disconnecting tower # 174 from the skywire reduces the current on both tower 174 and 176 to small values, and so the mode of resonance is indeed four-wavelength double-span resonance.

Fig. 3.3 shows the current modes expected for triple-span loop resonance. In this case, two adjacent towers are isolated, creating a three-span loop, which, with the tower spacings encountered on the power lines near CHFA, can be four-, five- or six-wavelength resonant. Four- and six-wavelength resonance are excited by the "difference mode" component of the incident field, whereas five-wavelength resonance is excited by the "common-mode" component. Once again, such resonances could exist on the power line with all towers connected if it happened that the intermediate two towers are connected at the maxima in the RF current for the mode, but this is unlikely, except perhaps for six-wavelength triple-span resonance which would require roughly even tower spacing. But this would call for three exceptionally long spans in a row, which does not occur.

The existance of multi-span resonances is demonstrated in the next Chapter in two tests of the "bulk isolation" approach to detuning. The next section presents formulae for making a rough estimate of the frequency of each resonance mode. The estimate will prove to be accurate enough to use as a basis for the choice of towers to isolate in order to detune the power line.

3.2 Resonant Frequency Estimates

The frequencies of the single-, double- and triple-span resonance modes are estimated in this section from the geometry of the spans, based on an approximation of the relationship of the electrical path length to the geometrical path length, obtained from previous computations for single-span resonance modes.

The geometrical length of the loop for a single-span resonance mode is given by

$$\ell_{g1} = 2(h_1 + s_{12} + h_2) \qquad \ldots 3.1$$

where h_1 and h_2 are the tower heights, and s_{12} is the span length. The "geometrical" resonant frequency of

$$f_{gn} = n \frac{c}{\ell_{g1}} \qquad \ldots 3.2$$

where c is the speed of light in free space, and n is the number of wavelengths into which the loop has been divided to obtain "n wavelength loop resonance". The geometrical resonant frequency is low in comparison to resonant frequencies found by computation and by measurement in Fig. 5.5 of Ref. (2). A better estimate of the frequencies of one- and two-wavelength loop resonance which agrees with the computations and measurements is given by

$$f_{1n} \simeq 1.08\, n \frac{c}{\ell_{g1}} \qquad \ldots 3.3$$

where n is one and two, respectively. The "1" subscript denotes a single-span mode of resonance. The factor of 1.08 accounts for the difference between the "geometrical" and the "electrical" path length, which must therefore be related by

$$\ell_{e1} \simeq 0.926\, \ell_{g1} \qquad \ldots 3.4$$

It will be assumed that this same factor of 0.926 can be used to estimate the electrical length of the path for double- and triple-span resonances.

A double-span loop is created when one tower is isolated with the adjacent two towers connected, and has a path length equal to the sum of the two tower heights, h_1 and h_3, plus the two span lengths, s_{12} and s_{23}, plus the return path on the images in ground, for a total length of

$$\ell_{g2} = 2(h_1 + s_{12} + s_{23} + h_3) \qquad \ldots 3.5$$

The electrical path length will be taken as

$$\ell_{e2} \simeq 0.926\, \ell_{g2} \qquad \ldots 3.6$$

and so the double-span resonant frequencies are estimated as

$$f_{e2} \simeq 1.08\, n \frac{c}{\ell_{g2}} \qquad \ldots 3.7$$

where n is the mode, being 3, 4 or 5 for Fig. 3.2 . Similarly, when two towers in succession are disconnected, a three span path is created of geometrical length

$$\ell_{g3} = 2(h_1 + s_{12} + s_{23} + s_{34} + h_4) \qquad \ldots 3.8$$

and the resonant frequencies are estimated as

$$f_{e3} \simeq 1.08 \frac{c}{\ell_{g3}} \qquad \ldots 3.9$$

where n is 4, 5 or 6 for the modes of Fig. 3.3 . Whereas the frequency estimate of equation 3.3 for single-span resonance has been verified by extensive computation in Ref. (3) for a specific power line configuration, the estimates for double- and triple-span resonant frequencies given by equations 3.7 and 3.9 have not been tested. The predicted frequencies appear to correlate well with the actual response of the power lines near CHFA in a set of 20 assorted computer tests of detuning by isolating towers, and two such cases are reported in detail below. These frequency estimates need to be the subject of a further study, aimed at refining the estimate and determining the bandwidth of these multi-span resonance modes.

Tables 3.1 to 3.6 give the resonant frequencies for the various modes for single-, double- and triple-span resonance for the north and the southeast power lines, and are obtained by evaluating equations 3.3, 3,7 and 3.9. Table 3.2 gives the three-, four- and five-wavelength loop resonance frequencies for double spans on the north line, and shows that because of the variable span length, the mode of resonance which is closest in frequency to 680 kHz varies. Thus the double span obtained by isolating tower # 186 is three-wavelength resonant near 680 kHz, whereas that obtained by isolating tower # 175 is four-wavelength resonant near 680 kHz. None of the double-spans are long enough to be five-wavelenth loop resonant at that low a frequency. Table 3.3 gives the frequencies of four-, five-, and six-wavelength triple-span loop resonance for the north power line, and once again the mode of resonance nearest 680 kHz varies because of the variable span length. Isolating towers 183 and 182 would create a five-wavelength resonant loop at about 660 kHz, and isolating towers 184 and 183 would give rise to a six-wavelength resonant loop at 679 kHz. All these loops might possibly be troublesome if 680 kHz lies within the bandwidth of the resonance mode.

3.3 Resonance Chart

A set of tables, such as Tables 3.1, 3.2 and 3.3 for the north power line, give the frequency of resonance for various modes of single-, double-, and triple-span resonace, and are put to use by scanning the columns for values such that 680 kHz lies within the bandwidth of the resonance mode. The actual bandwidth of one- and two-wavelength single-span resonance is taken from Fig. 5.5 of Ref. (3) to be about 120 kHz, as discussed in Sect. 2.3 . Thus if the span is resonant at frequency f_s , then it may respond strongly to any excitation in the frequency range (f_s -60) to (f_s +60) kHz. If the broadcast antenna's operating frequency lies within this range, then strong, resonant RF currents may be induced on the span. These frequency limits are somewhat arbitrary as resonance does not cut off abruptly but tapers gradually as a function of frequency. A span with a resonant frequency between 660 and 700 kHz is strongly resonant at CHFA's frequency of 680 kHz. Spans resonant near 620 or 740 kHz are "borderline" resonances and will not respond strongly. The bandwidths of the multi-span modes have not been investigated and will be taken to be about the same as for single-span resonance. The Tables of resonant frequency estimates alert the engineer to the existance of resonant spans and to where they are located on the power line. Whether a resonant span carries a large RF current flow depends on its excitation, as discussed in Sect. 2.3. Thus if a span is non-resonant it is not likely to carry strong RF currents, but if it is resonant it may carry such currents. It follows that if the resonant single-spans can be eliminated by isolating towers, without creating any resonant double- or triple-spans, then the "detuned" power line as a whole will be non-resonant and low reradiation can be expected.

The tables give the resonant frequencies of several modes for double- and triple-span resonance, most of which are not near to CHFA's frequency. It is useful to pick out from the tables those resonant frequencies which have CHFA's frequency within their bandwidth, or are at least closest to CHFA's frequency, regardless of mode. Thus a "resonance chart" can be prepared, depicting the resonant frequency estimates in a schematic form, as shown in Fig. 3.4 for the north line and Fig. 3.5 for the southeast power line. The charts show the power line pictorially with the tower spacing proportional to the actual span length. Above the center of each span the chart shows the single-span resonant frequency estimate. A double-span is created by isolating a single tower, and so above each tower is shown the resonant frequency of the double-span obtained by isolating that tower and leaving the adjacent two connected to the skywire. For example, on the north line, isolating tower # 163 creates a double-span from tower # 164 to tower # 162, which is estimated to be resonant at 680 kHz. The mode of resonance, if it is of interest, can be found from Table 3.2 . A triple-span is created by isolating two towers in a row, and the chart shows the resonant frequency for the triple-span above the center of the span between the two isolated towers. Thus isolating towers # 162 and 161 creates a triple-span from tower # 163 to # 160, which is resonant at 693 kHz. The chart shows at a glance which towers or pairs should not be isolated, lest the power line be made more strongly resonant at CHFA's frequency, and the reradiation problem thus be worsened.

3.4 Conclusion

A power line with all towers connected to the skywire and with a variable span length between towers includes some spans which are nearly resonant at the operating frequency of the nearby MF broadcast antenna. Some of these resonant spans may be excited strongly enough that the resulting RF currents on the power line towers reradiate significantly. When detuning the power line by isolating towers is attempted, new loops consisting of two adjacent spans, or three adjacent spans are created by isolating a single tower or two towers in a row, respectively, and such double- and triple-spans can also be near resonance at the station's frequency. The following section demonstrates that resonance modes on double- and triple-spans can be strongly excited by the broadcast antenna and can reradiate significantly. The object in the selection of which towers to isolate from the skywire must therefore be the avoidance of multi-span loops which are resonant. The subsequent Chapter uses the resonance charts to implement this principle and so "detune" the north and southeast power lines.

CHAPTER FOUR

BULK ISOLATION

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

4.1 Exciting Double-Span Resonances

Isolating every second tower constitutes a "bulk isolation" scheme. For the model of the north line used in Ref. (1), including towers 164 to 176, this scheme can be tested by isolating towers # 165, 167, 169, 171, 173, and 175, to obtain the field strength in CHFA's mimimum shown in Fig. 4.1(a). In comparison to the all-connected case, no improvement has been achieved. The field strength oscillates wildly and is considerably in excess of the protection limit. The RF currents flowing on the towers of the power line are shown in Fig. 4.1(b) and are uniformly large and about equal to 40 milliamps on the center part of the power line section. The RF current distribution on the skywires, Fig. 4.1(c), shows constant-phase with abrupt 180 degree reversals, and is characteristic of resonance, and the magnitude shows large amplitude standing waves. The "resonance chart" for the north line of Fig. 3.4

shows that the double-spans created by this bulk isolation scheme are all near resonance. A "resonance analysis diagram" for this detuning scheme can be prepared by selecting from the resonance chart the resonant frequencies of the specific single- and double-spans which result from isolating the specified set of towers and is shown in Fig. 4.1(d). Thus the double-span from tower 176 to tower 174 is expected to be in resonance at 690 kHz, and Table 3.2 shows that the mode is four-wavelength, double-span resonance. A comparison of the skywire current from tower 176 to tower 174 in Fig. 4.1(c) with the idealization of Fig. 3.2 shows a strong resemblance, with three distinct half-wavelength cycles of standing wave on the skywire proper and a fourth distributed between the two towers. Similarly, the double-span from tower 174 to tower 172 is resonant at 677 kHz, but Table 3.2 indicates that in this case the shorter span length gives three-wavelength double-span resonance. Indeed, two half-wavelength cycles of standing wave can be counted on the skywire from tower 174 to tower 172, with the third distributed between the two towers. Thus isolating individual towers can create resonant double-spans, which respond strongly to excitation by the broadcast antenna.

It is striking in Fig. 4.1 (b) that some of the "isolated" towers, namely numbers 171 and 173, carry RF currents which are as large as those on the "connected" towers, while other isolated towers, such as number 175, carry little current. This is readily explained in terms of the distribution of the voltage standing-wave for the resonance mode on each double-span loop. An isolated tower is a free-standing reradiator, and is excited both by the broadcast antenna and by the field across the skywire-plus-image transmission line. This latter field is largest at the maxima in the voltage standing-wave pattern, corresponding to the location of the current minima. Thus on the double-span from tower 176 to tower 174, the mode of resonance is four-wavelength loop resonance, and it is seen in Fig. 4.1(d) that a current maximum coincides with the position of tower 175. Thus tower 175 is at a voltage minimum of the skywire-plus-image transmission line, so is not excited and little current is seen. Conversely, double-spans 174 to 172 and 172 to 170 are in three-wavelength loop resonance, with a current minimum and hence a voltage maximum at the position of the isolated tower. Thus the isolated tower is strongly excited by the the skywire-image transmission line's field, and Fig. 4.1(b) shows large currents on towers 173 and 171. One conclusion is that if a strong current is seen on an isolated tower, the overhead skywire is probably part of a strongly-resonant loop. It is tempting to conclude that free-standing towers should be treated with tower-stub detuners to suppress the current. A better solution is the suppression of the strong resonance of the double-spans, so that no large voltage maxima are present on the skywires.

4.2 Exciting Triple-Span Resonances

Isolating two out of every three towers to obtain a configuration of "connected, isolated, isolated, connected, ..." is another possible bulk isolation scheme. Thus for the section of the north line from tower 164 to number 176, towers number 167 and 168, 170 and 171, and 173 and 174 can be isolated to test the potential of this scheme. The resulting field strength in CHFA's minimum is shown in Fig. 4.2(a), and it can be seen that a considerable improvement is obtained over the all-connected case. The protection requirement is still exceeded by more than 10 millivolts per metre at some angles. Fig. 4.2(b) shows that the section of power line from towers 164 through 171 has been detuned, including the strong RF currents on towers 165 through 168 in Fig. 2.2(c). But tower 172 now carries a much stronger current than it did previously. This is a five-wavelength, triple-span resonance mode. The "resonance chart" of Fig. 3.4 can be used to prepare the "resonance analysis diagram" of Fig. 4.2(d) for this set of isolated towers, and shows that the triple-spans from tower 166 to 169 and 169 to 172 are resonant at too low a frequency to be a problem at 680 kHz, whereas the triple-span from tower 172 to 175 is resonant at 706 kHz and responds strongly. The skywire currents show resonant phase behaviour on the triple-span from tower 172 to tower 175. The phase is roughly constant, except for 180 degree reversals at the nulls in the current distribution. The current distribution corresponds to five-wavelength triple-span resonance in Fig. 3.3. Tower 173 is near a current minimum and so is excited by the voltage across the skywire-plus-image transmission line, and responds with a strong RF current. Tower 174 is near a current maximum and hence is weakly excited and shows a low value of RF current. Thus an injudicious choice of towers for isolation from the skywire can result in a triple-span which is strongly resonant and carries large RF currents.

4.3 Conclusion

The "resonance chart" for the north line of Fig. 3.4 can be used to prepare a "resonance analysis diagram" for any proposal of a set of towers to isolate from the skywire, such as Figs. 4.1(d) and 4.2(d), and evidently such resonance analyses are a useful guide to the actual response of the power line. Thus in the tests presented in this Chapter, the spans expected to be double-span resonant or triple-span resonant respond strongly. In general, a span requires a favorable excitation to respond strongly, and so in general a span which has a multiple span resonance near the operating frequency may respond strongly but will not necessarily do so. The attraction of "bulk isolation" as a detuning technique was that the application of a regular "rule" for the choice of towers for isolation requires no previous knowledge of the RF currents flowing on the towers with all towers connected. The fatal defect of bulk isolation is the creation of strongly resonant multi-span loops. An attractive alternate approach is the use of the "resonance chart" to select towers for isolation such that no multi-span resonant loops are created, while at the same time opening all resonant single-span loops. This also requires no advance knowledge of the RF current flow. The next section investigates the efficacy of such an approach.

CHAPTER FIVE

SELECTIVE ISOLATION

Evidently, the reradiation from a power line into the protected arc of CHFA's pattern can be reduced by isolating some of the towers of the power line from the overhead skywire. Two bases for choosing which towers to isolate have been discussed. In Ref. (1), a short section of power line was modelled, and the current was computed on each tower with all towers connected to the skywire. Then those towers carrying relatively large RF currents were selected for isolation. Although multi-span resonances were not considered, by happy circumstance none were encountered and so a considerably improved radiation pattern was achieved. The second basis for choice was "bulk isolation", discussed in the last Chapter. This technique inevitably creates some resonant multi-span loops and so does not always improve the radiation pattern. This Chapter proposes to base the choice of towers for isolation upon the resonance chart. "Selective isolation" seeks to identify those towers which must be isolated to suppress specific resonances. The resulting power line is essentially non-resonant and carries relatively small RF currents, and so the radiation pattern has been systematically improved. This Chapter applies the selective isolation technique to both the north and southeast power lines to identify the set of towers which need to be isolated.

5.1 Partially Detuned Power Line

This section shows that a considerable improvement in the radiation pattern can be obtained by "detuning" only a small section of the line, carrying the largest currents. In Ref. (1), towers 164 to 176 of the north line were modelled and it was shown that by disconnecting four towers the power line was "detuned" and the radiation pattern was satisfactory. If the longer section of power line from tower 149 to 185 is modelled, and the center part of the line is detuned by isolating the same set of four towers as in Ref. (1), namely numbers 165, 167, 168 and 174, then in the current distribution with all towers connected, Fig. 2.3(c) it is seen that the towers with the largest currents are being "treated". The resulting field strength in the minimum is shown in Fig. 5.1(a), and a large improvement has been achieved. However, there are still substantial excursions above the protection limit, from 185 to 210 degrees, and other smaller excursions are present as well. This illustrates the improvement to be expected from treating a few troublesome spans.

The RF current distribution on the towers is shown in Fig. 5.1(b), and indicates that one span of the "untreated" portion of the power line is strongly resonant, namely that from tower 150 to tower 151. Evidently additional towers need to be isolated in order to detune this power line completely.

It is interesting to compare Fig. 2.3(c) with Fig. 5.1(b). Note that the large currents on tower 174 and and on tower 176 are both suppressed by disconnecting only tower 174. The double-span from tower 174 to tower 176 is in four-wavelength double-span resonance at 680 kHz, which is very close to the actual resonant frequency of 690 kHz. Isolating tower 174 breaks this double-span resonant loop and so supresses the current on both tower 174 and tower 176. It is interesting to note that the four-wavelength double-span resonance mode can exist even with tower 175 connected. As previously discussed, this resonance mode has a voltage minimum at the position of tower 175. Thus the field across the skywire-plus-image transmission line is small at tower 175 and so that tower can be connected across the voltage minimum with little effect on the resonance mode.

The following discusses two methods for choosing towers to disconnect from the skywire. The first is that of disconnecting those towers which carry large currents in the computer model with all towers connected. This risks the creation of resonant double- or triple-spans. The second method bases the choice primarily on the resonance chart, and uses the computed current distribution with all towers connected to refine the choice.

5.2 Supression of Large Tower Currents

A computer prediction or a direct measurement of the RF current flowing on each tower of a section of a power line with all towers connected to the skywire can be used as the basis for the choice of towers for isolation from the skywire. Thus for the "north" line, Fig. 2.3 (c) gives the RF currents on towers 149 to 185, and some of the towers which carry "large" RF currents can be isolated from the skywire to "detune" the power line. Thus if towers 150, 151, 159, 165, 167, 168, 174 and

176 are isolated from the skywire, the resulting field strength in CHFA's protected arc is shown in Fig. 5.2 (a). A substantial improvement in the pattern has been effected, and there are now only two small excursions above the protection requirement, both of small angular extent. Fig. 5.2(b) shows the tower currents, and it is seen that a large reduction in the tower currents has been achieved.

A "selective isolation" scheme based exclusively on large tower currents risks the creation of multi-span resonant loops, which may be strongly exicted by the broadcast antenna's field. The resonance chart of Fig. 3.4 must be consulted to make sure that no double-spans or triple-spans are created which are resonant. For example, based on Fig. 2.3(c) it might be decided to isolate tower 167, but the resonance chart shows that a double-span is created, resonant at 676 kHz, and this would result in large induced RF currents and an unsatisfactory pattern. A study of the resonance chart shows that in order to reduce the large currents flowing on towers 165, 166, 167 and 168, towers number 165, 167 and 168 can be isolated, with the result that the double-span from tower 164 to 166 is resonant at 605 kHz, and the triple-span from tower 166 to tower 169 is resonant at 615 kHz. Other choices also yield non-resonant multi-spans. Thus tower number 167 could be left connected to the skywire, and the resulting resonant frequencies are quite satisfactory. Fig. 5.2(c) shows a "resonance analysis" of the power line with towers number 150, 151, 159, 165, 167, 168, 174 and 176 isolated. It is seen that this choice, which was based exclusively on "large" currents and was made before the resonance chart had been devised, results in a near-resonant triple-span from tower 149 to tower 152, and a near-resonant double-span from tower 158 to tower 160. In addition there remain some near-resonant single-spans, namely spans 160-161, 177-178, 182-183, and 183-184, which have not been "treated" by isolating towers. Evidently, none of these spans are strongly excited and so carry little RF current and are not prominent when choosing towers with large for isolation. In the full scale situation such "dormant" spans could be excited by scattering from some nearby structure such as a free-standing tower which has not been included in the computer model. Thus merely selecting towers with large currents with an eye to avoiding the creation of resonant spans can leave "dormant" resonant single spans which may be a problem in the full scale situation. A more comprehensive suppression of resonance over the whole section of the power line being considered is suggested in the next section.

5.3 Tower Isolation for the Suppression of Resonances

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

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

(ii) the identification and listing of resonant spans ;

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

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

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

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

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

Step (i) of this procedure asks whether a span resonant at f_s will respond to CHFA's signal at f_o =680 kHz. In Sect. 2.3 it was noted that the bandwidth of resonance is about 120 kHz, and so the span will respond to CHFA's signal if CHFA's frequency f_o lies in the range

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

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

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

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

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

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

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

5.4 Selection of Towers for Detuning the North Line

Table 5.1 summarizes the selection of towers for isolation for the suppression of resonance for the north line. The resonance chart of Fig. 3.4 is consulted to construct columns 2 and 3 of the Table, which list potentially resonant single- and double-spans. All resonant single spans must be "treated" by selecting one or more towers for isolation. In column 2 the resonant frequency of each single-span resonant in the range 620 to 740 kHz is listed, in between the tower numbers of the two towers making up the span. In column 3, the resonant frequency of each double-span which is resonant in the range 620 to 740 kHz is listed opposite the tower number of the middle tower of the double-span. As previously pointed out, a double-span can show a resonant response even with the center tower connected, but the primary purpose of listing double span resonant frequencies is to aid in the selection of towers for isolation. Thus Table 5.1 indicates that spans 184-183-182, 179-178-177, 176-175-174, 168-167, 165-164, 161-160, 159-158, 153-152 and 151-150 are resonant close enough to 680 kHz to require "treatment" by tower isolation. The fourth column of the Table shows the towers selected for isolation, which are derived as follows. To detune the pair of spans 184-183-182, either tower 183 alone could be isolated, or towers 184 and 182 could be selected for isolation. Isolating tower 183 creates a double-span resonant at 735 kHz, whereas isolating tower 184 creates a double-span resonant at 631 kHz. Both of these are "borderline" resonances, and an arbitrary choice was made to isolate towers 184 and 182. To detune spans 179-178-177, tower 178 is selected for isolation, which breaks up both resonant single-spans and creates a double-span which is not resonant. If either tower 179 or 177 were selected for isolation, the resulting double-spans are "borderline" resonant at 634 and 635 kHz. To detune span 168-167, tower 168 is selected for isolation. Note that isolating tower 167 is not an alternative choice since the resulting double-span would be resonant at 676 kHz, very close to CHFA's 680 kHz. But both towers 167 and 168 could be chosen for isolation, since the resulting triple-span is shown in Fig. 3.4 to be resonant at 615 kHz, which is "safe". To detune span 165-164, tower 165 can be isolated. To detune span 161-160, tower 161 can be isolated, creating a double-span resonant at 744 kHz in preference to isolating tower 160 for a double-span resonant at 652 kHz. To detune span 159-158, tower 158 is isolated. To detune span 153-152, near the borderline of resonance at 735 kHz, tower 153 can be isolated. To detune span 151-150, either tower 151 or tower 150 can be isolated, and # 151 was arbitrarily chosen. Note that both towers 151 and 150 should not be isolated, since the resulting triple-span is shown in Fig. 3.4 to be resonant at 705 kHz, which is too close to CHFA's 680 kHz. Thus the method of "suppression of resonances" indicates that towers 150, 153, 158, 161, 165, 168, 174, 176, 178, 182 and 184 should be isolated from the skywire. This choice was tested by "running" the computer model and the resulting field strength in the minimum is almost identical to that shown below in Fig. 5.3(b) and so will not be reproduced separately.

Steps (iv) and (v) in the procedure outlined in the previous section call for the correlation of the towers chosen for isolation with the strength of the RF current flowing on the towers, with all towers connected to the skywire, which is given in Fig. 2.3(c). Thus the fifth column of Table 5.1 was derived from that figure by plotting the tower currents on an "asterisk" scale, using "*" to represent a current of between 5 and 10 mA, "**" for 10 to 20 mA, "***" for 20 to 40 mA and "****" for 40 to 80 mA. This "logarithmic" scale indicates at a glance which towers carry large currents and so are "problem" towers. The asterisks correlate well with the presence of resonant spans in column 2. The choice of towers for isolation in column 4 will evidently "treat" all of the towers carrying significant currents. To err on the side of caution, it was decided to isolate tower 167 in addition to tower 168, as these are the towers carrying the strongest RF currents. As previously mentioned, the resulting triple-span has an acceptable resonant frequency of 615 kHz. Thus column 5 accounts for both the estimated resonant behaviour of the power line and for the calculated RF current flow with all towers connected.

Fig. 5.3 shows the behaviour of the power line when the towers selected in column 6 of Table 5.3 are isolated from the skywire, namely towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184. The resonance analysis diagram for the resulting power line is shown in Fig. 5.3(a), and the line is non-resonant at 680 kHz. The field strength in the minimum, computed with this set of towers isolated, is shown in Fig. 5.3(b), and is a large improvement over the "all-connected" case. There is only one small excursion above the protection requirement, and that of small angular extent. The RF currents on the towers, shown in Fig. 5.3(c), are uniformly small. Thus the method of "suppression of resonances" systematically obtains a large reduction in the reradiation from the power line, and hence a greatly improved radiation pattern.

5.5 Selection of Towers for Detuning the Southeast Line

Table 5.2 sets out the steps in the selection of towers for isolation on the southeast line for the suppression of resonances. The resonance chart of Fig. 3.5 shows that the single spans 184-183-182, 181-180-179-178, 176-175, 167-166, 165-164, 161-160 and 158-157 have resonant frequencies close enough to CHFA's 680 kHz to be of concern. Column 3 lists the resonant freqencies of the double-spans whose bandwidth is estimated to include 680 kHz, as an aid in the selection of towers for isolation. To detune the spans from tower 184 to 183 and from tower 183 to 182, towers 184 and 182 were selected for isolation from the skywire, which creates a double-span resonant at 641 kHz, which is of borderline concern. A better choice would have been the isolation of tower 183 which creates a non-resonant double-span. No measures were taken to detune span 181-180 as its resonant frequency of 629 kHz is "borderline", although tower 181 could be safely selected for isolation. To detune spans 180-179 and 179-178, tower 179 is chosen for isolation, which creates a double-span resonant at 741 kHz, a "borderline" resonance not likely to be troublesome. Overall, a better choice would have been the isolation of towers 180 and 178, which creates only one "borderline" resonance. The criteria for choosing towers for isolation were not perfectly understood at the time that the selection given in Table 5.2 was made. To detune span 176-175, tower 176 was selected for isolation. To detune span 167 to 166, tower 167 was chosen for isolation. To detune span 165-164, tower 165 was selected, although this "bordeline" case could have been neglected. To detune span 161-160, tower 161 was chosen for isolation, and for span 158-157, tower 158 was selected for isolation. This completes the selection of towers for the "suppression of resonances".

Fig. 5.4(a) shows the resonance analysis diagram for the power line with towers 158, 161, 165, 167, 176, 179, 182 and 184 chosen for isolation from the skywire. "Borderline" single-span resonance is seen on span 180-181, and double-span resonance on spans 166-168, 178-180, 181-183 and 183-185. The field strength in the minimum shown in Fig. 5.4(b) has one small excursion above protection at 212 degrees azimuth. The RF currents on the towers show that towers 181, 180, 178, 176, 175, 174, 173, 172 and 171 carry the most current, but also that the currents are all less than 15 mA, and so are small compared to the resonant currents on the "north" line of 80 mA. It is interesting to note that single span 180-181 and double-span 178-180 respond with some RF current even though their resonant frequencies are near the "borderline" of non-resonance. Towers 174, 173, and 172 carry significant but non-resonant currents.

The RF current with all the towers connected to the skywire can be used to refine the choice of towers for isolation. Thus the current distribution of Fig. 2.5(c) was used to plot the tower currents in column 5 on the "asterisk" scale described above. Towers 176 and 175 carry the most current, but are adequately treated by isolating tower 176. Towers 169 to 156 lie progressively far into the minimum in CHFA's pattern and do not carry significant currents. Towers 174, 173, 172, 171 and 170 carry some RF current not treated by the tower selection for the suppression of resonances, and indeed the phase distribution of the skywire current in Fig. 2.5(d) does not indicate resonance on these spans. The small but significant currents seen on these towers can be "treated" by isolating towers 174 and 172, which does not create any undesirable double-span resonances. This is the "refined" selection given in column 6 of Table 5.2, and Fig. 5.5 shows the behaviour of the power line with this choice of towers for isolation. The field strength in CHFA's minimum has been reduced to a level below the protection requirement. Fig. 5.4(c) shows that the current flowing on most of the towers is small. Double-span 178-180, with tower 179 isolated, is expected to be resonant at 741 kHz and the skywires in part (d) of the figure carry a resonant current distribution at a low level. This serves to illustrate that borderline resonances can sometimes be significant. However, with towers 158, 161, 165, 167, 172, 174, 176, 179, 182 and 184 chosen for isolation, the power line reradiates at a sufficiently low level that the protection requirement is met.

Two more variations on tower isolation for the southeast line were tried, to explore the effect of alternate choices and of isolating towers carrying little current. Table 5.2 shows that towers 167 and 165 were selected to suppress the resonances of spans 164-165 and 166-167. An alternative choice is to regard the span 164-165 as "borderline" and of no concern, and isolate tower 166 to detune span 166-167. The resulting field strength in the minimum is shown in Fig. 5.6, and is almost the same as that of Fig. 5.5 . A second test concerns tower 184, which was chosen to "treat" a borderline resonance for span 183-184. Thus if tower 184 is left connected to the skywire, and towers 158, 161, 166, 172, 174, 176, 179 and 182 are isolated, then the field strength in the minimum is as shown in Fig. 5.7 . A slight rise in the field near 210 degrees is seen, compared to Figs. 5.6 or 5.5 . The current on tower 183 is a small amount greater with tower 184 connected to the skywire. These tests serve to illustrate that the computer model could be used to investigate the effect of tower isolation on a tower-by-tower basis, in order to minimize the number of towers for isolation. A further reduction beyond those isolated for Fig. 5.7 could be achieved by noting that towers 158 and 161 carry very little RF current in Fig. 5.7, and so could be left connected to the skywire. The effect of leaving tower 166 connected might be explored computationally as well, as this tower carries little current when connected in Fig. 2.5(c). Exploratory computations such as these thus lend insight into the relative importance of the towers selected for isolation.

5.6 Conclusion

The technique of selecting towers for isolation for the "suppression of resonances", using the resonance chart as a guide, generates a greatly reduced field strength in the minimum for CHFA operating near either the north or the southeast power line. The resonance chart can be prepared with a simple calculator for as many towers of the power line for which base coordinates and heights are available, and thus the technique is not limited to the number of towers which can be analysed on the available computer. Thus the resonance chart is searched for resonant single spans, and towers are selected for isolation in order to "open" the resonant single-spans, without creating any resonant double- or triple-spans. The procedure has been shown in this Chapter to result in a greatly improved radiation pattern without previous knowledge of the RF currents flowing on the towers with all towers connected to the skywire. Thus a simple means has been identified for selecting towers for isolation without the aid of a large digital computer.

The resonance chart does not indicate which resonant spans are excited strongly enough to carry significant RF currents. A measured or computed set of tower base currents with all towers connected to the skywire can be used to identify strongly responding spans. Thus resonant spans which are found to carry little RF current may not need to the "treated" by tower isolation. In addition, the current distribution shows that some spans, such as 175-174-173-172-171 on the southeast line, carry non-resonant currents of sufficient strength to be of concern. Thus additional towers can be selected for isolation to suppress these currents, provided no resonant double- or triple-spans are so created. Thus isolating some towers, such as # 176 on the southeast line, will have a major effect on the strength of the reradiated field, because of their large RF current, whereas isolating other towers will have much less effect. The following Chapter gives a classification of towers for isolation based on their importance in the suppression of the reradiated field, and sets out a procedure for tower isolation "in the field".

CHAPTER SIX

PROCEDURE FOR ISOLATING TOWERS

This Chapter outlines a procedure for carrying out the isolation of towers on site in the field. Towers will be isolated a few at a time in small groups. The object is to allow the effectiveness of the detuning to be assessed as each group of towers is isolated. This will be done by measuring the tower base currents and comparing with the base currents when all towers are connected to the skywire. The direct relationship between tower base currents and radiated field implies that if the tower base currents are all made small, the reradiated field will also be small. The field strength will be monitored at selected azimuth angles in the minimum of CHFA's pattern. In this way the engineer can be certain that each group of towers has indeed been detuned, and can assess the degree of improvement that has been achieved in the radiation pattern.

6.1 Classification of Towers for Isolation

The current distributions of Fig. 2.3(c) and Fig. 2.5(c) show that a few towers on each power line carry "strong" currents, others carry "significant" currents, and most carry "small" currents. The choice of which towers to isolate was made in Chapter 5 such that all possible resonances of the power line are suppressed, regardless of whether each resonance is actually excited by the broadcast antenna. Fig. 5.1 demonstrates that by isolating only those few towers carrying "strong" currents, a large improvement in the radiation pattern can be achieved. Thus the towers designated for isolation which are associated with the "strong" currents on the power line will be classified as "Group 1" towers. Table 5.1 shows the currents of Fig. 2.3(b) on a logarithmic "asterisk" scale. The asterisks show that of the set of towers chosen for isolation on the north line, namely towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184, the "Group 1" towers are numbers 165, 167 and 168. A large improvement in the radiation pattern is obtained by isolating the

"Group 1" towers. "Group 2" towers will be any others designated for isolation which carry "significant" currents, and includes towers number 150, 153, 158, 161, 174, 176 and 178. The remaining towers in the list, numbers 158, 161, 182 and 184, are towers of "dormant" resonant spans which are not excited significantly by the broadcast antenna, and will be designated "Group 3" towers. No great change in the radiation pattern is anticipated by isolating these towers. Table 6.1 summarizes the classification.

Fig. 2.5(c) or the "asterisk" scale in Table 5.2 should be consulted in order to classify the towers selected for isolation on the southeast power line. The group of towers isolated to obtain Fig. 5.6 will be chosen, namely towers 158, 161, 166, 172, 174, 176, 179, 182 and 184. To suppress the "strong" currents seen on towers 176 to 174, towers number 174 and 176 should be isolated, and these two constitute the "Group 1" towers. Towers number 166, 172, 179, and 182 form "Group 2", and towers 158, 161, and 184 make up "Group 3".

6.2 Procedure for Isolating Towers

The procedure will consist of the gathering of measured reference data, followed by the isolation of towers one "Group" at a time, verifying the results by further measurement, in comparison with the reference case.

It is assumed that a careful measurement of the azimuth radiation pattern, and particularly of the station's field strength throughout the protected arc is available. This data is necessary for the identification of a reradiation problem. It is recommended that the relative base currents flowing on all the towers be measured, with all the towers connected to the skywire. This provides a standard against which the currents measured with some towers isolated can be compared, to assess the degree of improvement being achieved. Elder(Ref. (5)) measured the field strength near a free-standing tower in order to assess the strength of the RF current flowing on the tower. Jones and Madge(Ref. (6)) provide a direct method for the measurement of RF current flow, using a toroidal coil.

The power lines will be detuned one at a time, starting with the north line, which causes the largest amount of reradiation. To begin the detuning of the north line, the towers of Group 1 in Table 6.1 should be isolated, namely towers 165, 167 and 168. Then the tower base currents for towers number 164 through 169 should be measured and compared with previous results. Uniformly small currents should be seen. The field strength at some specific azimuth angles between 190 and 220 degrees should be measured, to verify that an improved pattern is obtained. The second step is the isolation of Group 2 towers, namely numbers 150 and 153, 158 and 161, and 174, 176 and 178, followed by the measurement of the tower base currents on towers 149 to 154, 157 to 162, and 173 to 179, to verify that uniformly small values are achieved. The field strength should then be verified in the pattern minimum.

The procedure is then repeated for the southeast line. First, the towers of Group 1 are isolated, namely numbers 174 and 176, and the base currents measured for towers 173 through 177 to verify that they are uniformly small. The field strength at azimuth angles in the range 220 to 236 degrees should be verified. Then the towers of Group 2 should be isolated from the skywire, namely towers 166 and 172, and 179 and 182, and the tower base currents for towers 164 to 167, 171 to 173, and towers 178 through 185 should be verified. Once again, the field strength in the pattern minimum should be verified.

If desired, the towers of each line designated Group 3 can then be isolated. This must be followed up with measurements of the base currents on these and adjacent towers, and by verification of the field strength in the pattern minimum. It is anticipated that isolation of the Group 3 towers should cause little change in the radiation pattern, as they carry relatively small currents in the computer model.

6.3 Conclusion

This Chapter has suggested a procedure based on extensive measurements in the field, designed to guarantee that a systematic improvement in the pattern of CHFA will be achieved by isolating towers. The following Chapter reviews the project relative to shortcomings in the computer model, and makes recommendations for further work.

CHAPTER SEVEN

CONCLUSION

This report has presented an analysis of the reradiation from the north and the southeast power lines near station CHFA, Edmonton. A computer model has been used to predict the field strength to be expected in the minimum of CHFA's pattern in the presence of either power line. Such computer models are not perfectly accurate representations of full-scale power lines, and the degree of agreement to be expected is reviewed below in Sect. 7.1 . This report has presented a systematic procedure for selecting towers for isolation from the skywire based on estimates of the resonant frequencies and the bandwidth of resonance for a typical power line span. Sect. 7.2 below suggests that the method of "suppression of resonances" can be used without computer modelling, based on measured base currents for the power line towers. A procedure which might be used "in the field" to carry out the isolation towers is suggested. The final section of this Chapter summarizes the results and suggests further investigations.

7.1 Simplifications Inherent in the Computer Model

The computer model of the power line used in this report is not perfectly accurate. The degree of agreement expected between measured and computed results is illustrated by the comparison of the field strength in the minimum of CHFA's pattern, in Fig. 2.2(b) or Fig. 2.4(b). There is a good general correspondence between the measured and computed curves, and both show that the primary effect of reradiation is seen from 185 to 220 degrees azimuth, where the field strength is well in excess of the protection requirement, but detailed point by point agreement cannot be claimed. Possible causes of the differences are reviewed in this section.

It is expected that there will be a general correspondence of measured tower base currents with those obtained by computation in this report. Thus where a group of resonant spans have been identified by computation, it is expected that the measured currents will show resonance, although the magnitude of the current on the individual towers may be somewhat different than in the computation. It is also expected that a few individual towers may carry strong currents not predicted by the computer model. Simplifications in the computer model are the root cause of such differences. Among these may be cited :

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

(ii) imperfect ground conductivity ;

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

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

This list is not intended to be complete.

Concerning obstacles such as other towers or buried pipelines, these themselves reradiate and so the power line "sees" the broadcast antenna's field perturbed by the reradiated field of these structures. Thus the map of Ref. (7) shows that buried oil and gas pipelines run parallel and very close to the southeast power line between towers 144 and 170. This change in the excitation field could affect the response of some of the spans.

Concerning ground conductivity, the present computer model uses highly-conducting "perfect" ground to save computer costs. The behaviour of power lines over ground of realistic conductivity has been explored in Ref. (2). A realistic value of ground conductivity of the order of 10 millimhos/metre, and a realistic relative permittivity of 15, and such a ground is a "good conductor" in the sense that $\sigma \gg \omega\epsilon$. The principal effect of such a ground is the reduction of the magnitude of resonance effects but not a change in the frequency of resonance. Thus imperfect ground conductivity introduces additional damping into the resonant response. A real power line thus should respond at the same frequencies as the computer model over perfect ground, but the magnitude of its response is less. The perfect ground model represents the "worst case".

Concerning local differences in topology, certain individual spans of the power line cross deep gullies, or cross highways raised above the general level of the ground. The deviation from the flatness of the ground may cause a shift in the resonant response of the ground, which could result in stronger currents than expected from the computer model if the resonance is shifted closer to CHFA's frequency. The maps of Refs. (7) and (8) show that on the southeast line span 161 to 162 crosses the Whitemud

Creek, and span 175 to 176, and 180 to 181 recross the creek. The span from tower 175 to 176, in particular, is the one which responds most strongly in Fig. 2.5(c), and so the response of this span on the real power line may be different. On the north line, span 160 to 161 crosses the North Saskatchewan River, and span 175 to 176 crosses the gully of Whitemud Creek.

Concerning power line geometry, it should be pointed out that the computer model of type Z7S towers used here has not been "fine tuned". The model was derived using the same principles as that of the type V1S tower in Ref. (9), but that model was verified against scale model measurements at various frequencies over the one-wavelength and two-wavelength resonance frequency bands. The Z7S geometry is quite different, and such a validation against measured data would allow the radii of the wires of the tower model to be "finely adjusted" to match the bandwidth of the measured resonance. The ability of the computer model to respond with the same resonant frequencies and about the same bandwidth as the full scale power line is the basis of its usefulness in dealing with power line reradiation.

Another source of error in the computer model concerns the relative location of the CHFA broadcast array to the power lines. The position of each power line tower was determined in Ref. (1) from data supplied by Trans-Alta(Ref.(10)), which locates each power line tower relative to the next one along the power line in terms of a distance and an angle. The position of the CHFA array was determined from the map of Ref. (7), on a scale of 1:25000, which shows the towers of the array, but not the power lines. The broadcast array's position was found from the map relative to a road junction which also appears on the Trans-Alta maps. The accuracy of this procedure is difficult to establish. The error is of the order of the spacing of the CHFA towers. A surveyed position for CHFA relative to the closest towers of the southeast line would be useful. Errors in the broadcast antenna's location result in errors in the phase of the excitation of each tower of the power line, and thence lead to errors in the induced current flowing on the power line.

Taken together, it is anticipated that these factors will result in a somewhat different current computed for each tower than that which will be found by measurement.

7.2 Procedure for Isolating Towers Based on Measured Current Flow

In some cases it may be desirable to select towers for isolation without "running" a large computer model. The measurement technique itself can be used as a guide to the selection of towers, with the aid of a "resonance chart", following the procedure outlined in Sect. 5.3. A "resonance chart" is drawn from a knowledge of the height of each tower, and the length of each span, and towers are chosen for isolation for the "suppression of resonances". A measurement is made of the base current flowing on each tower of the actual power line, and this data is correlated with the towers selected for isolation. Additional towers can be chosen for isolation if required. In this way a "design" for tower isolation can be arrived at without computer modelling.

A procedure for carrying out tower isolation "in the field" consists of isolating towers a few at a time, followed by verification by the measurement of tower base currents that no resonant double- or triple-spans have been created. The objective of the verification step is to ensure that each tower or pair of towers isolated actually improves the situation. If a single tower is isolated to create a double-span, then the current on that tower and on the two adjacent towers must be measured. The measured base currents should be compared with the "all connected" reference case, and a substantial reduction is expected. Strong currents on the adjacent towers clearly indicate that a resonant double-span has been created, and either the tower should be connected to the skywire once again, or one of the two adjacent towers must be disconnected, to create a triple-span. When two adjacent towers have been isolated, it is necessary to verify by measurement that the base currents on those two towers and on the two adjacent connected towers are all acceptably low in value. Large currents indicate that a resonant triple-span has been created. Proceeding in this way, it should be possible to arrive at a suitable choice of towers for isolation such that all tower base currents are small, and so the power line is effectively detuned.

7.3 Topics for Further Investigation

This report has studied the CHFA broadcast array operating in the presence of either the north or the southeast power line, and for each case has assessed the reradiation from the power line, and suggested a set of towers for isolation from the skywire in order to suppress the reradiation. An empirical procedure for choosing towers for isolation "in the field" has also been suggested.

A shortcoming of this work is that the pattern of the CHFA array was not calculated in the presence of both power lines together, but instead two patterns were examined, for the antenna in the presence of each individual power line. Detuning was designed based on these "CHFA-plus-single-line" calculations, and it was not proven by computation that isolating the specified towers would result in a satisfactory pattern for CHFA in the presence of both lines together. The case of both lines together requires computer resources not readily available at the time of this writing. The removal of this restriction must be the subject of a further report.

It has been suggested that the tower base currents be measured before any towers are isolated from the skywire, as a reference case for later comparison. Such a measurement would provide a valuable yardstick for testing the ability of the computer model to predict precise results, in spite of the deficiencies outlined above in Sect. 7.1 . It would be of interest to seek specific sources on the map of the site for differences between measured and computed currents. Such a comparison would more clearly define the usefulness and the limitations of the computer modelling technique.

This report has chiefly been concerned with the suppression of resonant currents flowing on the power lines, and the term "detune" appropriately refers to the procedure of open-circuiting "tuned" resonant spans. The result is a greatly reduced reradiated field strength into the pattern minimum, but the pattern of Fig. 5.3(b) still shows a small excursion above the protection limit. The empirical procedure of "suppression of resonances" developed in this report does not provide any ready means of further improving the pattern. If mathematical optimization techniques were applied to the problem of suppression of resonances, it may be that the pattern could be further improved, but at great expense in computation. The currents which flow over the power lines in Figs. 5.3 and 5.5 are largely non-resonant currents. As the depth of a minimum in a broadcast array's pattern is increased to meet more stringent protection requirements, non-resonant currents become increasingly important. Any isolated tower which carries a significant RF current as a free-standing reradiator could be treated with a "tower stub" detuner. But if a connected tower is so treated, the open-circuit thus created across the skywire-image transmission line may create an unwanted resonant multi-span loop. It is not at present clear how the non-resonant currents on a "detuned" line can be suppressed without creating multi-span, resonant loops. The subject of suppressing non-resonant currents is recommended for further study.

The detuning of the power lines near CHFA has been accomplished in this report primarily by the use of the "resonance chart", and could be repeated for other sites without the aid of a large digital computer. The additional information derived from a computer run with all towers connected indicates the relative importance of the various towers selected for isolation, and similar information could be derived from a measurement of the tower base currents "in the field". It is recommended that the measures suggested in this report be undertaken to detune the power lines near CHFA, and that the result be assessed through both the measurement of tower base currents and of the field strength in the pattern minimum, and that a comparison of the computed and measured tower base currents and azimuth pattern be the subject of a further report.

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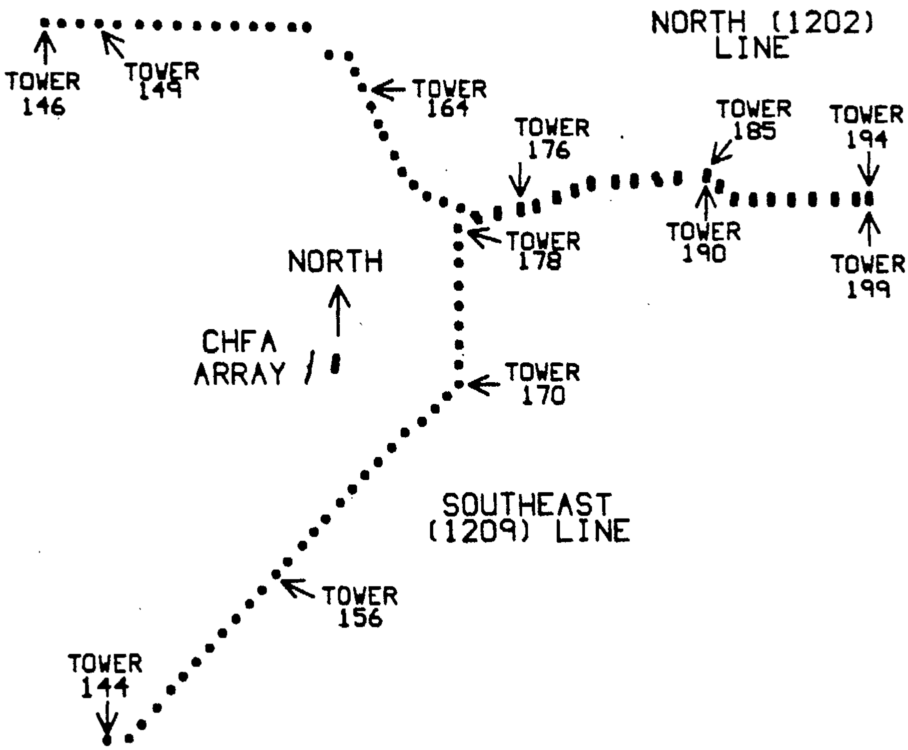


Fig. 2.1 Plan view of the CHFA site.

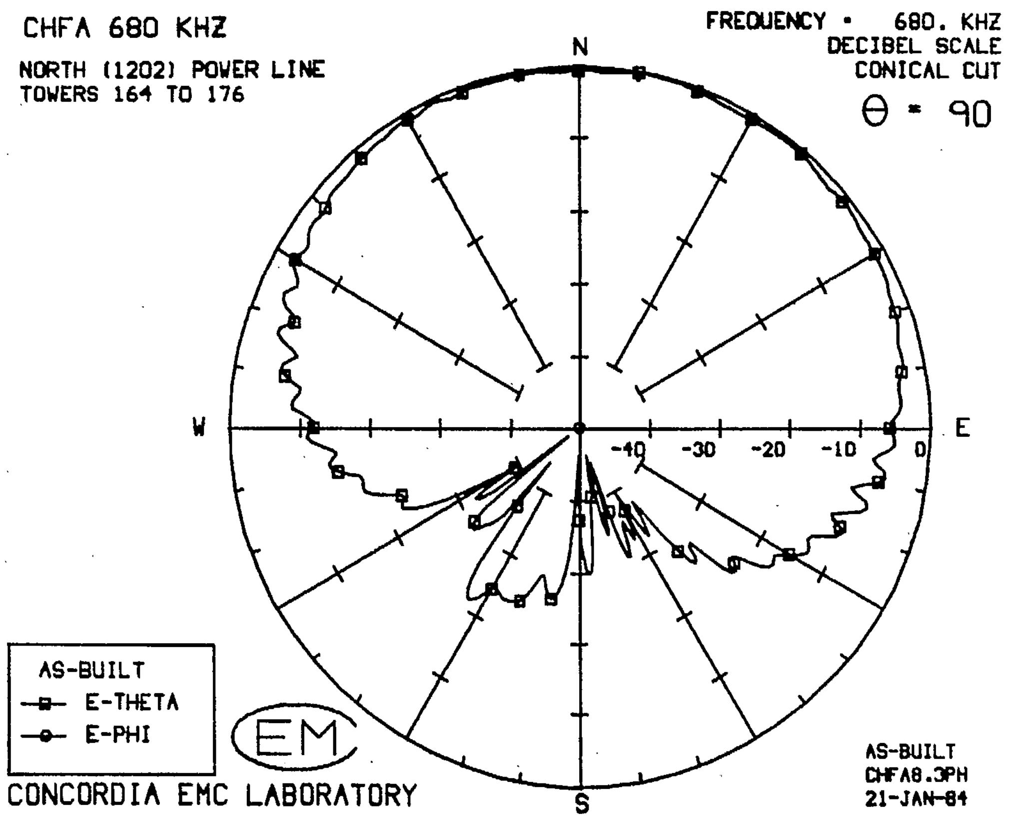


Fig. 2.2 (a) Radiation pattern of CHFA operating near towers 164 to 176 of the north line.

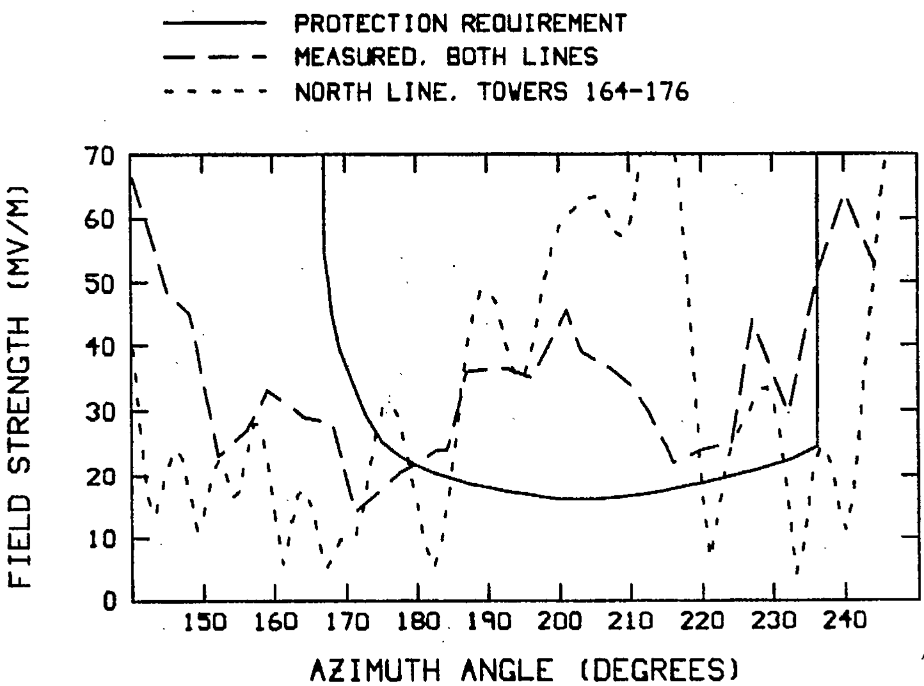


Fig. 2.2 (b) Field strength in the minimum.

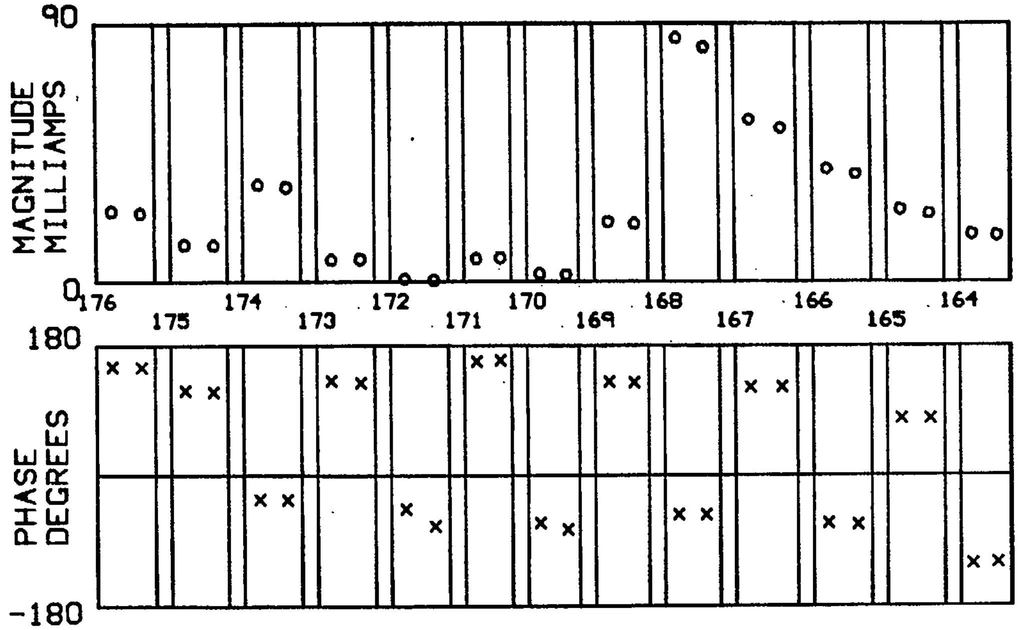


Fig. 2.2 (c) RF currents flowing on the power line towers.

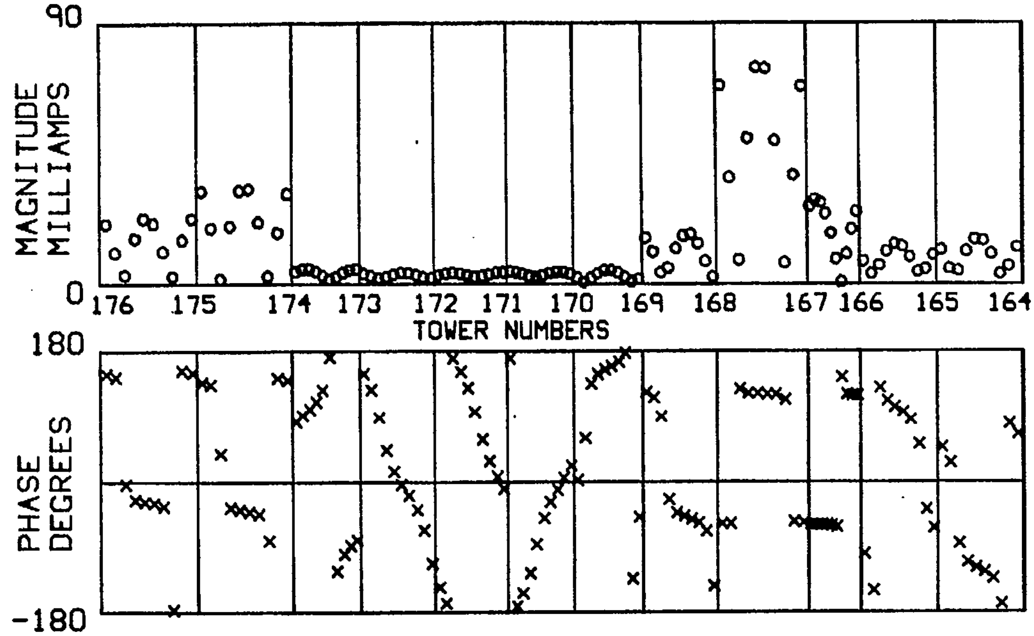


Fig. 2.2 (d) RF currents flowing on the skywires.

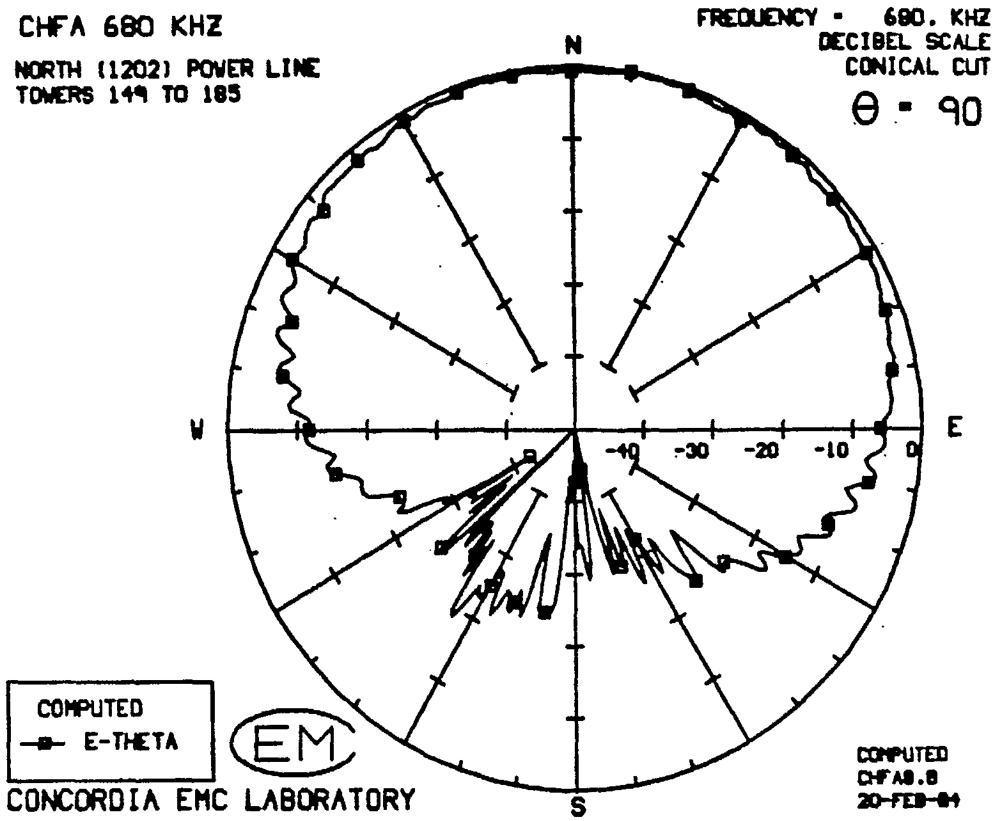


Fig. 2.3 (a) Radiation pattern of CHFA operating near towers 149 to 185 of the north line.

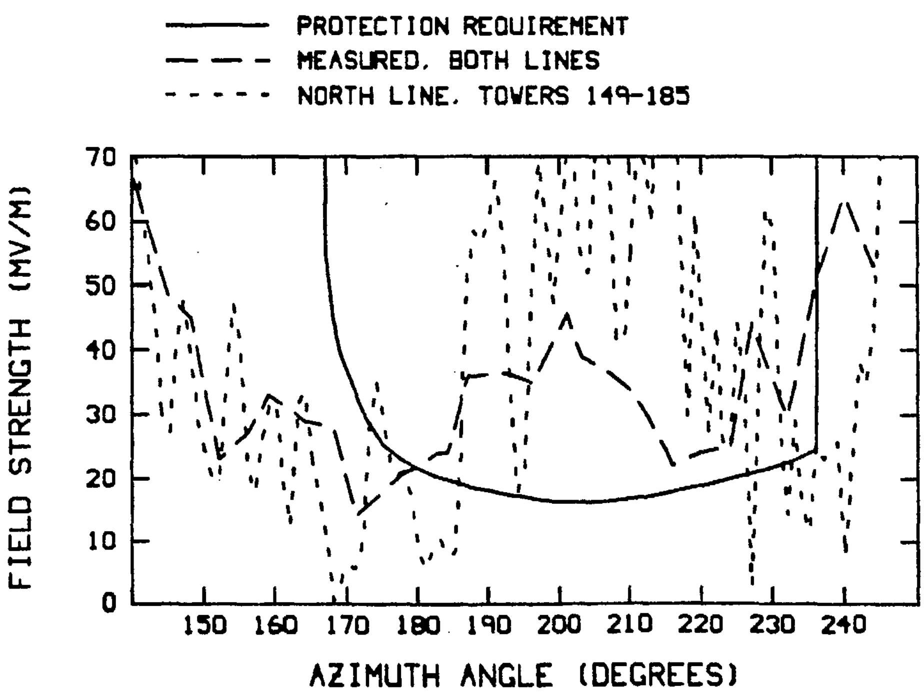


Fig. 2.3 (b) Field strength in the minimum.

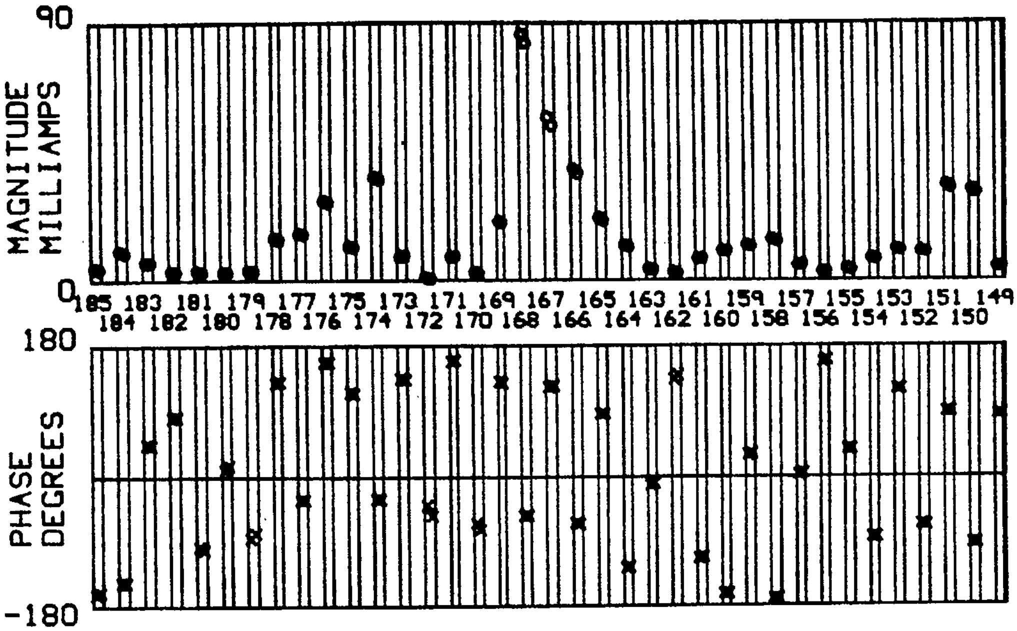


Fig. 2.3 (c) RF currents flowing on the power line towers.

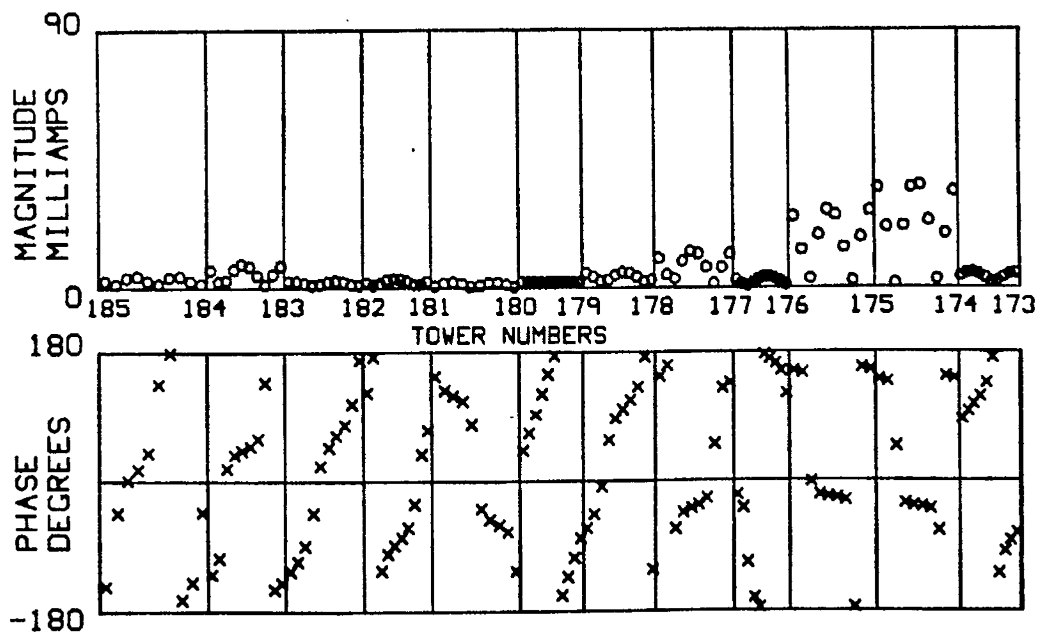
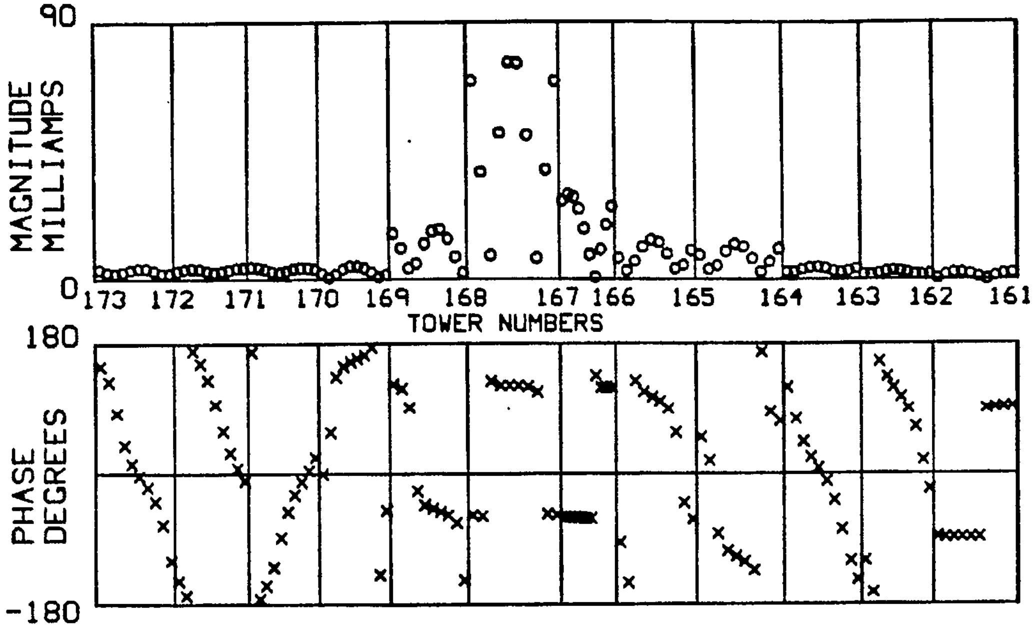


Fig. 2.3 (d) RF currents flowing on the skywires.



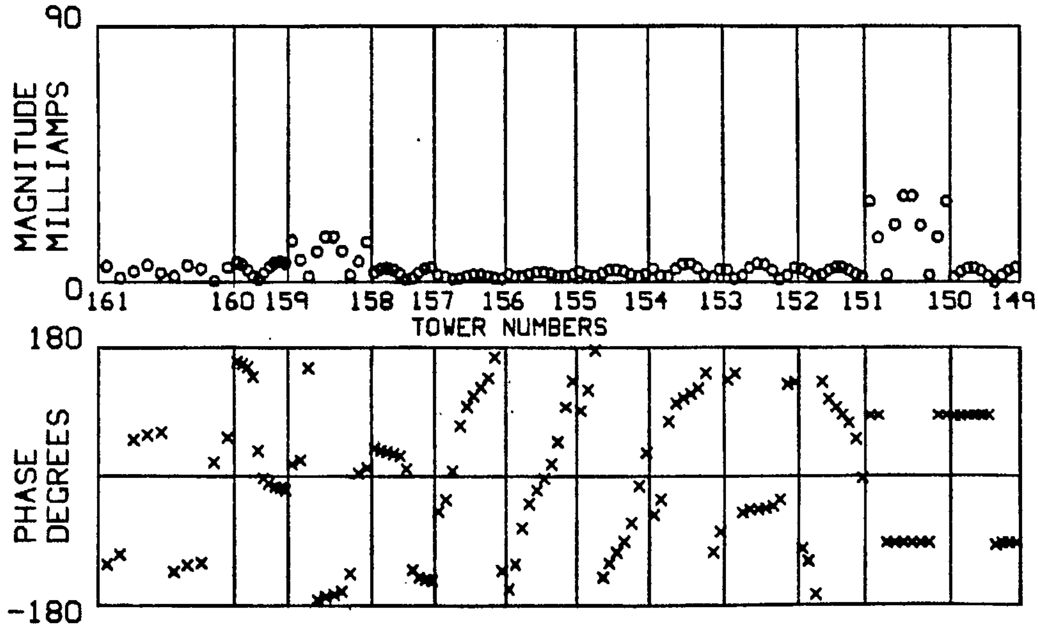


Fig. 2.3 (d) continued

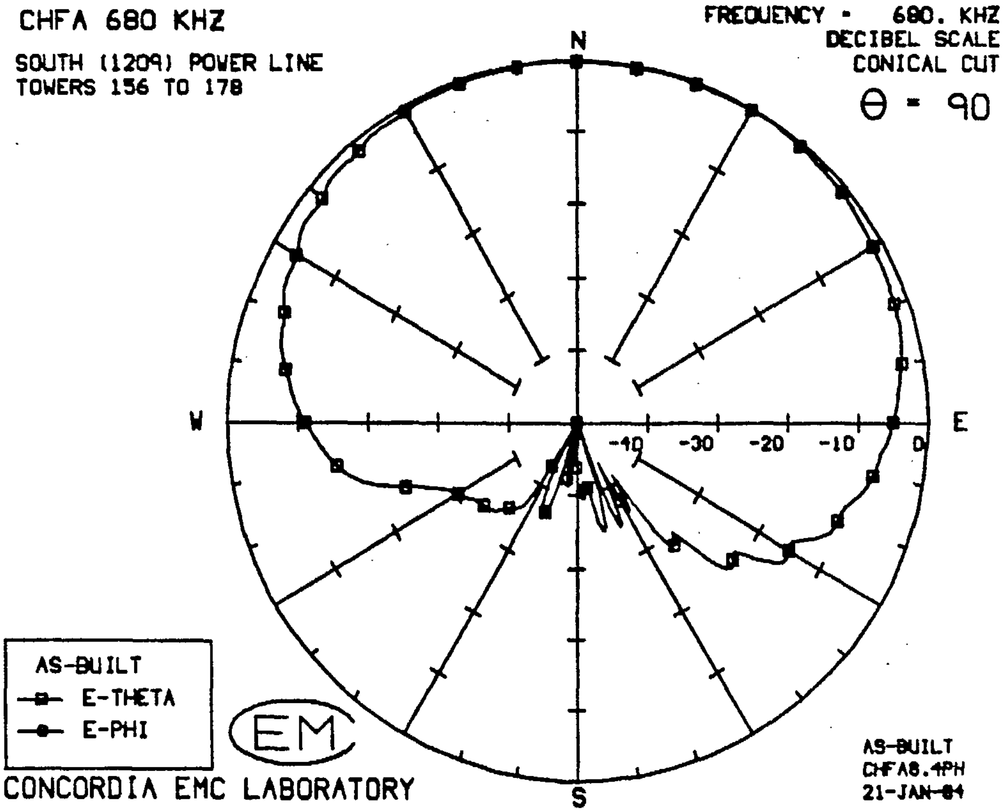


Fig. 2.4 (a) Radiation pattern of CHFA operating near towers 156 to 178 of the southeast line.

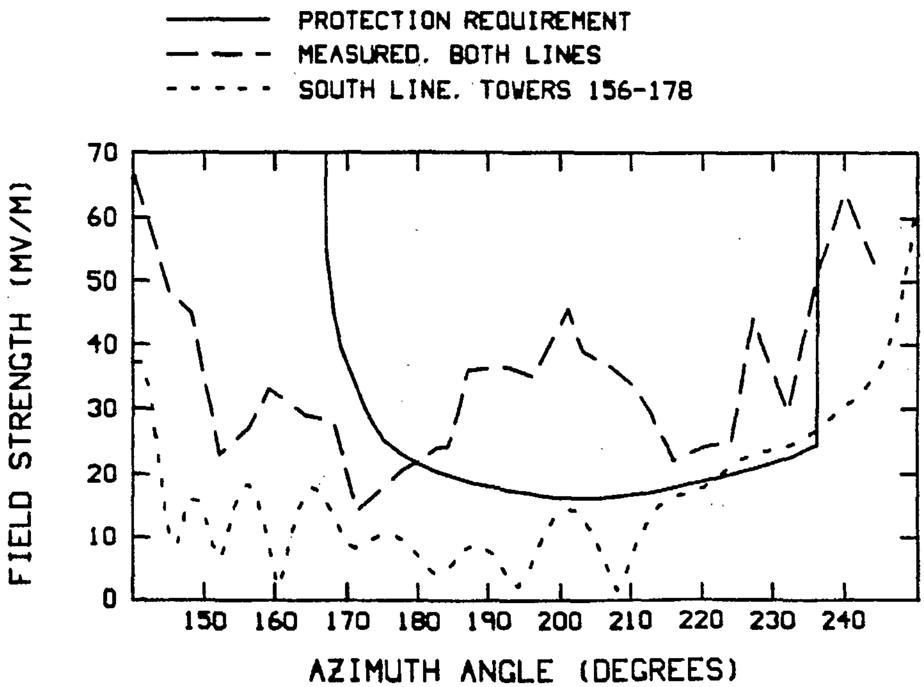


Fig. 2.4 (b) Field strength in the minimum.

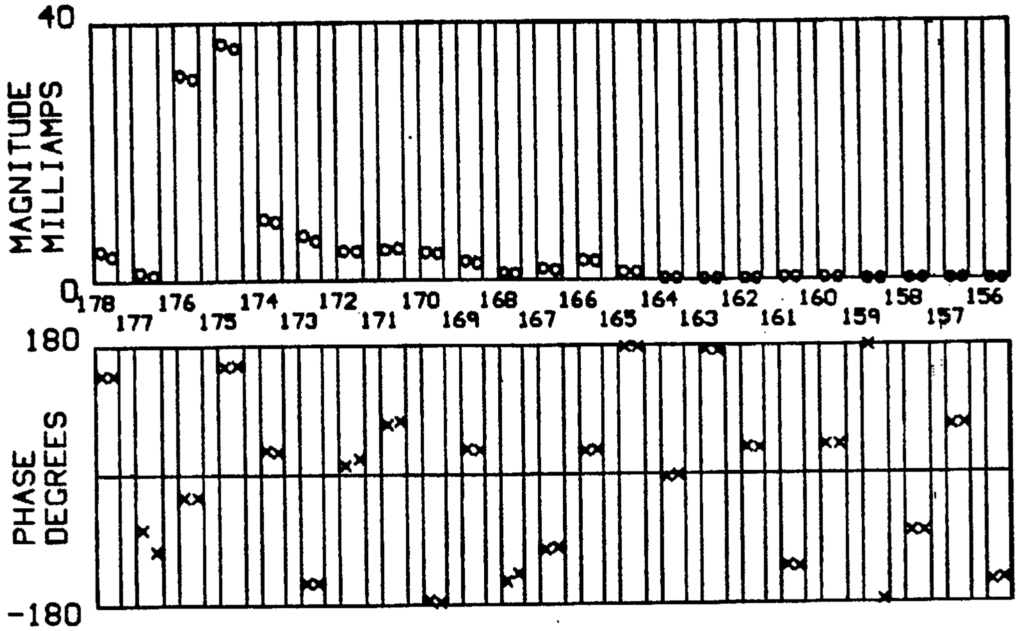


Fig. 2.4 (c) RF currents flowing on the power line towers.

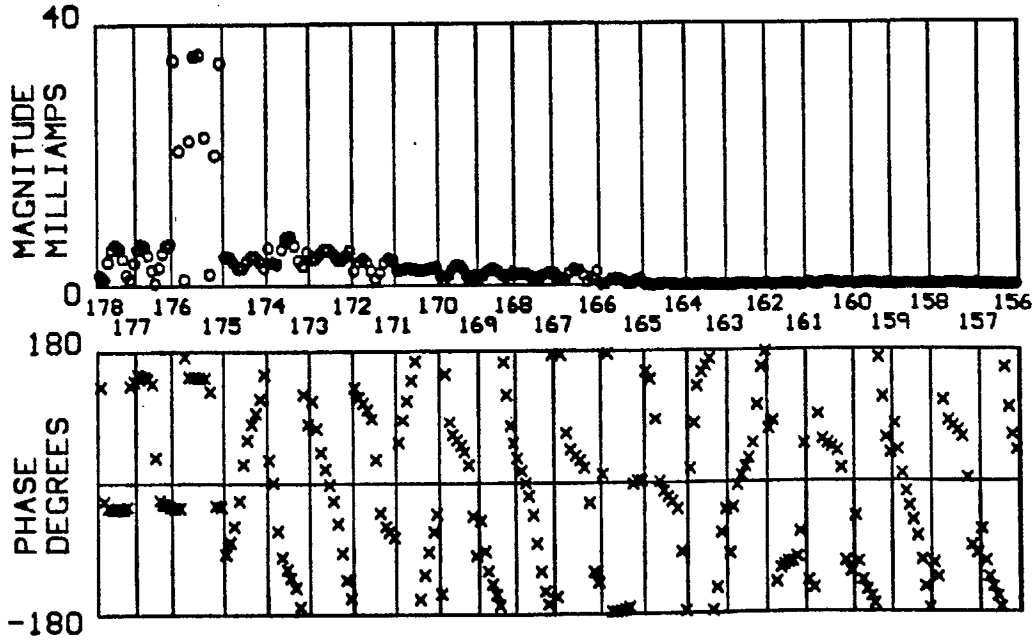


Fig. 2.4 (d) RF currents flowing on the skywires.

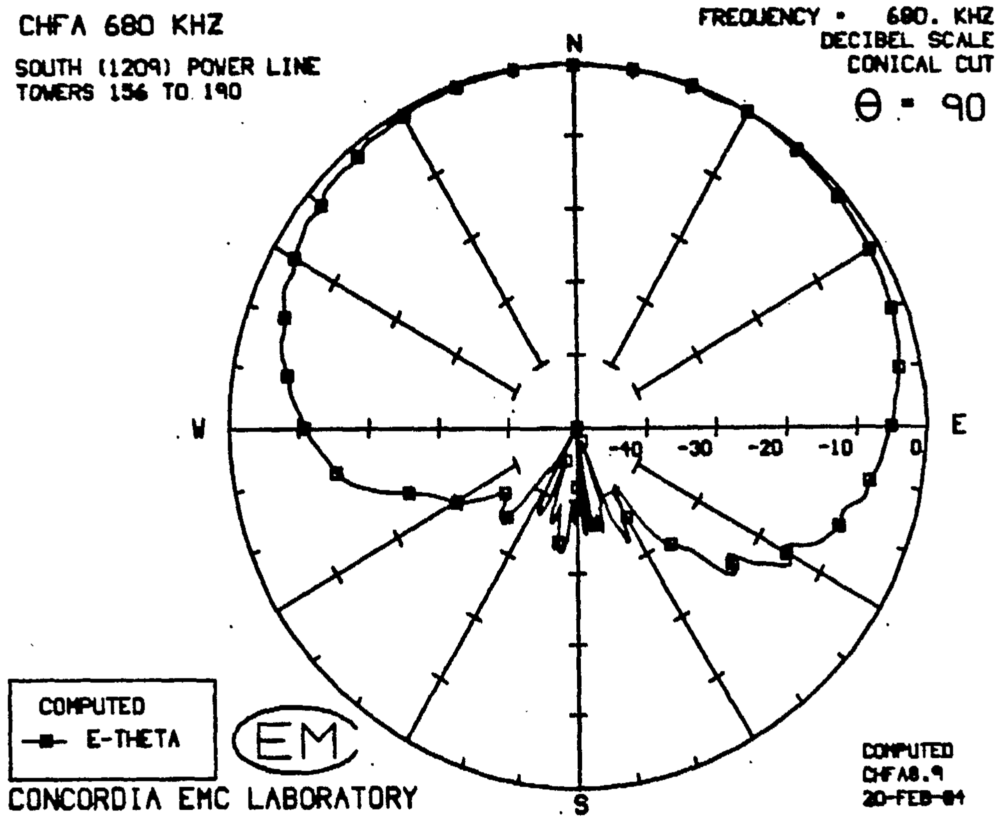


Fig. 2.5 (a) Radiation pattern of CHFA operating near towers 156 to 190 of the southeast line.

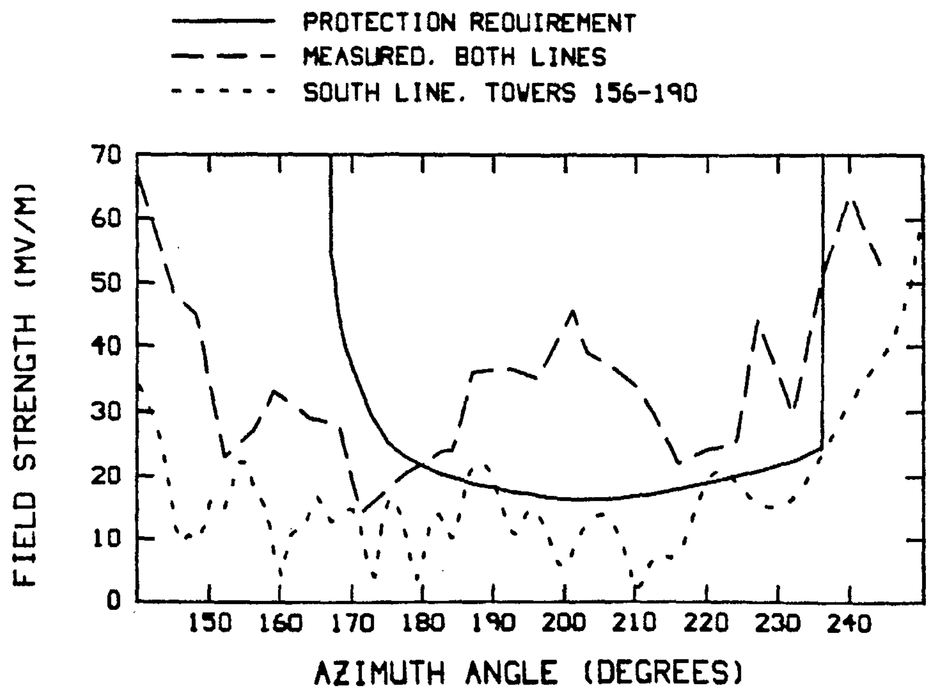


Fig. 2.5 (b) Field strength in the minimum.

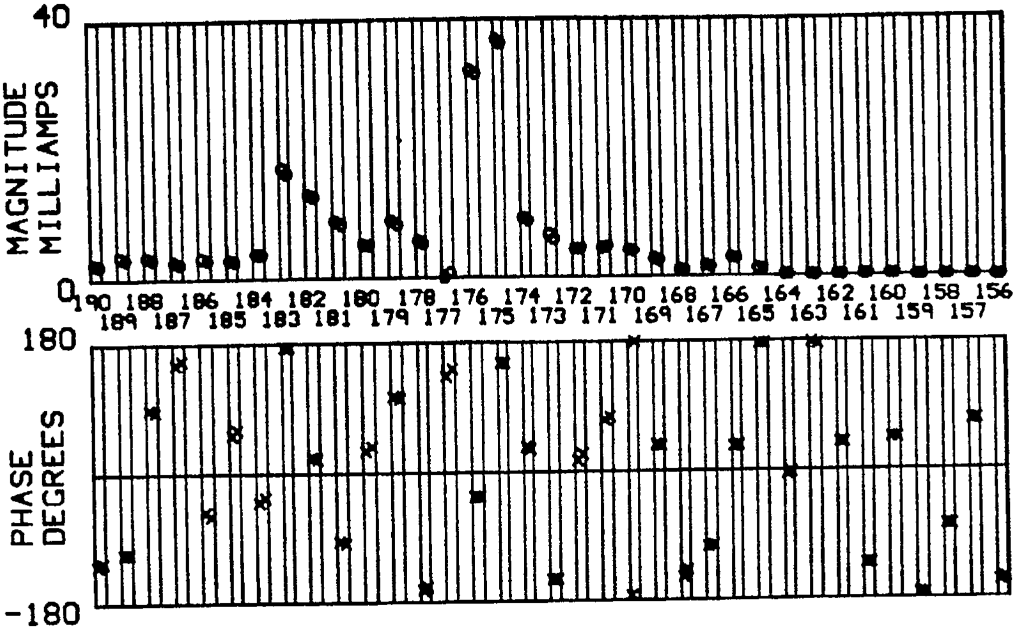


Fig. 2.5 (c) RF currents flowing on the power line towers.

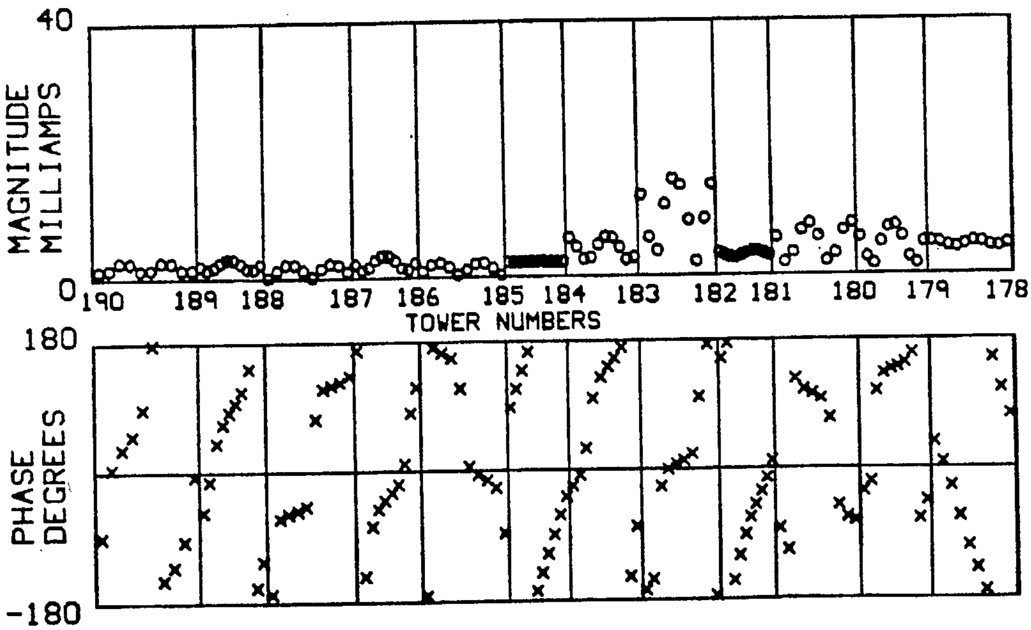
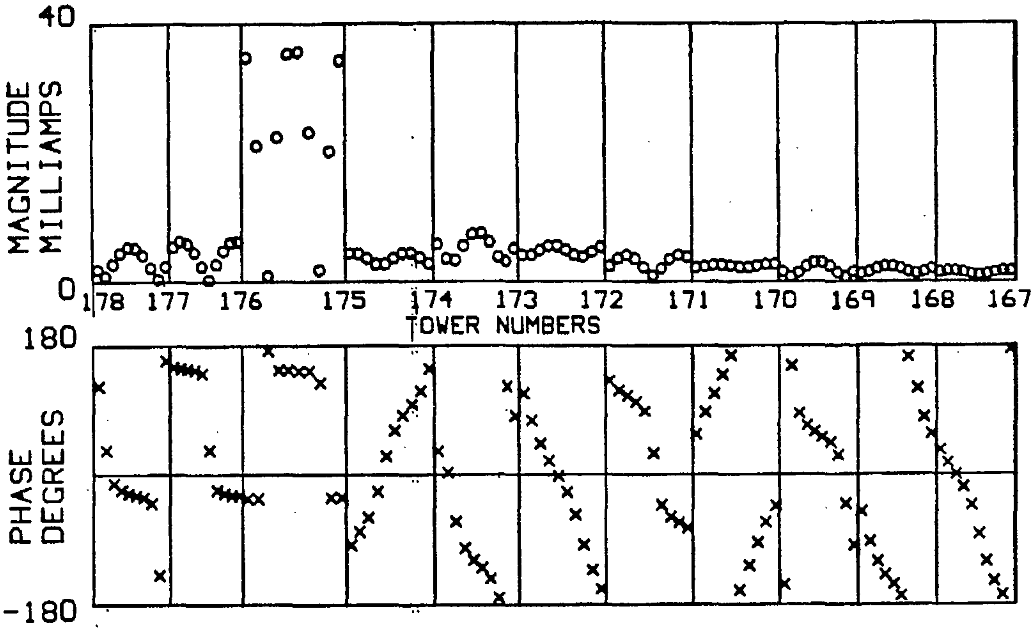


Fig. 2.5 (d) RF currents flowing on the skywires.



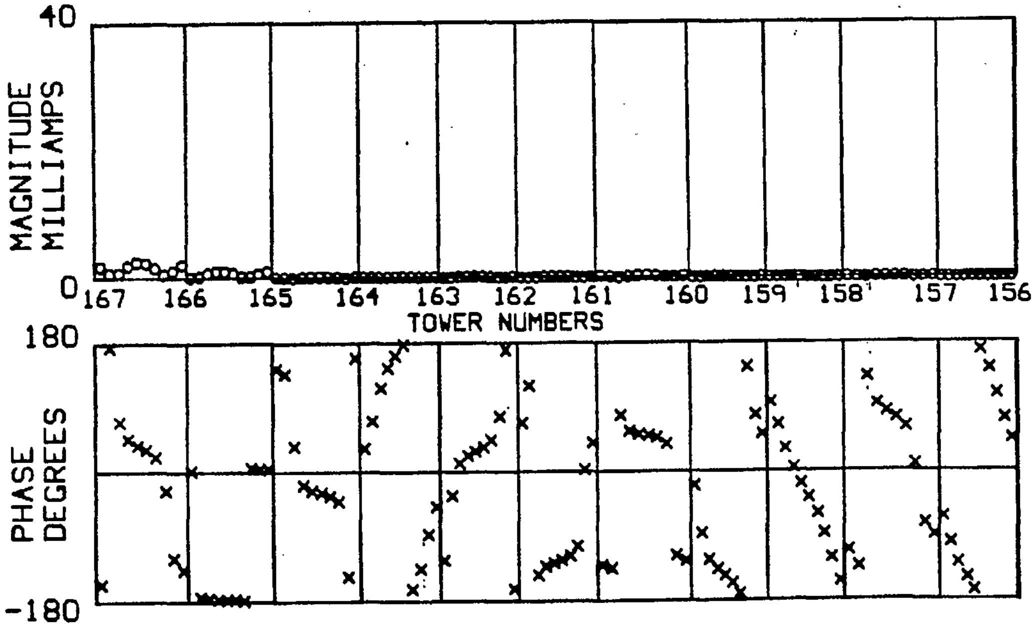


Fig. 2.5 (d) continued

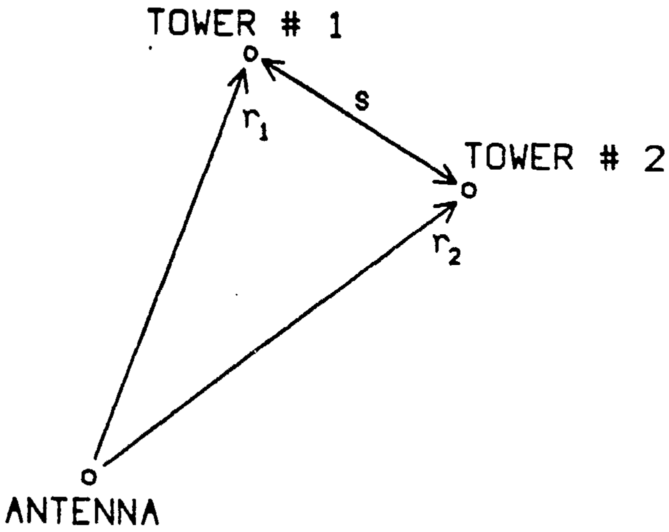


Fig. 2.6 Geometrical distances used to analyse the span excitation.

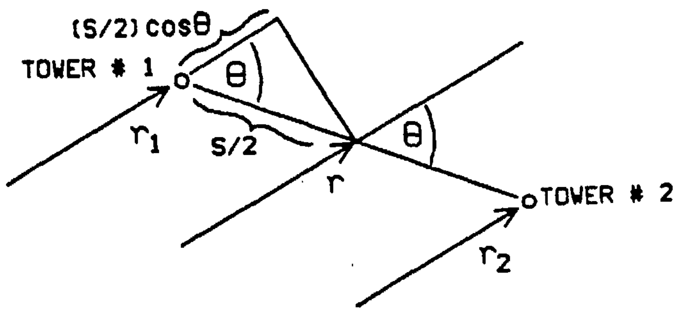
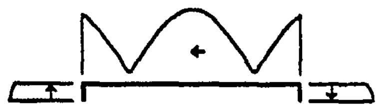
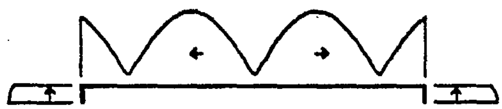


Fig. 2.7 Comparison of distances for $r \gg s$.

(A) ONE WAVELENGTH SINGLE-SPAN LOOP RESONANCE



(B) TWO WAVELENGTH SINGLE-SPAN LOOP RESONANCE



(C) THREE WAVELENGTH SINGLE-SPAN LOOP RESONANCE

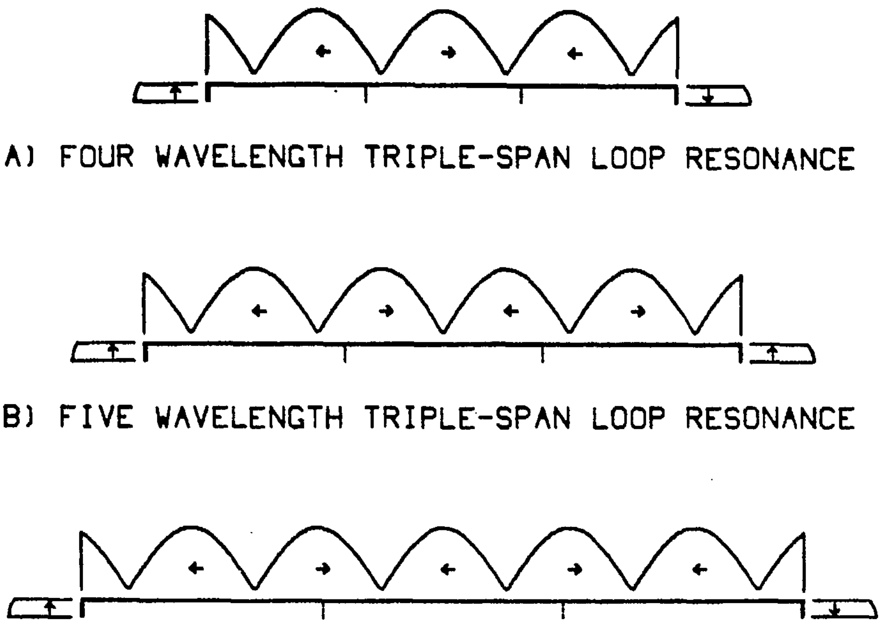
Fig. 3.1 Single-span loop resonance modes.

(A) THREE WAVELENGTH DOUBLE-SPAN LOOP RESONANCE

(B) FOUR WAVELENGTH DOUBLE-SPAN LOOP RESONANCE

(C) FIVE WAVELENGTH DOUBLE-SPAN LOOP RESONANCE

Fig. 3.2 Double-span loop resonance modes.



(A) FOUR WAVELENGTH TRIPLE-SPAN LOOP RESONANCE

(B) FIVE WAVELENGTH TRIPLE-SPAN LOOP RESONANCE

(C) SIX WAVELENGTH TRIPLE-SPAN LOOP RESONANCE

Fig. 3.3 Triple-span loop resonance modes.

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.
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.

Table 3.1 Single-span resonant frequencies for the north line.

SPAN TOWER TO TOWER		SPAN LENGTH M	PATH LENGTH M	ONE-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)	TWO-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)
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 3.1 Continued

Table 3.2 Double-span resonant frequencies for the north line.

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	THREE WAVE LOOP	FOUR WAVE LOOP	FIVE WAVE LOOP
194	192	680.	907.	1133.
193	191	559.	746.	932.
192	190	562.	749.	936.
191	189	582.	776.	970.
190	188	624.	832.	1040.
189	187	654.	873.	1091.
188	186	629.	838.	1048.
187	185	672.	896.	1120.
186	184	521.	694.	868.
185	183	473.	631.	788.
184	182	551.	735.	919.
183	181	589.	785.	982.
182	180	553.	737.	922.
181	179	561.	748.	935.
180	178	634.	845.	1056.
179	177	572.	763.	953.
178	176	635.	846.	1058.
177	175	613.	817.	1021.
176	174	517.	690.	862.
175	173	600.	800.	1000.
174	172	677.	902.	1128.
173	171	668.	890.	1113.
172	170	691.	922.	1152.
171	169	713.	950.	1188.
170	168	681.	908.	1135.
169	167	591.	789.	986.
168	166	675.	900.	1125.
167	165	732.	976.	1220.
166	164	604.	806.	1007.
165	163	616.	821.	1027.
164	162	680.	906.	1133.
163	161	654.	873.	1091.
162	160	446.	595.	744.

Table 3.2 Continued

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	THREE WAVE LOOP	FOUR WAVE LOOP	FIVE WAVE LOOP
161	159	489.	652.	815.
160	158	652.	869.	1086.
159	157	619.	825.	1031.
158	156	668.	891.	1113.
157	155	633.	844.	1055.
156	154	627.	836.	1044.
155	153	617.	823.	1029.
154	152	603.	804.	1005.
153	151	632.	843.	1053.
152	150	593.	791.	989.
151	149	592.	789.	986.
150	148	642.	856.	1069.
149	147	640.	854.	1067.
148	146	677.	902.	1128.

Table 3.3 Triple-span resonant frequencies for the north line.

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	FOUR WAVE LOOP	FIVE WAVE LOOP	SIX WAVE LOOP
194	191	580.	725.	869.
193	190	514.	643.	772.
192	189	521.	651.	781.
191	188	557.	696.	836.
190	187	578.	722.	866.
189	186	588.	735.	882.
188	185	604.	755.	906.
187	184	504.	630.	757.
186	183	486.	607.	728.
185	182	453.	566.	679.
184	181	528.	660.	793.
183	180	505.	632.	758.
182	179	535.	669.	803.
181	178	526.	658.	790.
180	177	552.	690.	828.
179	176	568.	709.	851.
178	175	539.	674.	809.
177	174	529.	662.	794.
176	173	519.	649.	779.
175	172	564.	706.	847.
174	171	625.	782.	938.
173	170	622.	778.	934.
172	169	640.	800.	960.
171	168	634.	793.	952.
170	167	573.	716.	859.
169	166	614.	768.	922.
168	165	604.	755.	906.
167	164	621.	776.	932.
166	163	567.	709.	851.
165	162	587.	734.	880.
164	161	602.	752.	902.
163	160	462.	577.	692.

Table 3.3 Continued

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	FOUR WAVE LOOP	FIVE WAVE LOOP	SIX WAVE LOOP
162	159	479.	599.	719.
161	158	460.	575.	690.
160	157	617.	772.	926.
159	156	573.	716.	860.
158	155	597.	747.	896.
157	154	576.	720.	864.
156	153	568.	710.	852.
155	152	557.	697.	836.
154	151	571.	714.	857.
153	150	545.	682.	818.
152	149	564.	705.	846.
151	148	551.	688.	826.
150	147	591.	738.	886.
149	146	605.	756.	907.

SPAN TOWER TO TOWER		SPAN LENGTH M	PATH LENGTH M	ONE-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)	TWO-WAVELENGTH LOOP RESONANCE FREQUENCY(KHZ)
199	198	246.0	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.
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.

Table 3.4 Single-span resonant frequencies for the southeast line.

SPAN TOWER TO TOWER		SPAN LENGTH M	PATH LENGTH M	ONE-WAVELENGTH LOOP RESONANCE FREQUENCY (KHZ)	TWO-WAVELENGTH LOOP RESONANCE FREQUENCY (KHZ)
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 3.4 Continued

Table 3.5 Double-span resonant frequencies for the southeast line.

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	THREE WAVE LOOP	FOUR WAVE LOOP	FIVE WAVE LOOP
199	197	680.	906.	1133.
198	196	559.	746.	932.
197	195	561.	749.	936.
196	194	582.	776.	970.
195	193	624.	831.	1039.
194	192	644.	859.	1073.
193	191	610.	813.	1016.
192	190	672.	896.	1121.
191	189	537.	716.	895.
190	188	507.	676.	845.
189	187	553.	737.	922.
188	186	551.	735.	918.
187	185	555.	740.	926.
186	184	571.	761.	951.
185	183	640.	854.	1067.
184	182	570.	759.	949.
183	181	626.	835.	1043.
182	180	605.	807.	1008.
181	179	550.	733.	917.
180	178	555.	740.	925.
179	177	588.	784.	980.
178	176	715.	953.	1191.
177	175	603.	804.	1005.
176	174	564.	751.	939.
175	173	615.	820.	1025.
174	172	619.	826.	1032.
173	171	621.	827.	1034.
172	170	616.	821.	1027.
171	169	646.	861.	1076.
170	168	684.	911.	1139.
169	167	681.	908.	1136.
168	166	628.	837.	1047.
167	165	596.	794.	993.
166	164	610.	814.	1017.

Table 3.5 Continued

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	THREE WAVE LOOP	FOUR WAVE LOOP	FIVE WAVE LOOP
165	163	627.	835.	1044.
164	162	663.	883.	1104.
163	161	663.	884.	1105.
162	160	613.	818.	1022.
161	159	619.	825.	1031.
160	158	670.	893.	1117.
159	157	609.	812.	1015.
158	156	611.	815.	1019.
157	155	623.	830.	1038.
156	154	595.	793.	992.
155	153	612.	815.	1019.
154	152	598.	797.	997.
153	151	597.	796.	995.
152	150	615.	820.	1024.
151	149	609.	812.	1015.
150	148	620.	827.	1034.
149	147	580.	774.	967.
148	146	532.	710.	887.
147	145	575.	766.	958.
146	144	583.	778.	972.

Table 3.6 Triple-span resonant frequencies for the southeast line.

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	FOUR WAVE LOOP	FIVE WAVE LOOP	SIX WAVE LOOP
199	196	580.	724.	869.
198	195	514.	643.	772.
197	194	521.	651.	781.
196	193	557.	696.	836.
195	192	571.	714.	857.
194	191	576.	720.	864.
193	190	598.	747.	897.
192	189	511.	638.	766.
191	188	517.	647.	776.
190	187	457.	571.	685.
189	186	530.	662.	795.
188	185	485.	607.	728.
187	184	542.	677.	813.
186	183	532.	665.	798.
185	182	552.	690.	828.
184	181	564.	704.	845.
183	180	534.	667.	801.
182	179	553.	691.	830.
181	178	494.	617.	740.
180	177	543.	678.	814.
179	176	576.	720.	864.
178	175	583.	729.	874.
177	174	556.	695.	834.
176	173	531.	663.	796.
175	172	563.	703.	844.
174	171	568.	710.	852.
173	170	566.	708.	850.
172	169	583.	729.	875.
171	168	602.	752.	903.
170	167	625.	782.	938.
169	166	591.	739.	887.
168	165	570.	712.	855.
167	164	548.	685.	822.

Table 3.6 Continued

TOWERS		RESONANT FREQUENCIES (KHZ)		
FROM	TO	FOUR WAVE LOOP	FIVE WAVE LOOP	SIX WAVE LOOP
166	163	572.	715.	858.
165	162	586.	732.	878.
164	161	609.	761.	913.
163	160	574.	718.	862.
162	159	579.	724.	869.
161	158	583.	729.	875.
160	157	576.	720.	865.
159	156	578.	722.	866.
158	155	547.	684.	821.
157	154	567.	709.	850.
156	153	547.	684.	821.
155	152	551.	689.	827.
154	151	549.	686.	823.
153	150	553.	692.	830.
152	149	556.	695.	834.
151	148	568.	710.	852.
150	147	534.	668.	802.
149	146	516.	645.	774.
148	145	508.	635.	762.
147	144	518.	647.	777.

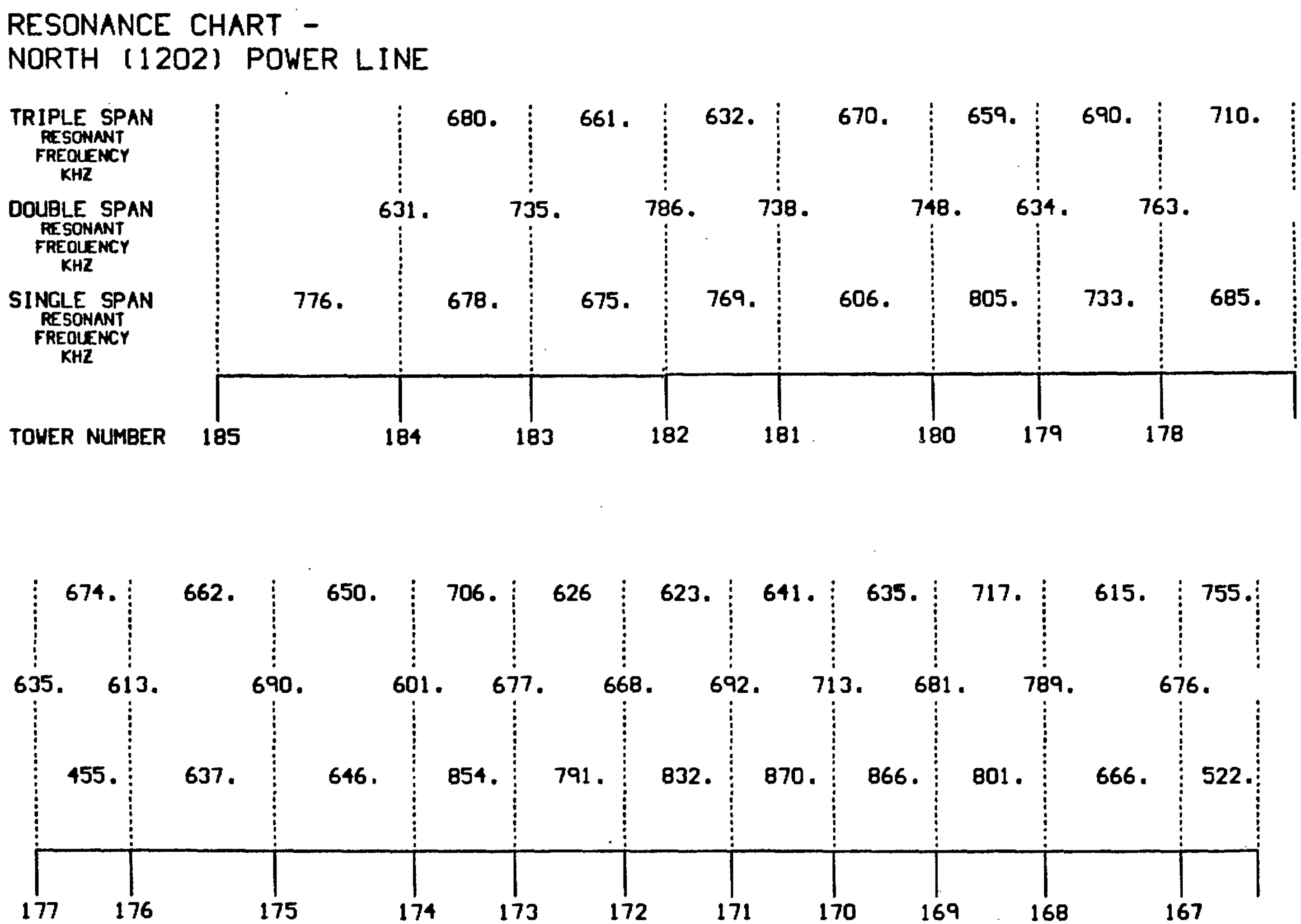


Fig. 3.4 Resonance chart for the north line.

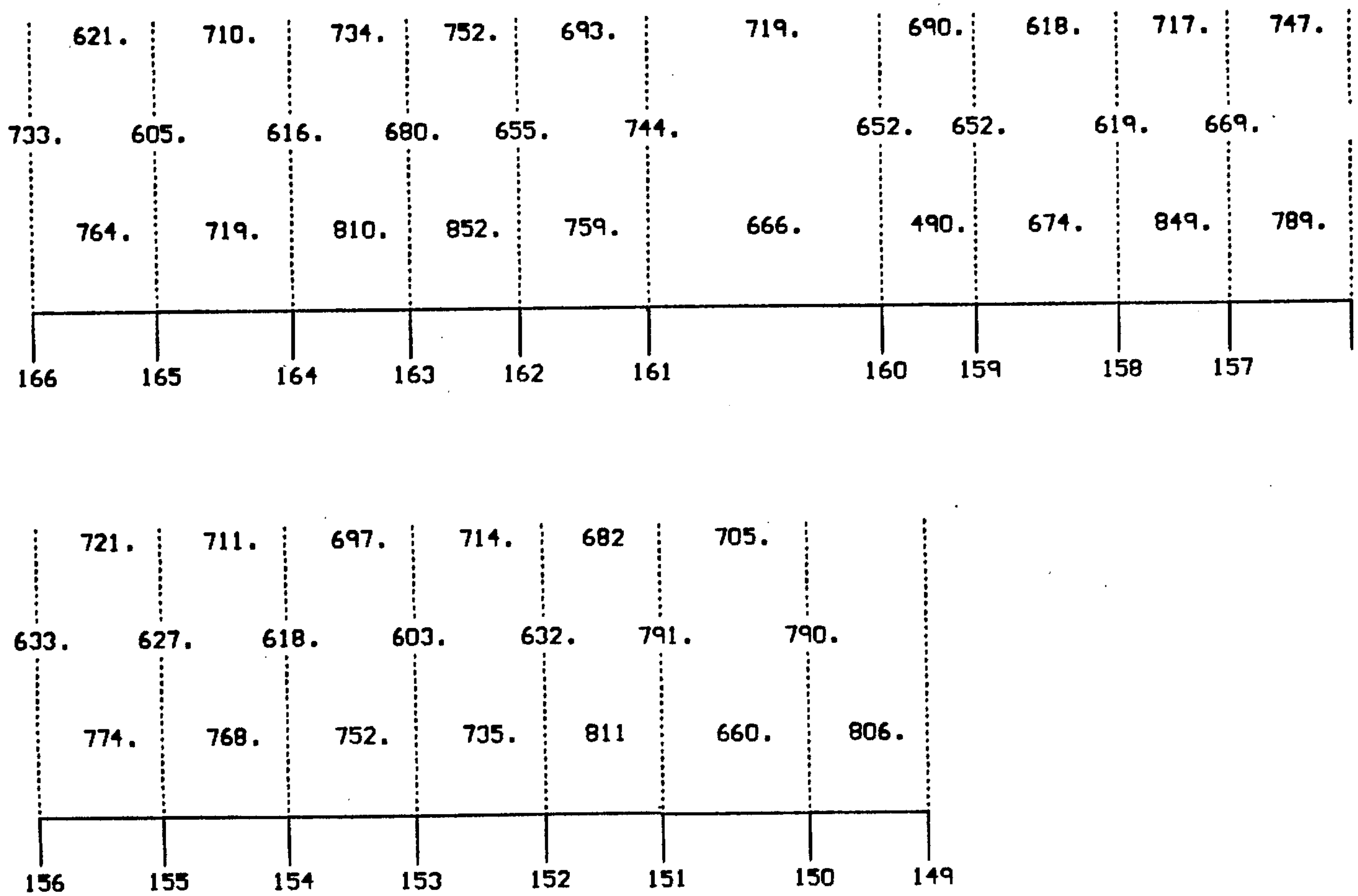


Fig. 3.4 Continued

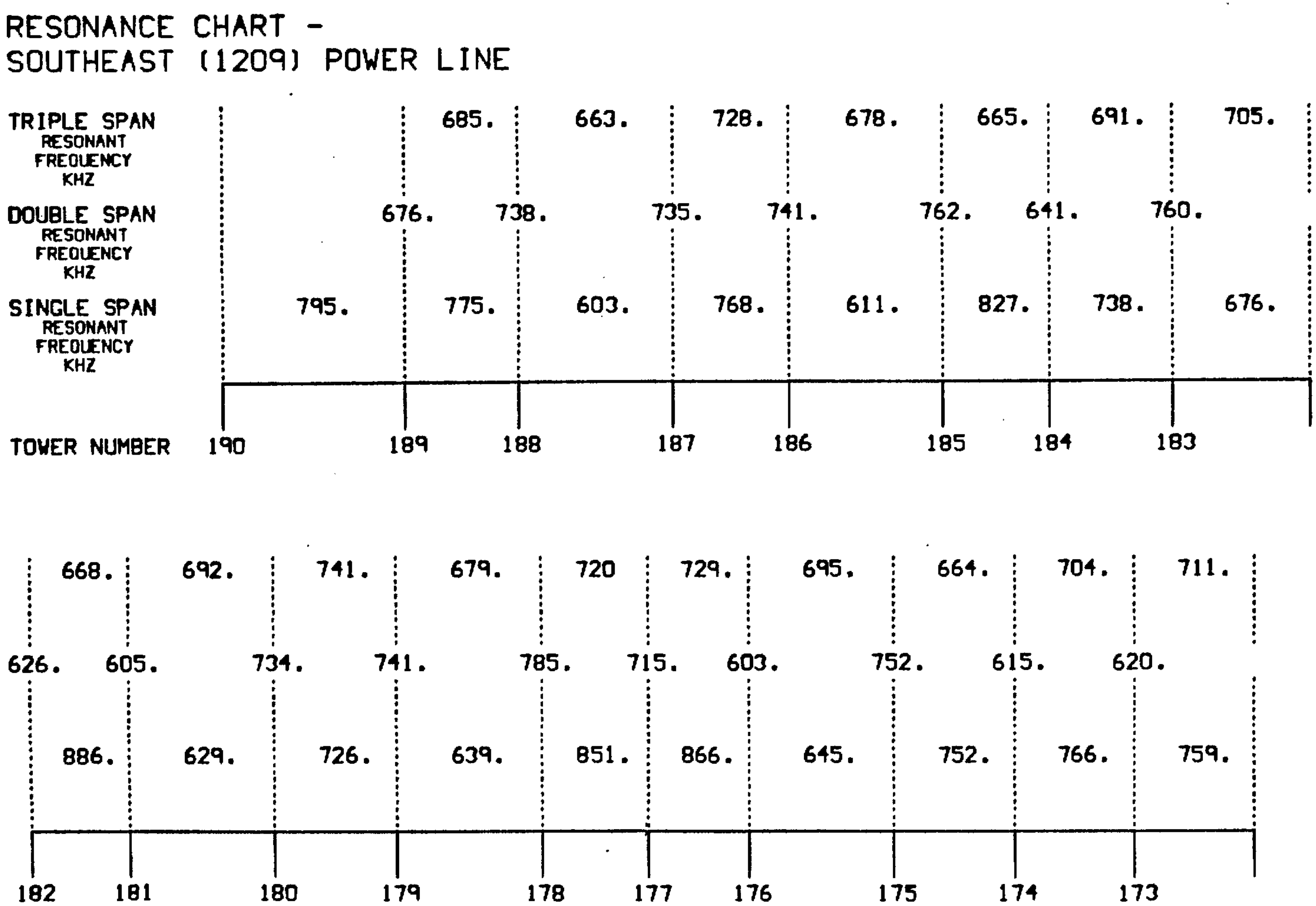


Fig. 3.5 Resonance chart for the southeast line.

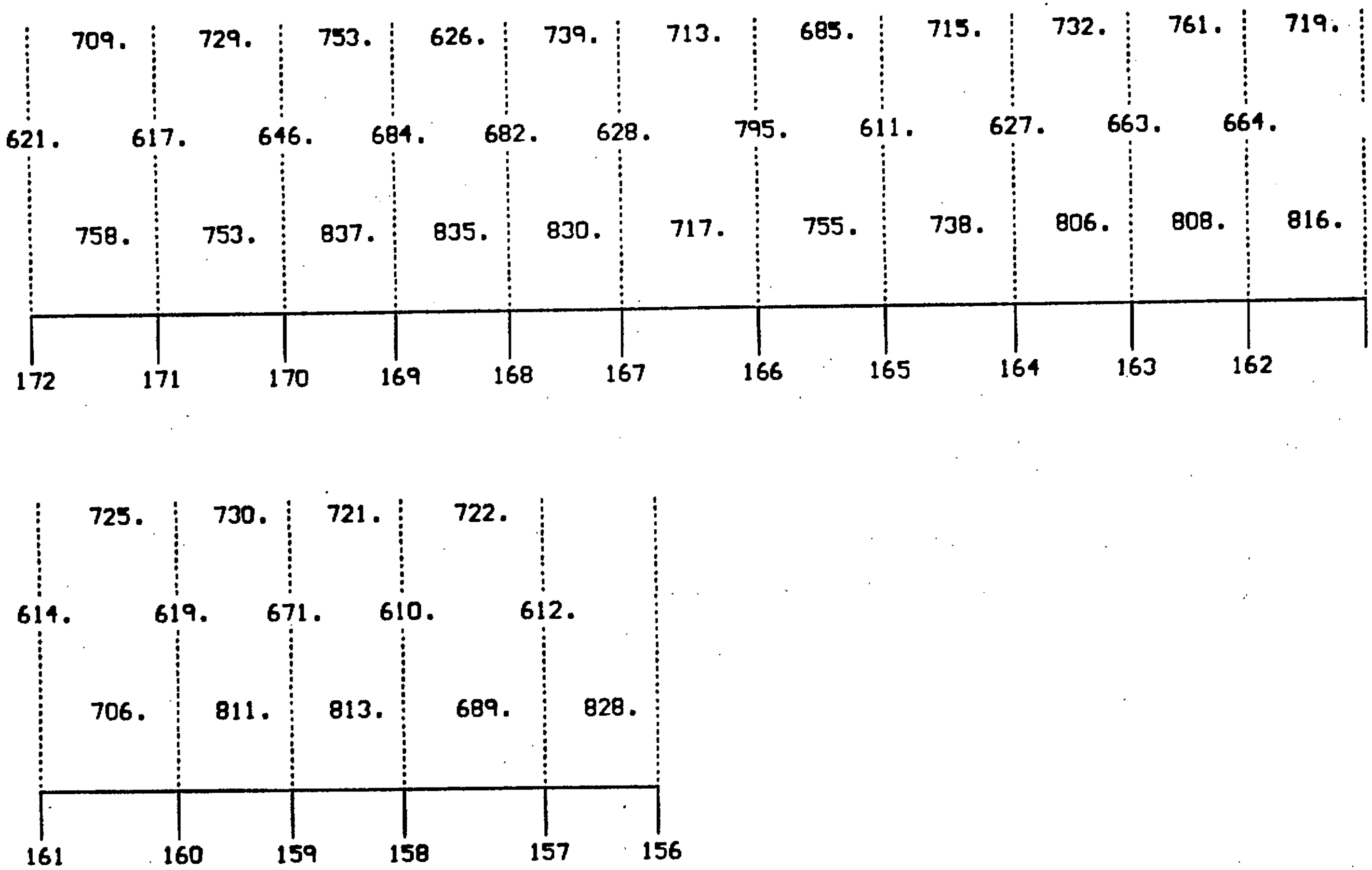


Fig. 3.5 Continued

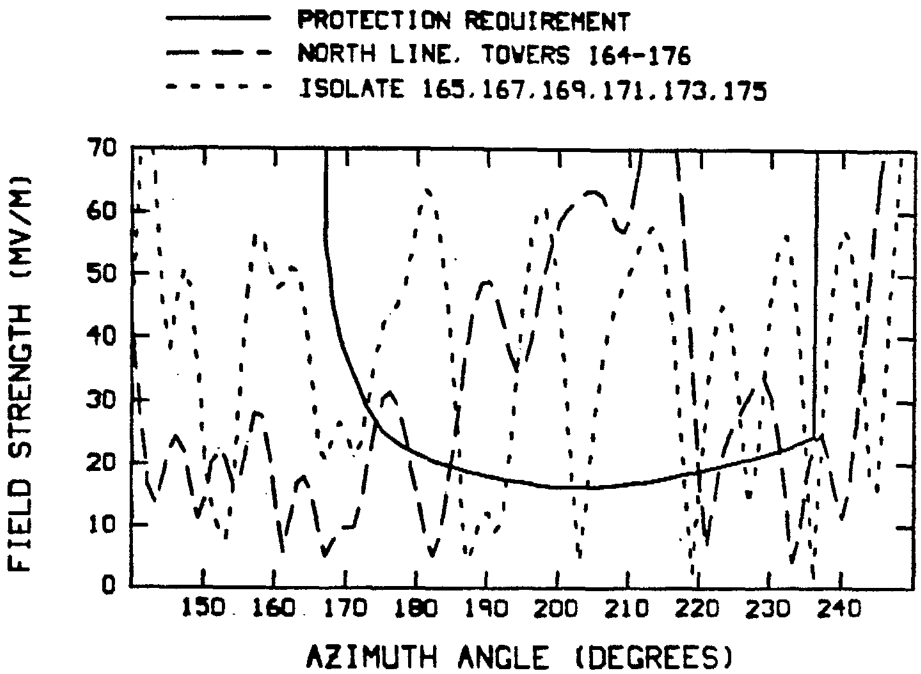


Fig. 4.1 (a) Field strength in the minimum with towers 164 to 176 of the north line, when towers 165, 167, 169, 171, 173, and 175 are isolated from the skywire.

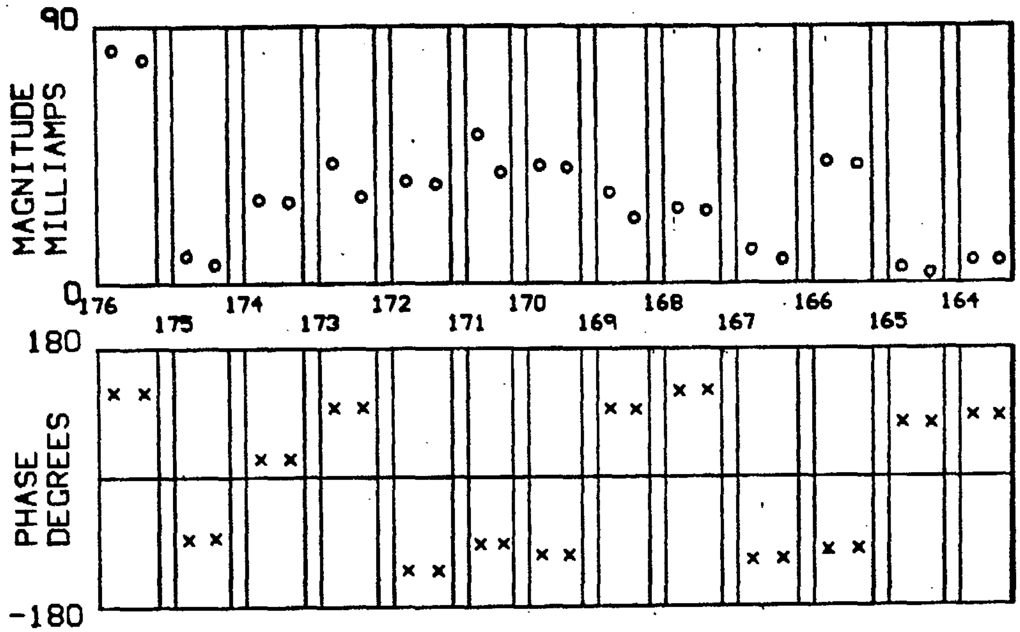


Fig. 4.1 (b) Currents on the towers, with towers 165, 167, 169, 171, 173, and 175 isolated.

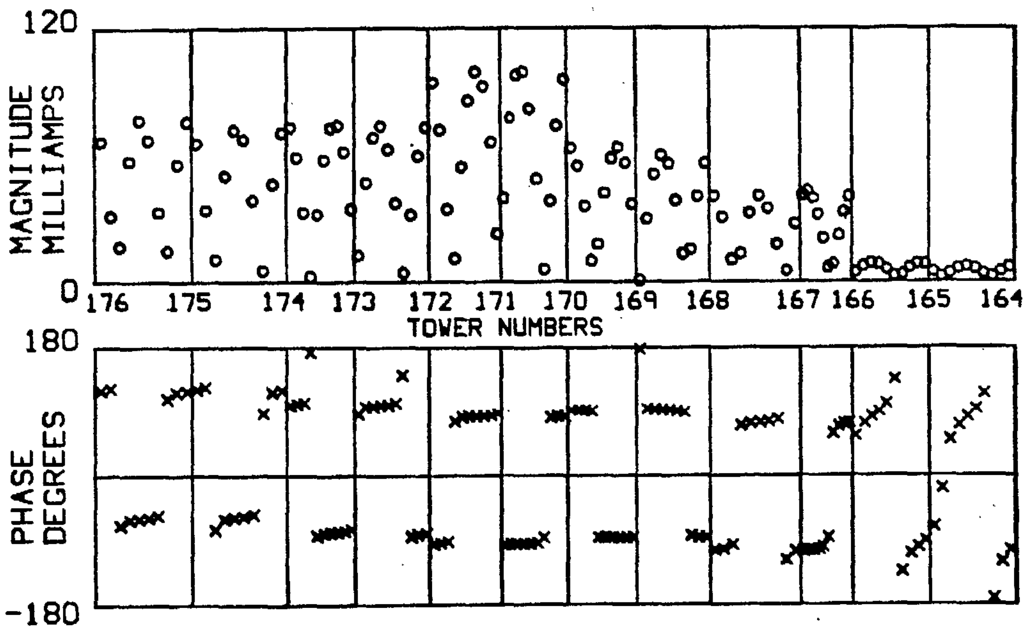


Fig. 4.1 (c) Currents flowing on the skywires.

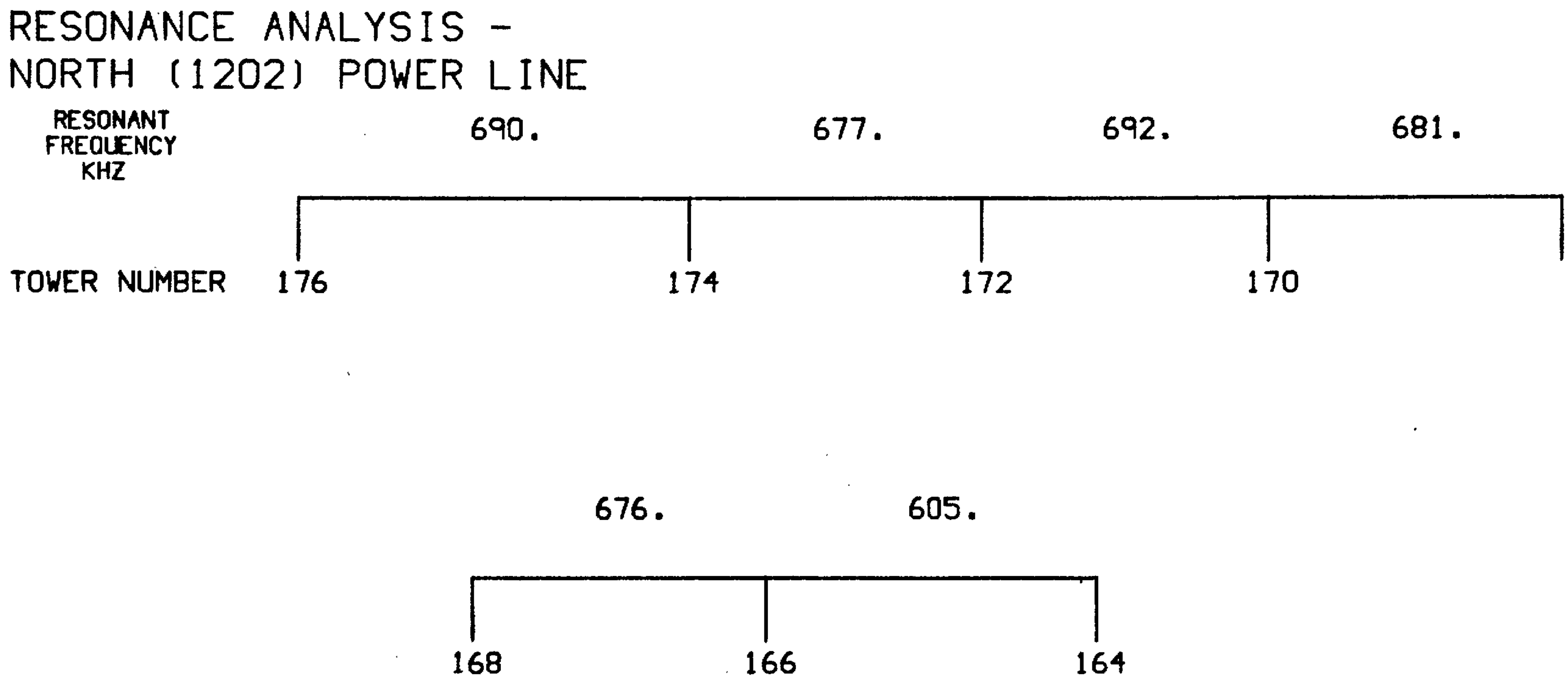


Fig. 4.1 (d) Resonance analysis of the north line with towers 165, 167, 169, 171, 173, and 175 isolated from the skywire.

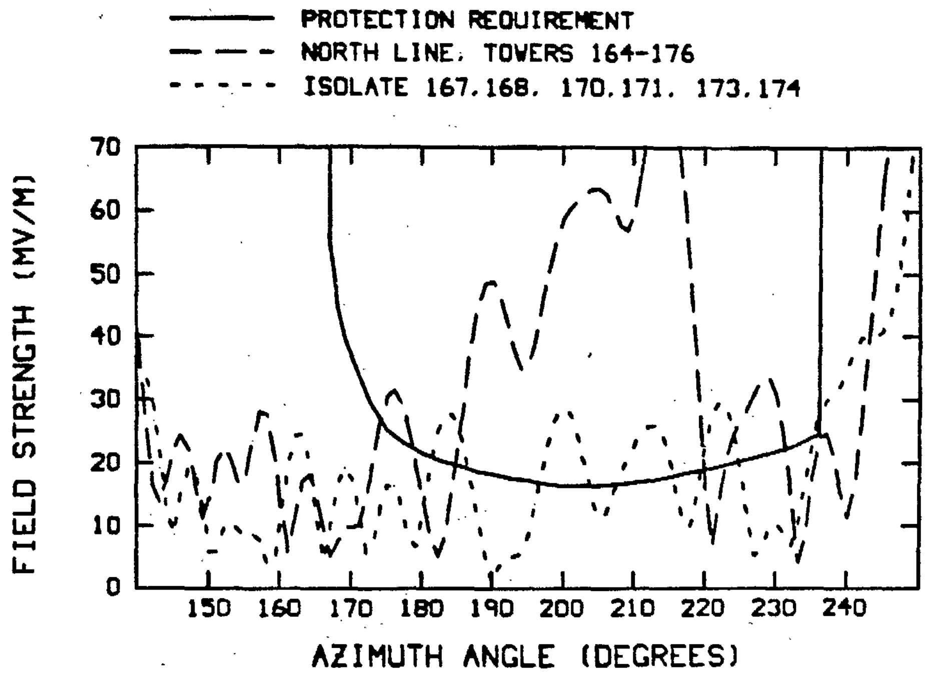


Fig. 4.2 (a) Field strength in the minimum with towers 164 to 176 of the north line, when towers 167, 168, 170, 171, 173, and 174 are isolated from the skywire.

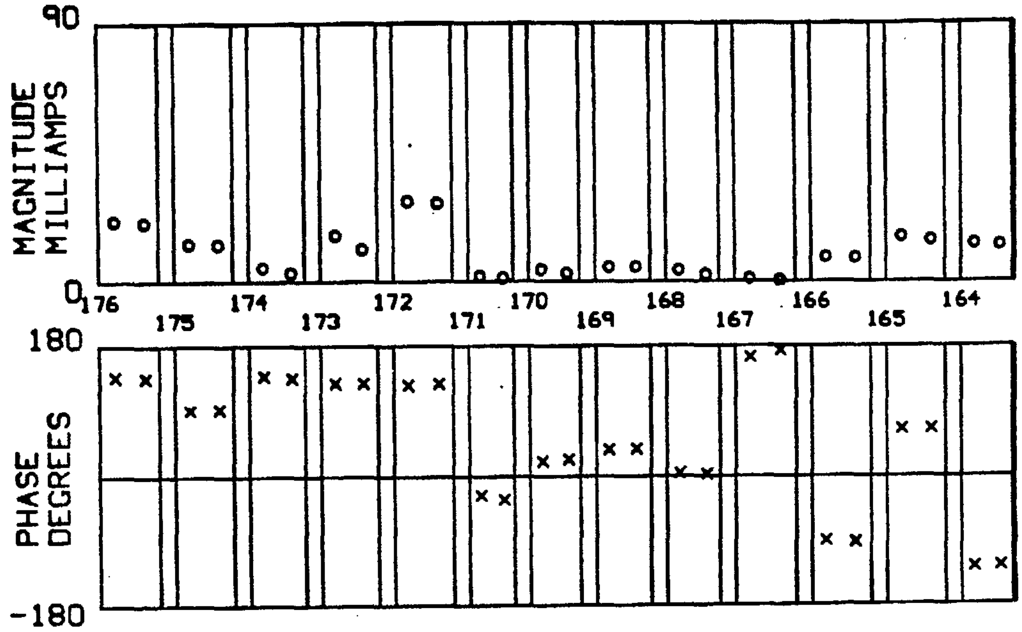


Fig. 4.2 (b) Currents on the towers, with towers 167, 168, 170, 171, 173, and 174 isolated.

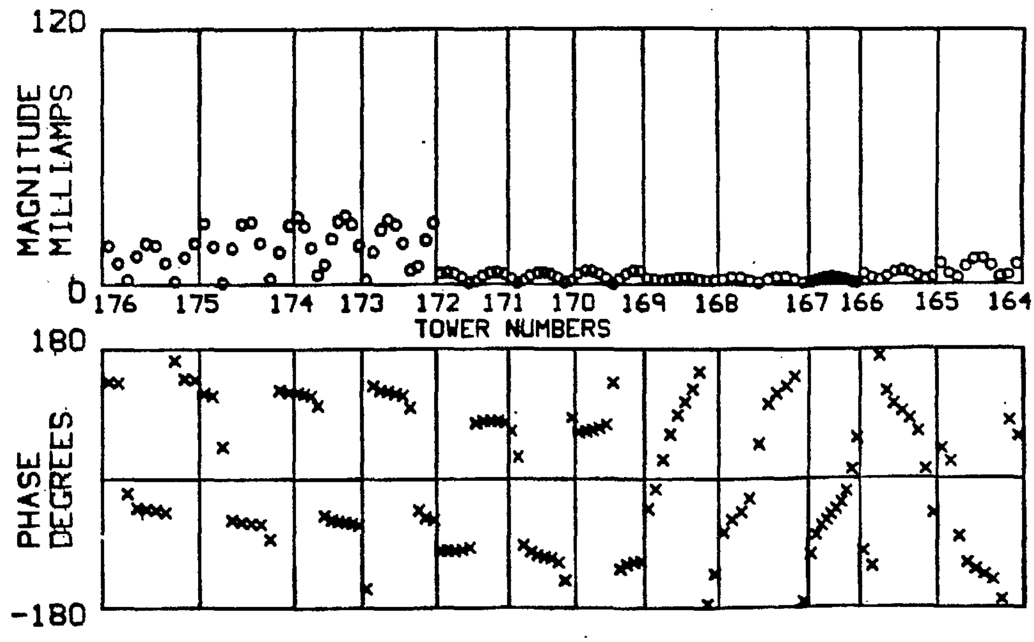


Fig. 4.2 (c) Currents flowing on the skywires.

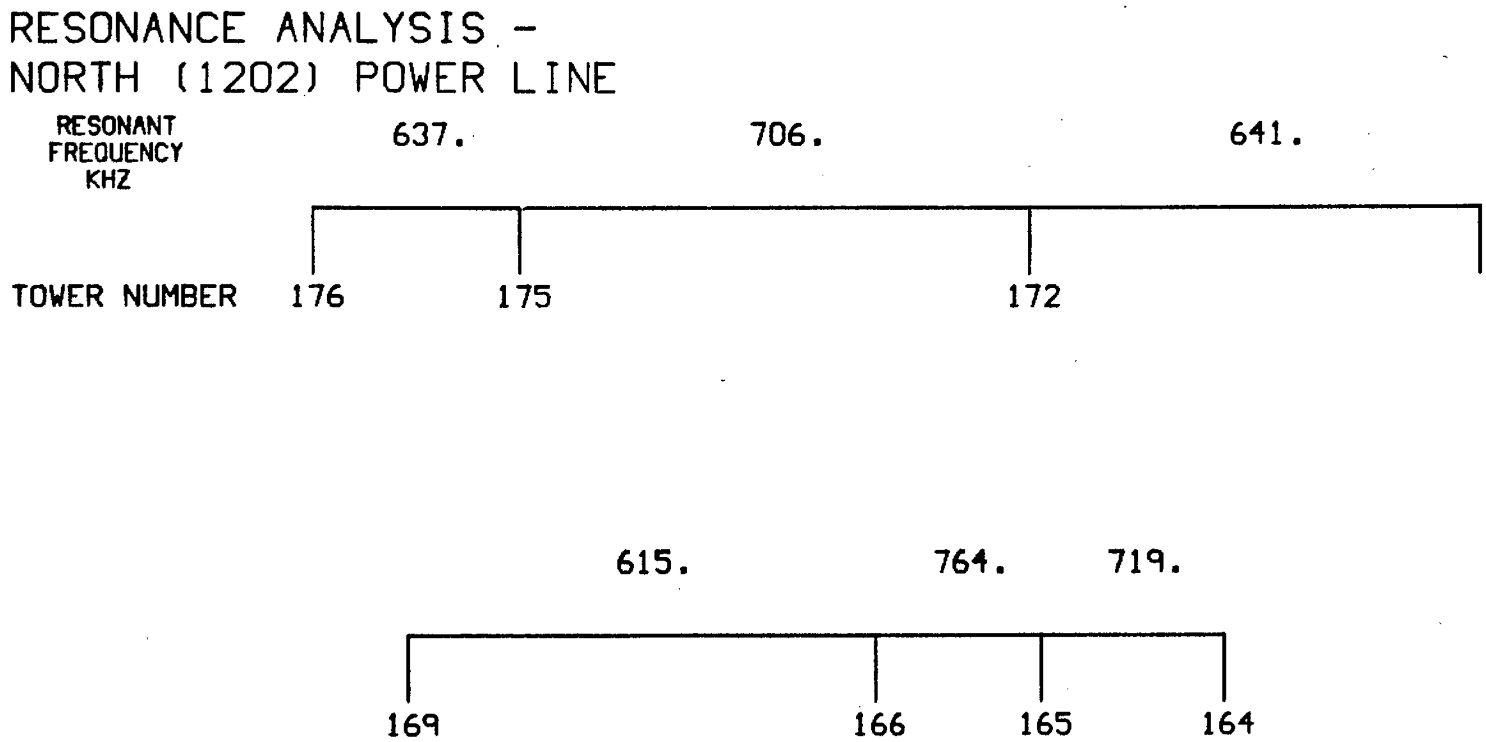


Fig. 4.2 (d) Resonance analysis of the north line with towers 167, 168, 170, 171, 173, and 174 isolated from the skywire.

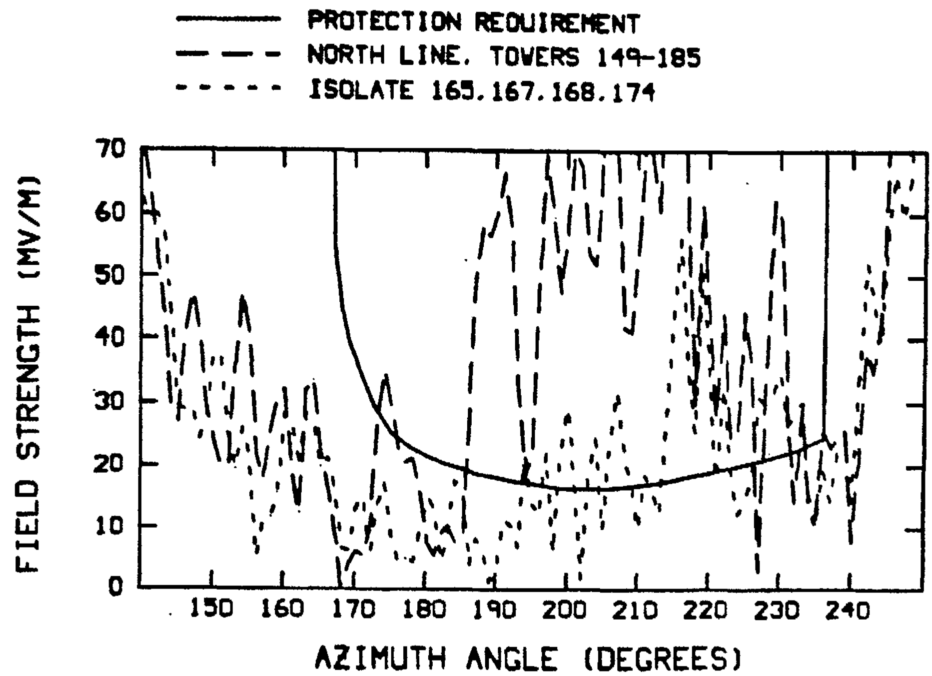


Fig. 5.1 (a) Field strength in the minimum with towers 149 to 185 of the north line, when towers 165, 167, 168 and 174 are isolated from the skywire.

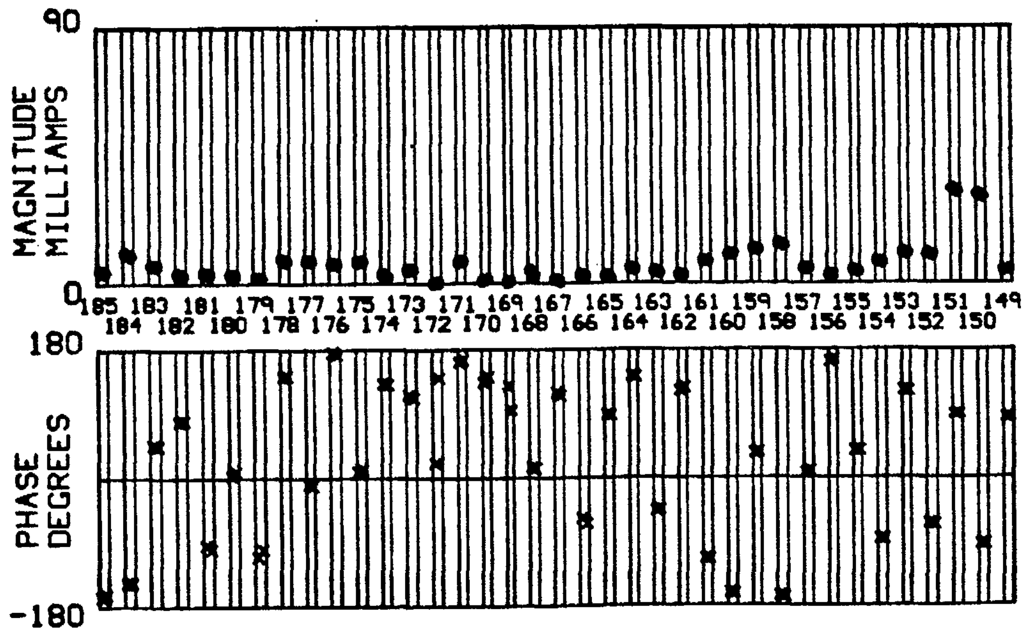


Fig. 5.1 (b) Currents on the towers.

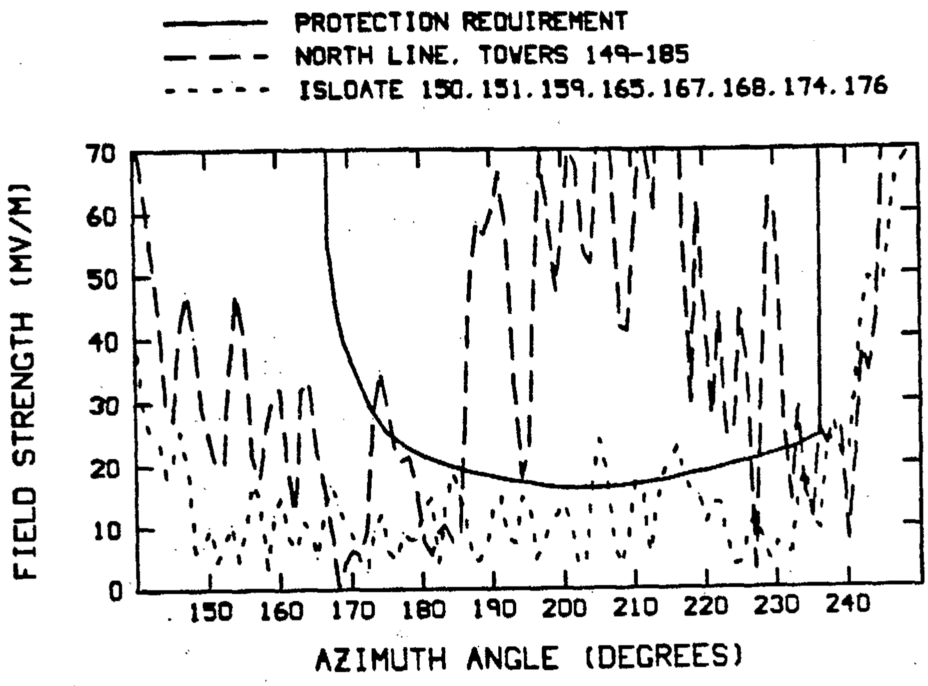


Fig. 5.2 (a) Field strength in the minimum with towers 149 to 185 of the north line, when towers 150, 151, 159, 165, 167, 168, 174 and 176 are isolated from the skywire.

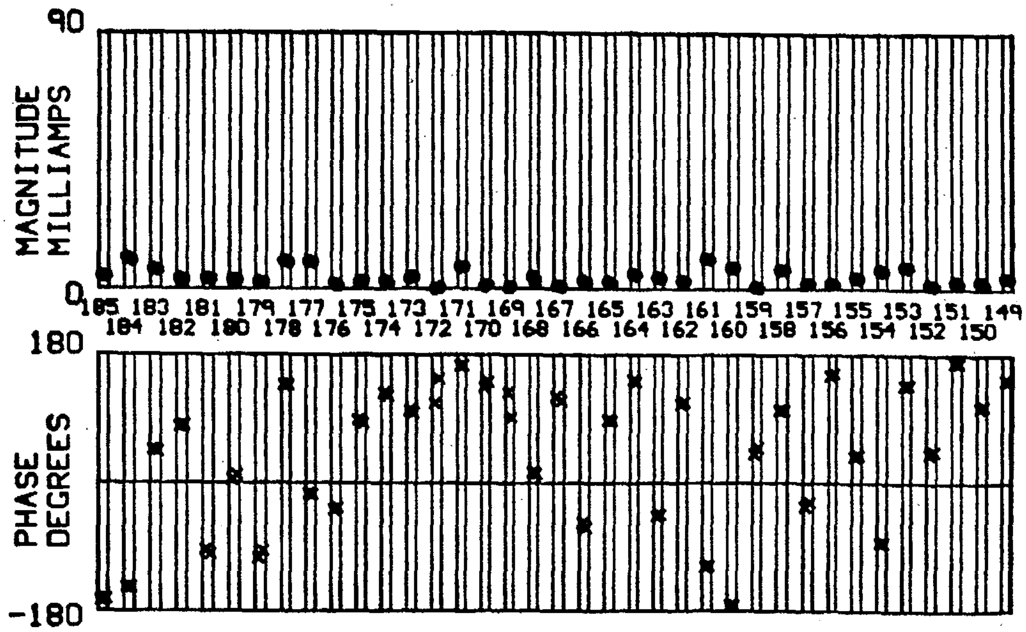


Fig. 5.2 (b) Currents on the towers.

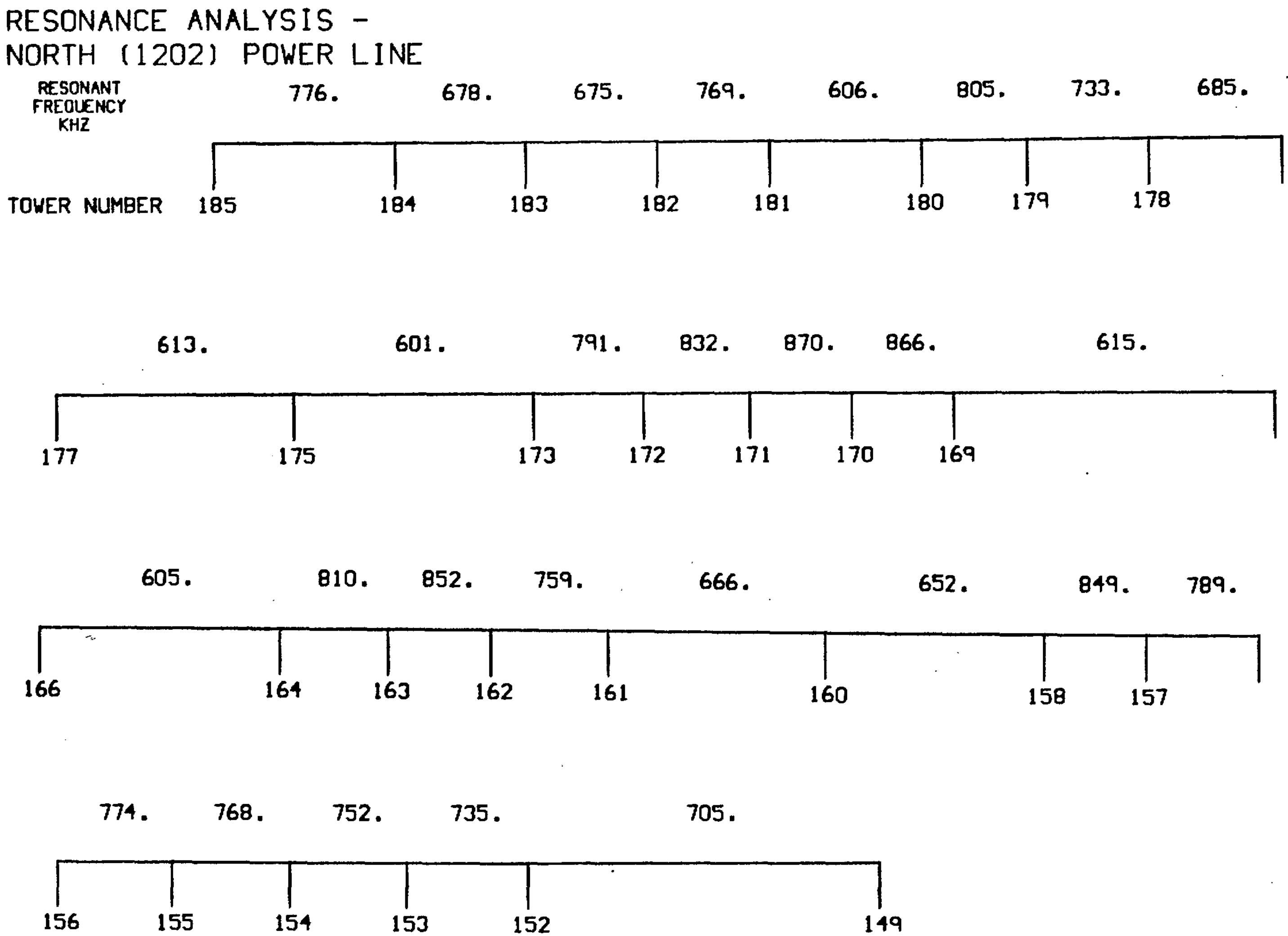


Fig. 5.2 (c) Resonance analysis of the north line when towers with large RF currents are selected for isolation.

TABLE 5.1

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

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

TABLE 5.1 Continued

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

Scale for representation of currents :

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

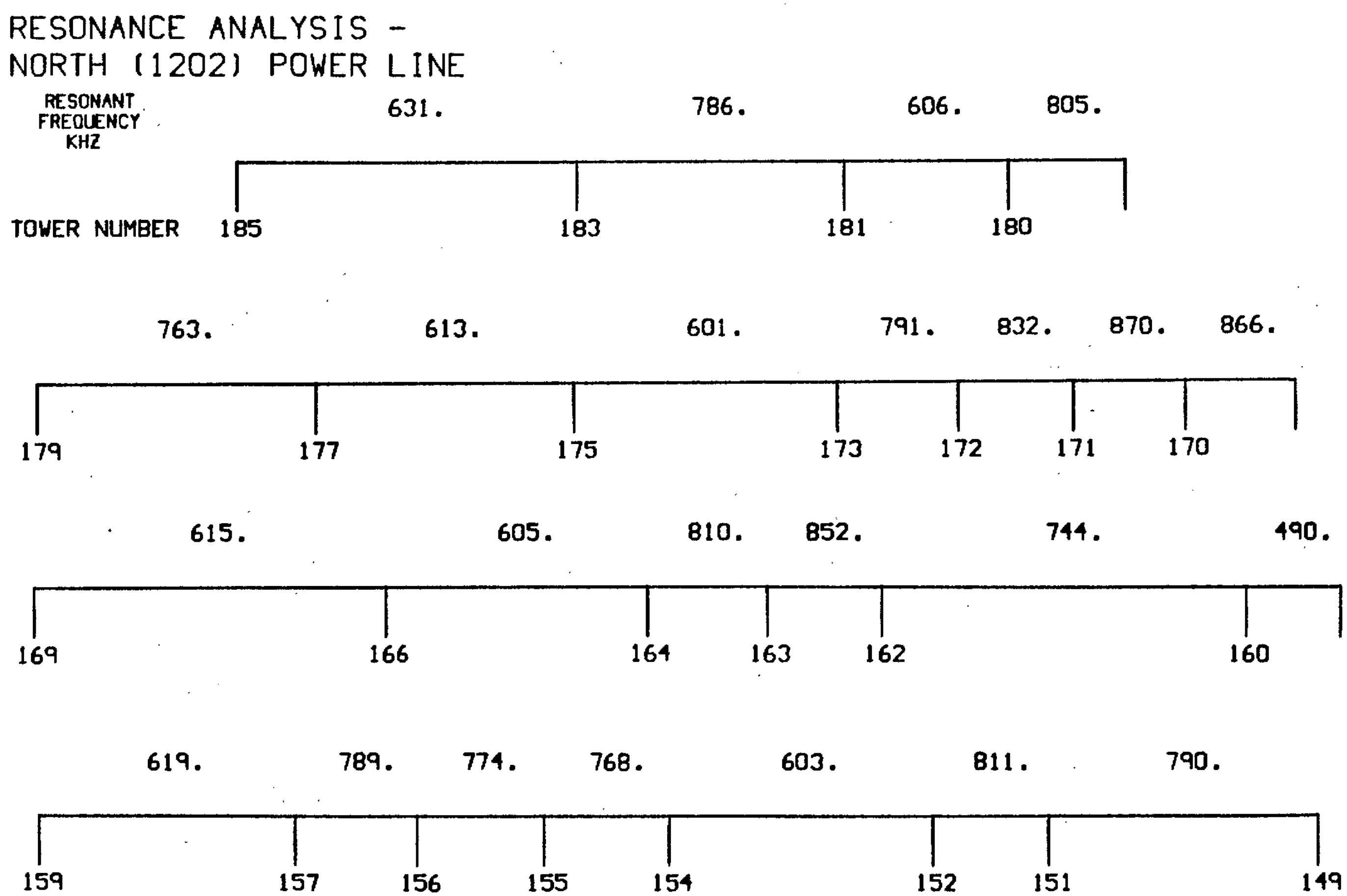


Fig. 5.3 (a) Resonance analysis of the north line with towers selected for isolation for the suppression of resonances.

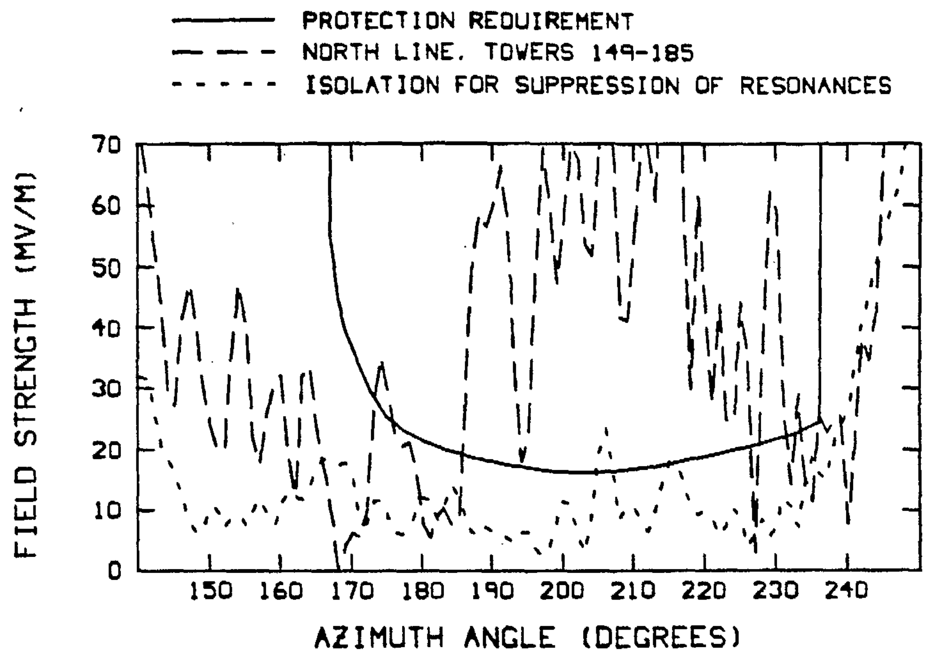


Fig. 5.3 (b) Field strength in the minimum with towers 149 to 185 of the north line, when towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184 are isolated from the skywire.

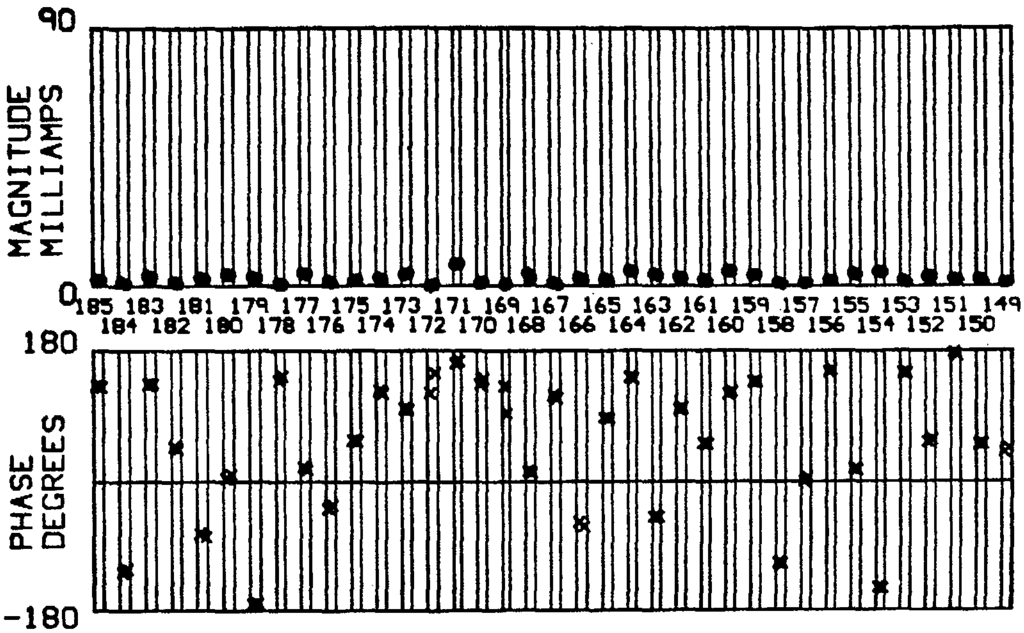


Fig. 5.3 (c) RF currents on the towers, with towers 150, 153, 158, 161, 165, 167, 168, 174, 176, 178, 182 and 184 isolated from the skywire.

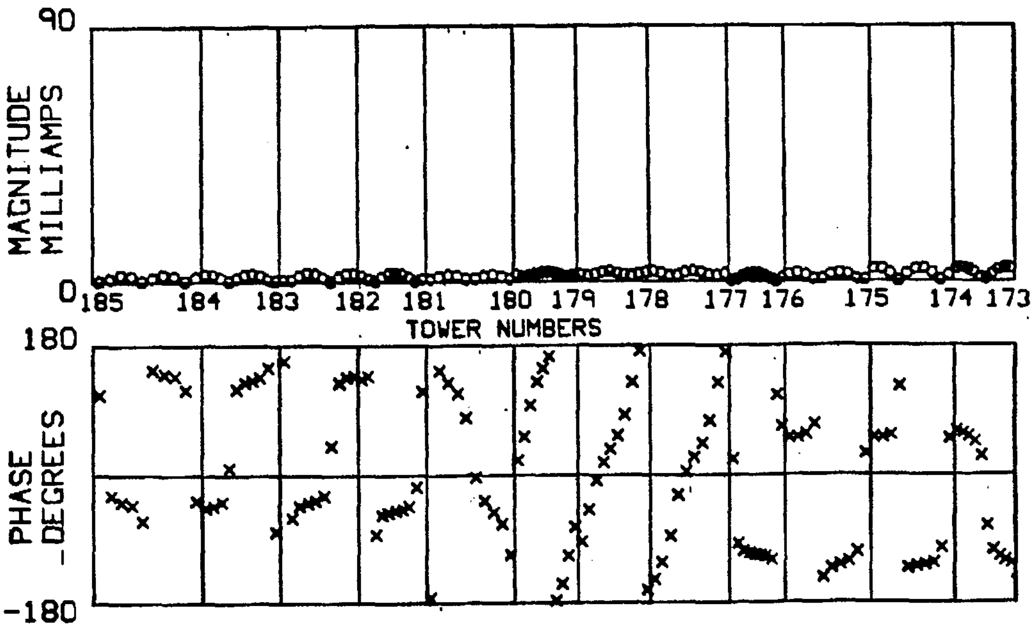


Fig. 5.3 (d) Currents on the skywires.

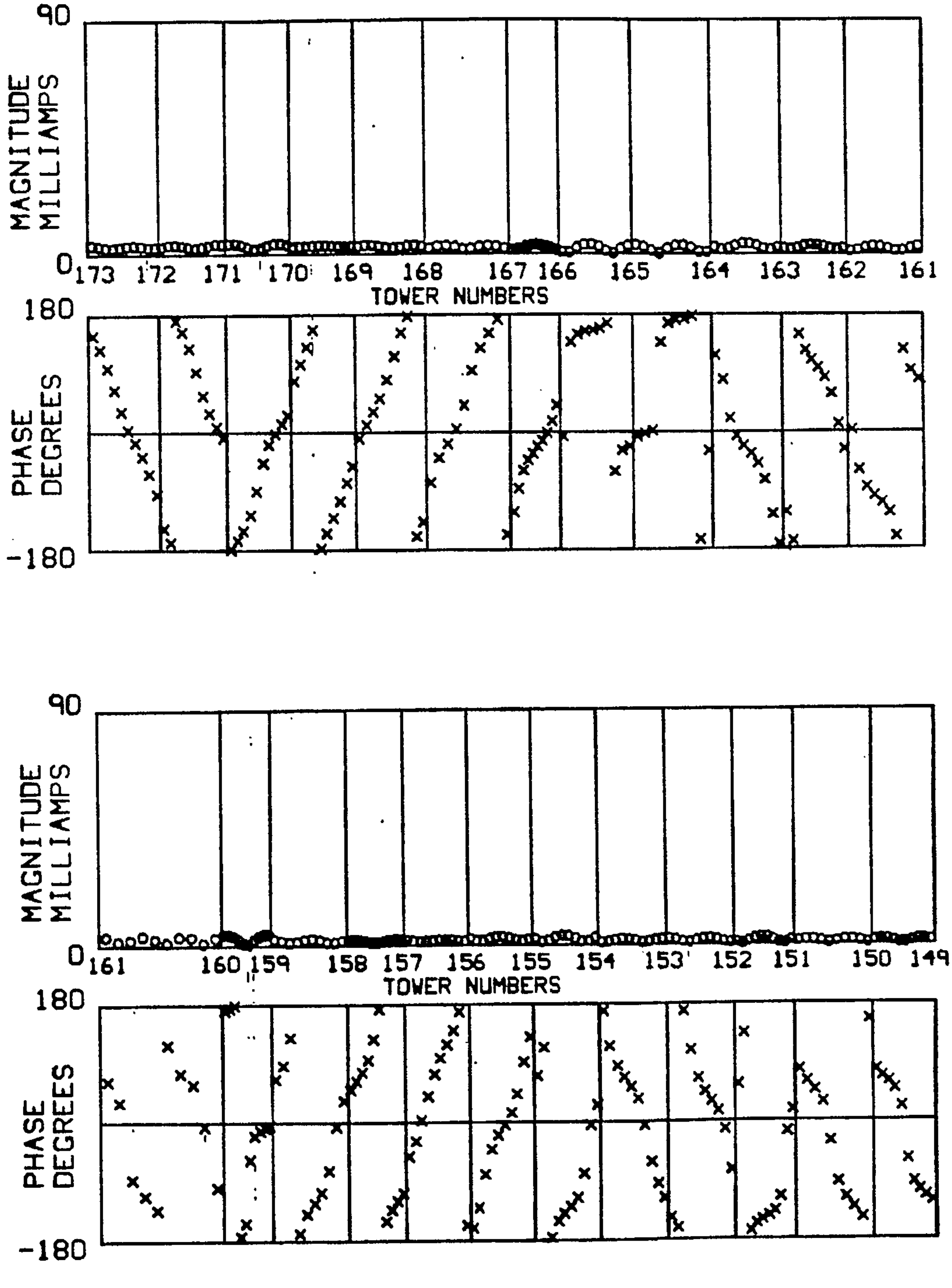


Fig. 5.3 (d) Continued.

TABLE 5.2

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

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

TABLE 5.2 Continued

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

Scale for representation of currents :

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

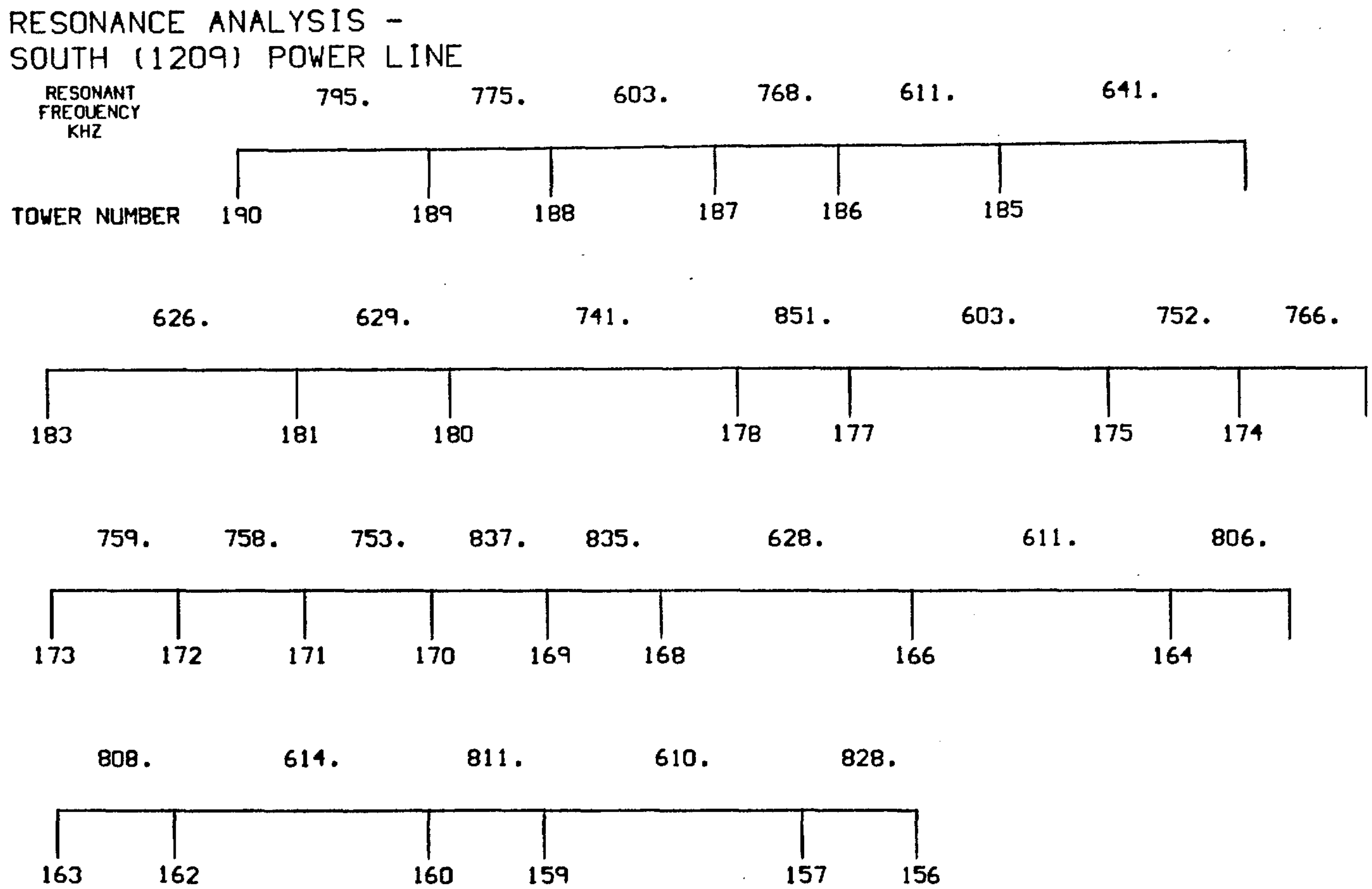


Fig. 5.4 (a) Resonance analysis of the southeast line with towers selected for isolation for the suppression of resonances.

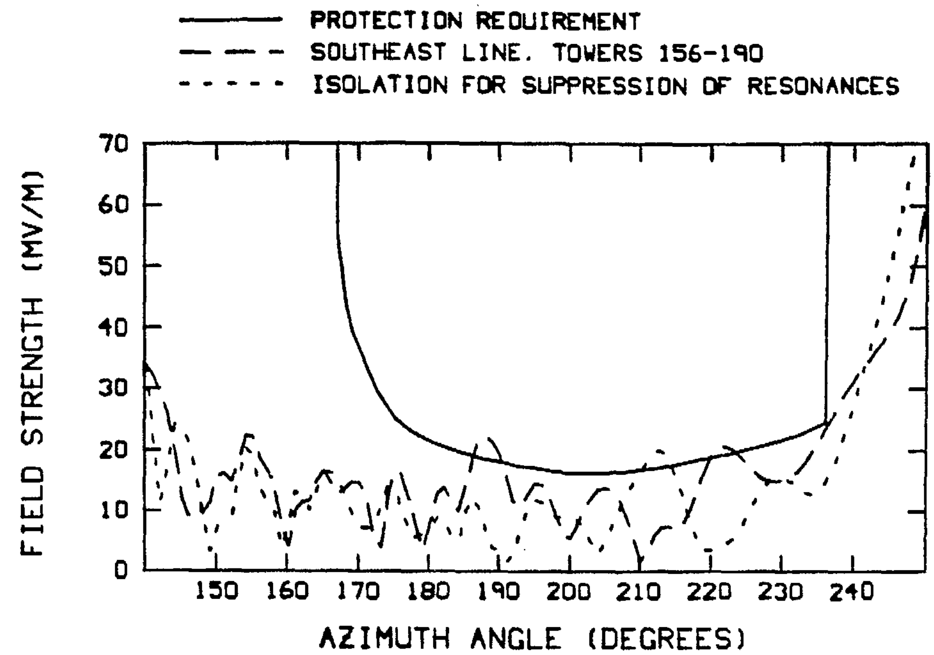


Fig. 5.4 (b) Field strength in the minimum with towers 156 to 190 of the southeast line, when towers 158, 161, 165, 167, 176, 179, 182, and 184 are isolated from the skywire.

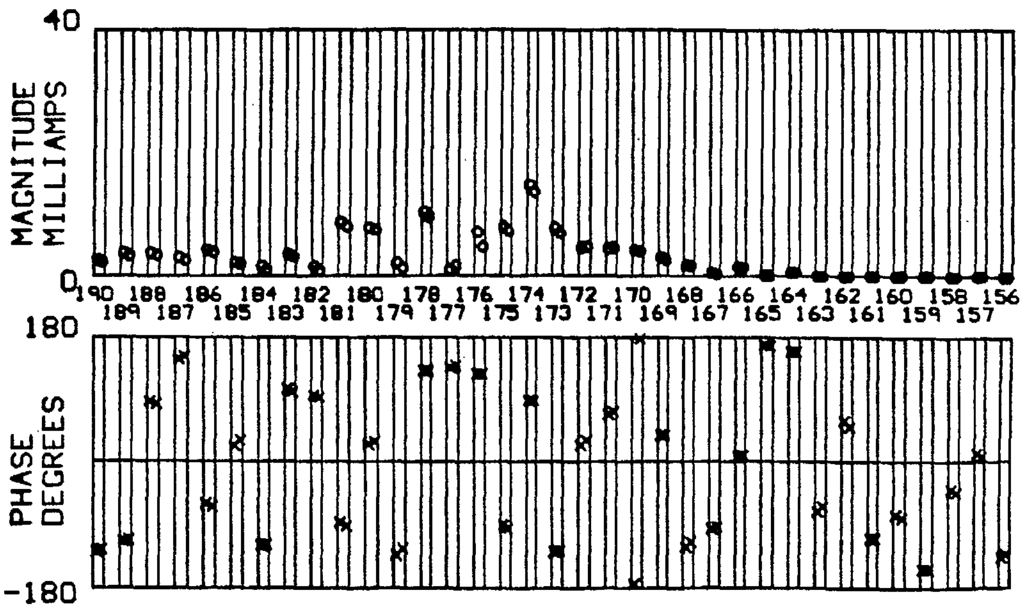


Fig. 5.4 (c) RF currents on the towers, with towers 158, 161, 165, 167, 176, 179, 182, and 184, isolated from the skywire.

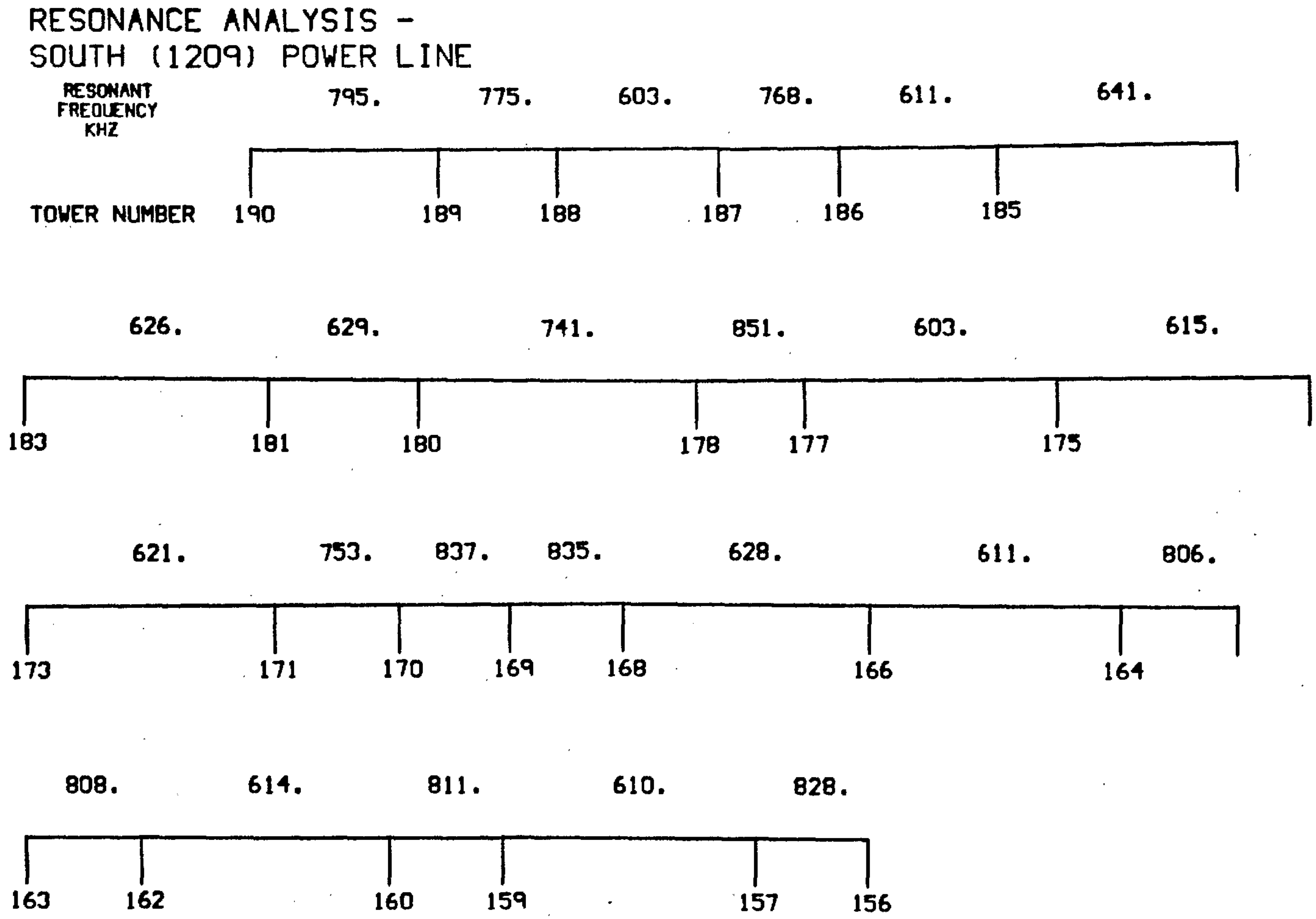


Fig. 5.5 (a) Resonance analysis of the southeast line with towers selected for isolation for the suppression of resonances.

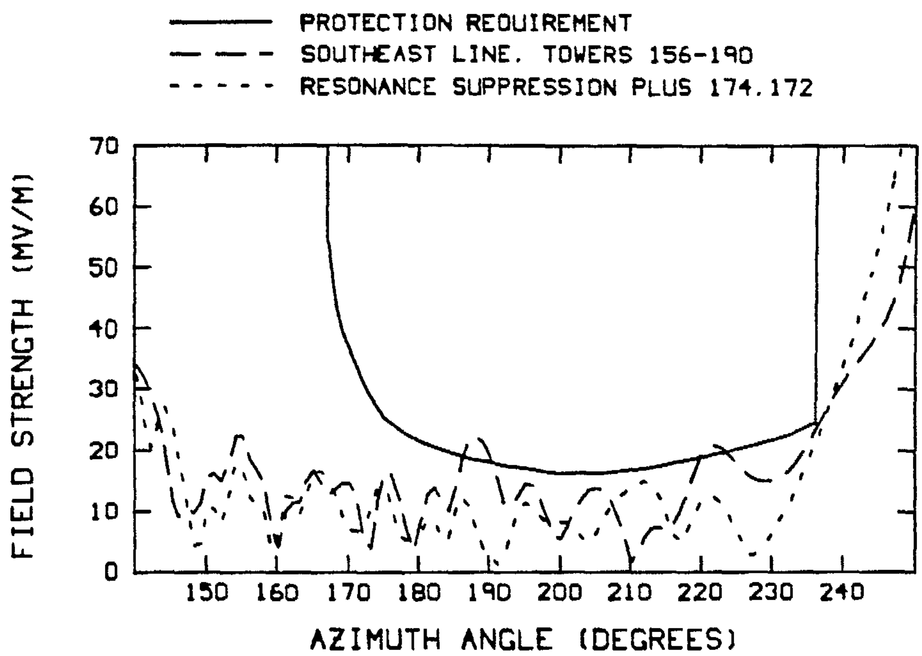


Fig. 5.5 (b) Field strength in the minimum with towers 156 to 190 of the southeast line, when towers 158, 161, 165, 167, 172, 174, 176, 179, 182, and 184 are isolated from the skywire.

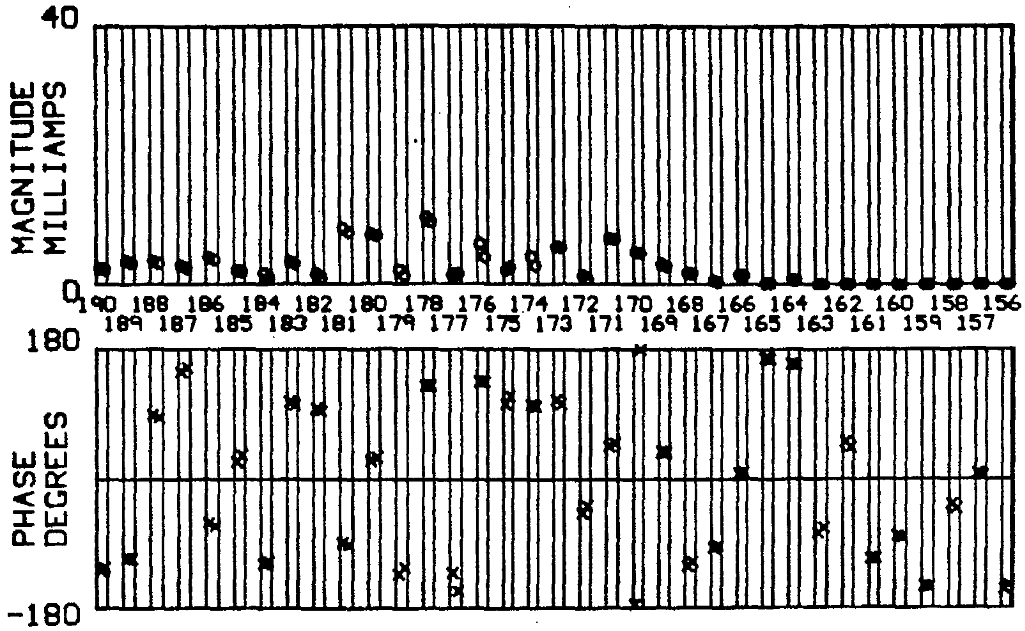


Fig. 5.5 (c) RF currents on the towers, with towers 158, 161, 165, 167, 172, 174, 176, 179, 182, and 184 isolated from the skywire.

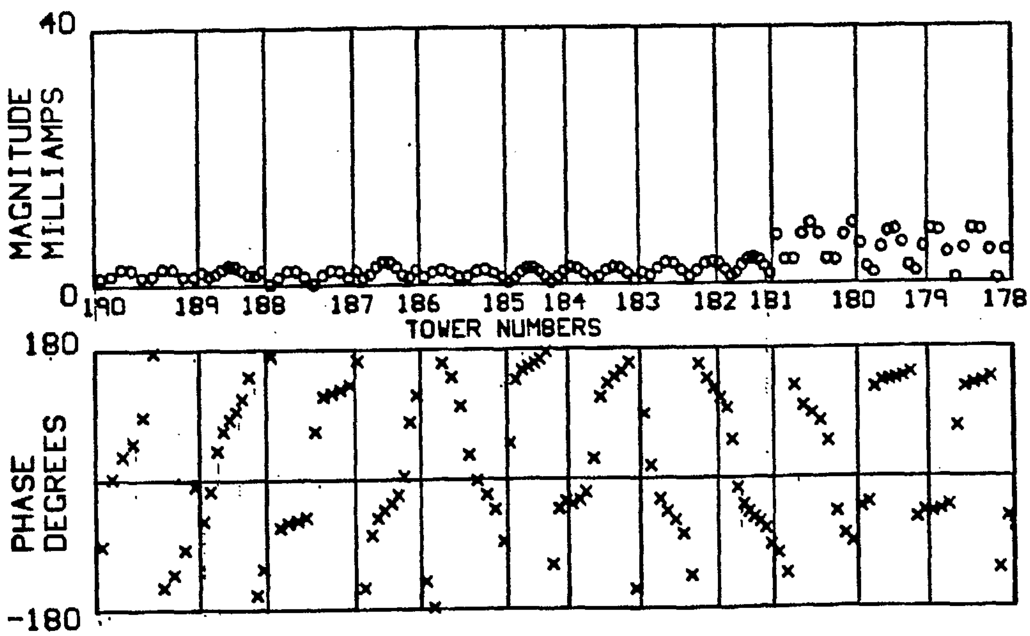


Fig. 5.5 (d) Currents on the skywires.

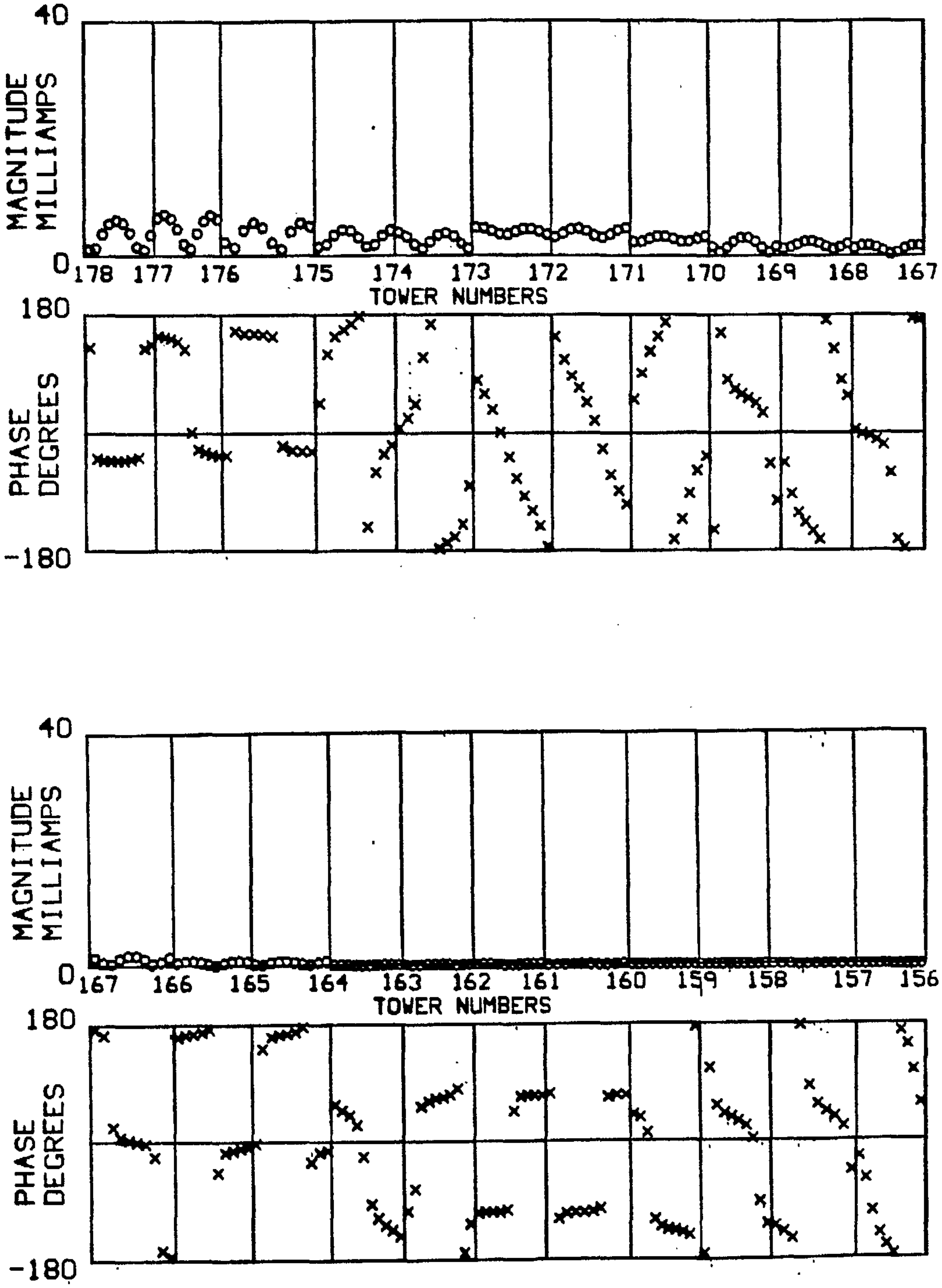


Fig. 5.5 (d) Continued.

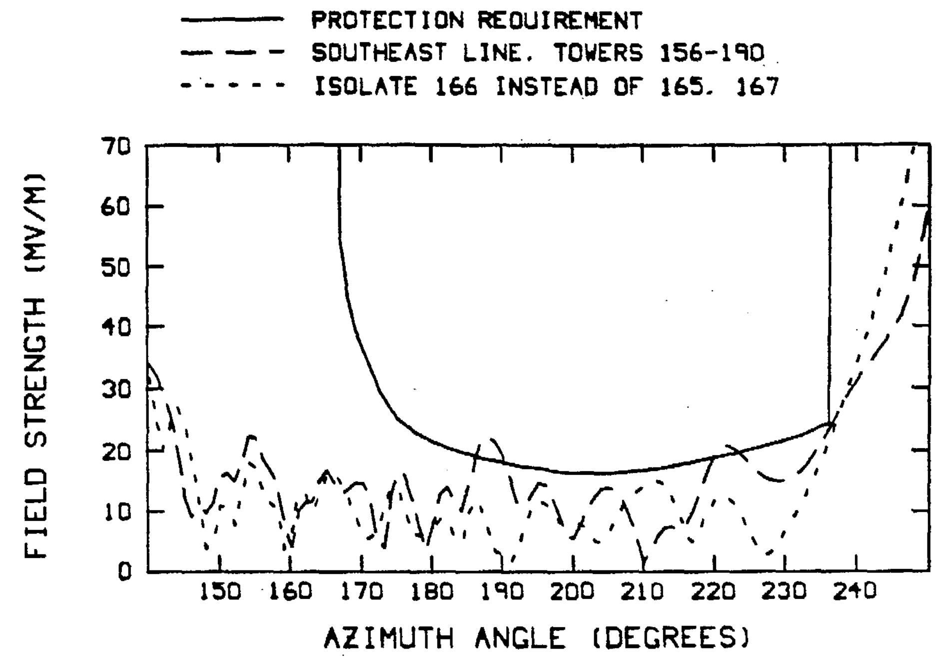


Fig. 5.6 (a) Field strength in the minimum with towers 156 to 190 of the southeast line, when towers 158, 161, 166, 172, 174, 176, 179, 182 and 184 are isolated from the skywire.

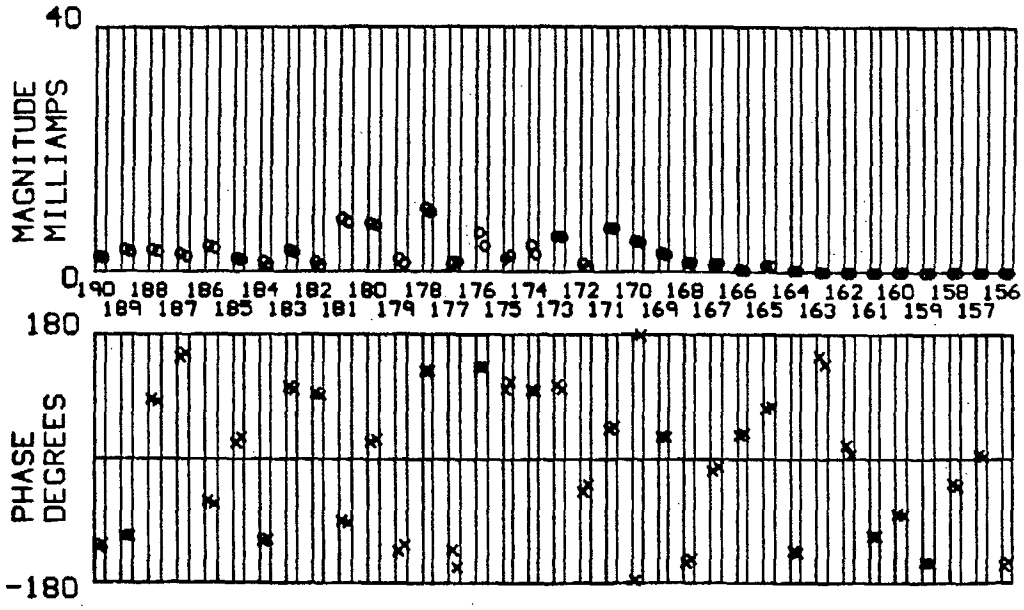


Fig. 5.6 (b) RF currents on the towers, with towers 158, 161, 166, 172, 174, 176, 179, 182, and 184, isolated from the skywire.

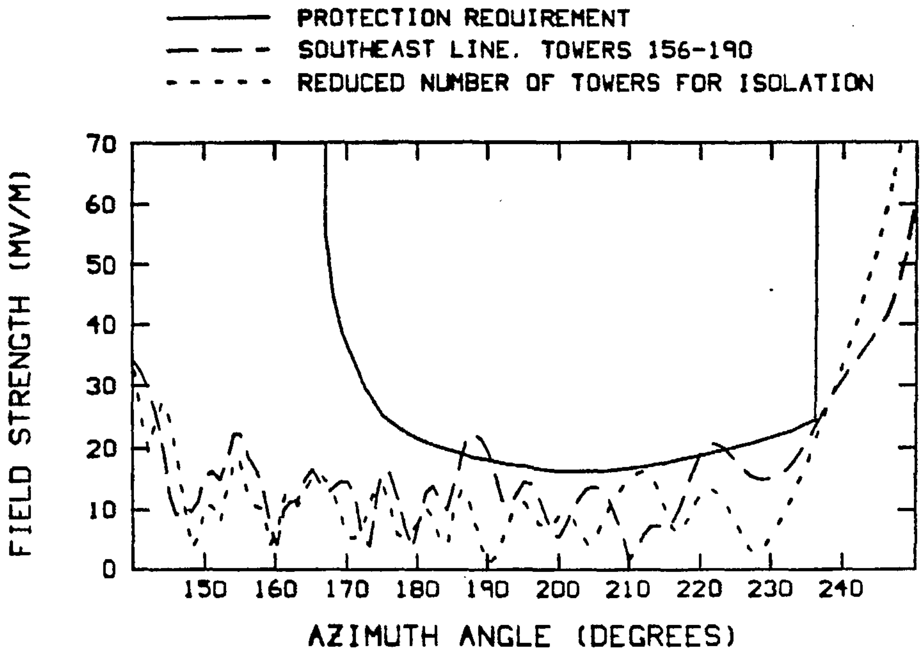


Fig. 5.7 (a) Field strength in the minimum with towers 156 to 190 of the southeast line, when towers 158, 161, 166, 172, 174, 176, 179, and 182 are isolated from the skywire.

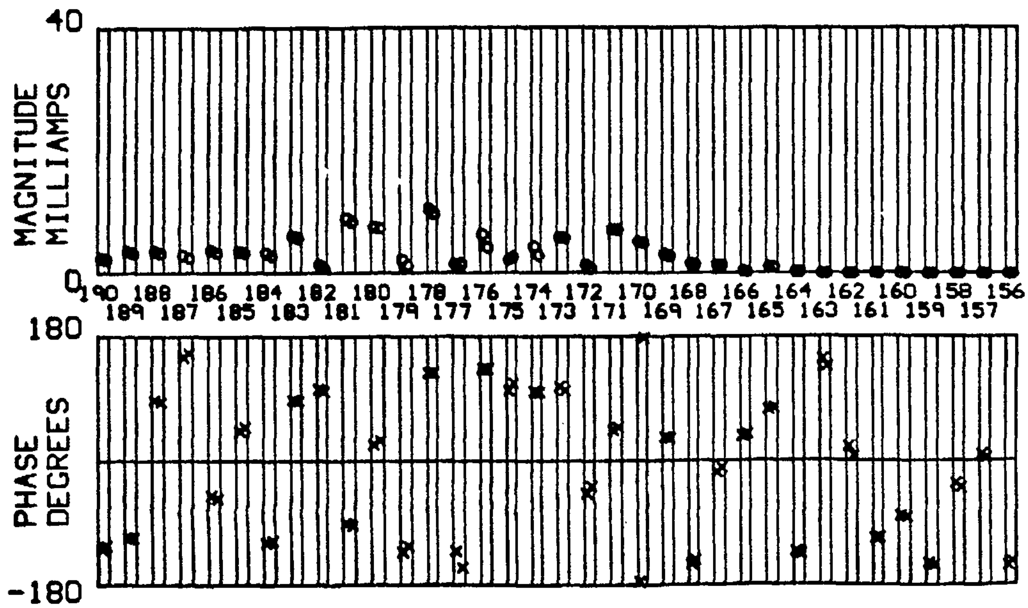


Fig. 5.7 (b) RF currents on the towers, with towers 158, 161, 166, 172, 174, 176, 179, and 182, isolated from the skywire.

Table 6.1 Classification of Towers for Isolation.
Group 1 Dominant towers.
Group 2 Secondary towers.
Group 3 Optional towers.

NORTH LINE

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

SOUTHEAST LINE

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