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EFFECTS OF POWER LINE RE-RADIATION ON THE PATTERNS OF A DUAL-FREQUENCY MF ANTENNA

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Abstract

A detailed computer simulation of AM broadcast re-radiation from a power line is described and the computations compared with measurements. The power line is in the vicinity of the London, England two-frequency directional antenna array of the U.K. Independent Broadcasting Authority. A simplified equivalent computational model is derived for the individual power line towers, and the ground effect due to the tower footings is estimated. The computational model includes the overhead ground wire (skywire) but excludes the power carrying wires. Computations are described for the power line induced currents and for the antenna radiation patterns as modified by the power line currents. The comparison of the computed results with full-scale radiation pattern measurements shows sufficient quantitative agreement to support the utility of computational predictions for power-line re-radiation. The frequency sensitivity of the re-radiation is studied theoretically and found to have a noticeable effect for deviations of $\pm$ 10 kHz.

Introduction

The scattering by re-radiating structures of AM radio signals in the medium-frequency broadcast band has progressively increased over the past few years. With the spread of urban population there has been a corresponding spread of urban structures, particularly high rise buildings. Other large structures such as electricity power lines and smoke stacks are to be found almost anywhere, not necessarily close to cities. Their dimensions can be of the order of a wavelength in the 500-1600 kHz broadcast band and thus they could be effective re-radiators of radio waves, creating an undesirable distortion in the radiation pattern of any MF transmitting antenna in the vicinity.

The broadcaster may have little choice but to build his station in proximity to such existing structures. Furthermore, he may find over the years a change or an increase in the number of these structures, all of which will be outside his control. The former problem has been encountered by the Independent Broadcasting Authority in the United Kingdom, and the resulting experimental and theoretical studies that arose will be of interest to those concerned with the increasing problem of scattering by large structures.

Historical Notes

Until 1972, radio broadcasting in the United Kingdom was provided at national and local level solely by the British Broadcasting Corporation, on a non-commercial basis. The MF services were transmitted from antennas generally having little or no directivity and furthermore those stations that shared the same channels within range of skywave interference from each other carried the same program.

The UK Sound Broadcasting Act of 1972 empowered the then Independent Television Authority (ITA) to establish an additional service of radio broadcasting as an alternative to that of the BBC. This would be purely for local as opposed to national coverage, in which major conurbations in the United Kingdom would be served by independent consortia on a self-financing commercial basis. The ITA, renamed the Independent Broadcasting Authority (IBA), would be responsible for building the transmitting stations and for ensuring that the various Independent Local Radio operators maintained specific standards for technical performance, advertising and program content.

Up to 60 independent MF stations were originally planned (37 of which are in service at present) and considerable re-use of the UK's available MF frequencies became necessary. The IBA, finding little or no experience in the UK and Europe of providing deep and stable co-channel protection nulls in MF antenna patterns, looked for examples and consultation to North America and the many thousands of highly directional arrays successfully being used to control co-channel problems.

One of the most valued franchises for commercial radio, of course, was Greater London. Two program companies were granted licenses to operate independently, necessitating two separate channels and implying two separate transmitting stations. The IBA could foresee very great difficulties in obtaining two antenna sites at suitable ranges and orientations relative to Central London, bearing in mind the high population density and the possibility of objections from nearby residents. Moreover, a considerable saving in costs would accrue from co-siting the services with a single transmitter building and antenna array, albeit that the antenna would itself be more complicated owing to dual-frequency operation.

With ten co-channel stations to protect in the UK - five on each frequency - it was required that groundwave nulls with depths of up to 24dB relative to the main lobe be provided at various angles to the north and west. A four-mast endfire array was required, occupying a ground-mat area of some 300 metres by 130 metres.

The expected difficulties of obtaining a site of this size were inevitably encountered. The station had to be within a reasonable range of the city in order to satisfy the criterion of "local" radio, but this would place it within the protected Green Belt of Outer London. Some 200 sites were investigated, most of which proved technically unsuitable or were contested by City Planning Authorities. Finally in 1973, a mere three sites emerged as possible candidates, and all three had high voltage electricity power lines passing close by.

The IBA had previous experience with power line re-radiation effects at a few directional-antenna installations. The resulting pattern distortion had turned out to be acceptable and no detuning of the support towers had been necessary. The London situation seemed by far the most severe, however, not the least reason being that two frequencies were involved. It was understood that in North America tower detuning (usually at single frequencies) was often undertaken in collaboration with the power companies but this appeared to be a very time-consuming procedure. The disturbing prospect arose in the minds of the engineers that the resulting re-radiation problem might require the towers to be detuned at two channels simultaneously. Detuning even a single channel was unprecedented in the UK, and the administrative delays in negotiating the technical details (as well as safety and maintenance matters) with the Electricity Board together with the time required to install and adjust detuners, would jeopardise

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the dates for which the commercial radio companies were geared to commence their operations.

Of overriding need was a computer model that would predict the re-radiation from power lines and pylons. None was available to the IBA at that time, so a first-order study was initiated as follows [1]. The proposed antenna sites were adjacent to power-line towers of various heights between 27 and 32 metres and about 500 metres away at their closest approach. At one site the lines would pass across in front of the main antenna lobe. At the other sites, the wires would be to the side and rear of the main lobe, but the situation was complicated by the presence of an isolated 24-metre steel tower, for clay pigeon shooting, 700 metres in front of the antenna in the main lobe. At each site, the mutual coupling between the antenna masts and the nearest 28 pylons was computed using the Induced EMF Method and assuming sinusoidal current distributions on all the vertical radiators. The four theoretical currents for the antenna masts themselves were the design currents prepared by the consultant for the antenna array in the absence of any re-radiators.

In order to make use of existing computer programs the re-radiating structures had to be assumed to be vertical radiators all of the same height as the masts, namely 71 metres. This first-order approximation was partly justified by the presence of the towers' horizontal top earth wires which, it was thought, would "top-load" them at MF frequencies, rendering them considerably higher electrically than their physical height. Horizontal currents were deemed not to contribute to far-field vertical polarisation in the groundwave signal, and were expediently ignored for the skywave contribution. That such currents might alter the pylon currents according to pylon spacing had to be totally ignored as well. Although the computer simulation left much to be desired it had the merit of providing insight into which of the pylons would probably carry the greatest induced currents and hence distort the nulls in the antenna pattern. Furthermore, by computing the radiation patterns from this giant array of 32 radiating sources (which included the four antenna masts) additional insight was gained into the extent to which the antenna patterns would break up into a series of minor lobes.

The towers were "grounded" by a top wire (for lightning protection) but their bases consisted only of the steel tower leg extensions set in concrete with no special grounding provisions. Therefore the base impedances of the towers were assigned various values on the order of 200 to 300 ohms magnitude with phase angles ranging between zero and -90 degrees. This had the merit that unrealistically large estimates of the base impedance magnitude could be made to offset the assumption of 71 metres physical height. Consequently the final step in establishing this very approximate computational model would have to be the adjustment of the base impedance values to produce a reasonable correspondence between the calculated and measured far fields. All pylons in this model had the same base impedance and therefore would re-radiate directly in proportion to the incident illuminating signal from the main antenna.

As one would expect, the predictions showed that regardless of the phase of the pylon base impedance (and hence the re-radiated phase) the resulting antenna patterns would be broken up in the null regions by up to a dozen narrow lobes at both channels. The computer model highlighted the probable limitations in the angular sectors over which nulls of sufficient depth could be established in the groundwave and skywave patterns. As a result, the site where pylons crossed in front of the antenna was shown to be untenable. On the other hand one of the other sites, while having not insignificant re-radiation, appeared to offer the hope that pylon detuning might in the end be dispensed with. The site was acquired 19 km north of Central London, and from its location the Antenna Pattern Specifications were derived, as shown in Table 1. It should be noted that all measurements and computations in this paper have been carried out at the pre-1978 European channel frequencies of 1151 kHz and 1546 kHz prevailing at the time. After November 1978 all European MF channels were changed to multiples of 9 kHz, the London station being retuned to 1152 kHz and 1548 kHz.

Antenna Commissioning in the Presence of the Power Lines

The antenna was commissioned in late 1974, the aim being to find the minimum backlobe levels achievable without detuning any towers. At 1546 kHz, relative to the main lobe, levels of -23dB toward Bristol on bearing 263° and -17dB toward other co-channel stations over the arc 315° to 350° (East of True North) were achieved and found to be acceptable. They were difficult to improve on and appeared to be limited by re-radiation effects much as had been predicted by the computer study.

At 1151 kHz, levels of -23dB were initially obtained over the arc 300° to 350°. However, it was critical that a level not higher than -24dB be established towards Birmingham over the arc 301° to 316°, and by further adjustments to the currents on the antenna masts a null of -35dB was generated toward central Birmingham with -24dB at the extreme edges of the arc. No tower retuning was necessary. The antenna has been in service in this condition since March 1975, and regular monitoring of critical nulls has revealed that whereas the -35dB null has drifted, particularly after the frequency change in 1978, the co-channel protection limits are still being met.

To measure the groundwave patterns in late 1974, field strength was plotted against range on 16 bearings at ranges typically from 1 to 20 kilometres, involving 240 monitoring locations. To obtain valid information about the depths of the nulls in the far-field over the arc 260° to 350°, the measurements had to be made at ranges of at least 10 kilometres in order to be ten times further from the antenna than those pylons that were believed to contribute the larger part to the re-radiation. (The investigation of the Birmingham null was carried out as far as Birmingham itself, 145 km away). Note: Where measured results are plotted in this paper the spread of uncertainty shown on the bearings 13° and 40° ETN reflects the very cursory examinations carried out in this angular sector, which has no significance to the service area or co-channel protection.

In the intervening years there has been no evidence of any addition, removal or relocation of the electricity pylons, so the IBA's re-radiation experience might have rested there, had it not been for the realization in 1978 that the use of general-purpose thin-wire computer programs [2] such as that of Richmond [3] might shed some light on this particular re-radiation problem. Recently other computer programs have also been used in the study of power-line re-radiation by Trueman and Kubina [4]. In addition, attention should be drawn to the pioneering work of Alford and French [5].

Computer Model Development

A computer model was developed in order to obtain some insight into the re-radiation problems experienced by IBA at the London site. The computations for the model were carried out using a slightly modified version of a computer program [3] which performs a frequency domain analysis of thin-wire antennas and scatterers. The wire structure can be any interconnection of straight wire segments. Piecewise sinusoidal expansion and testing functions are used in the process of solving numerically the integral equation for the current distributions.

The signal source is a set of ideal voltage generators at the bases of the antenna towers and the output data includes the current distribution, input impedances, radiation efficiency, total gain, near-zone fields, and radiation contribution to the total gain from the scatterers (this contribution is called "scattered gain" in this paper). "Gain" is in dB referenced to a short monopole.

The computer model consists of a four-mast array with specified base currents, a simplified equivalent power-line tower model, an overhead ground wire, and an approximate representation of ground effects due to tower footings. All wires are assigned a conductivity of 10^7 mhos/m.

The antenna array masts are 70.1 m in height and equally spaced by 61.0 m along a line oriented 159.6° east of north. A problem encountered when modelling such a structure stems from the fact that the thin-wire program accepts only voltages as input data and not currents. Therefore it was necessary to convert the specified base currents into the required voltages by calculating the admittance matrix Y and using $V = Y^{-1}I$, where V and I are respectively the base voltage and specified base current column matrices. Tables 2 and 3 show the voltages for the specified design currents and actual array currents, at the two frequencies of interest. In the tables, the specified currents are the original theoretical currents specified for the array, and the adjusted array currents are those measured at the mast bases subsequent to both some adjustment during commissioning and slight drift after commissioning. The adjustments are those already referred to in the introduction.

The power line towers varied in height and shape along the line. Their heights averaged approximately 30 metres and their widths at ground level averaged approximately 4.5 metres, and so these average dimensions were used to define a "typical" tower of the type depicted in Figure 1; in the computational model, all towers were taken to be identical and having these "typical" dimensions. The conductors consisted of an overhead ground wire (skywire) with diameter 1.4 cm and six power-carrying wires with diameter 1.93 cm (the latter not included in the computational model). Since the computer program allows only one wire thickness and since towers and skywire are of very different conductor thicknesses, an equivalent tower model using a thin wire with 1 cm radius was developed. A detailed tower computational model (Figure 2) was first designed so that it would be similar to the actual tower, and its re-radiation properties were computed for various strut radii ranging from 0.01 m to 0.2 m, with the expectation that the actual tower would be represented by strut radii between 0.1 m and 0.2 m. A simplified model (Figure 3) was then postulated and its dimensions obtained by comparing its scattered gain with the more complicated model both with and without a skywire. The procedure used to calculate the simplified model dimensions was suggested by M.A. Tilston (personal communication) and consists of three steps:

(i) short circuit the top of both models by attaching a skywire extending a quarter wavelength on each side of the tower top. Adjust the leg separation of the new model so that the scattered gains of both towers are matched.

(ii) open circuit the top of both towers by removing the skywires and attaching a pair of crossarms at the top of the new tower model. Adjust the arm length so that scattered fields are matched.

(iii) for verification repeat step one with the short crossarms now included in the simpler model.

Figures 4 through 7 show the scattered gains for the two tower configurations with and without the skywire. At 1151 kHz it was found that for the case without the skywire the scattered field produced by the detailed model with a wire radius of 0.2 m was approximately 0.5 dB larger than the one obtained for the same tower with wire radius of 0.1 m, and very close to the gain obtained for the simpler model. At the same frequency but for the tower with skywire, the discrepancy between the two scattered gains produced by the same model but different radii was 1.0 dB. Since these are two extreme cases ($\lambda/4$ skywire produces a high current at the tower top and no skywire produces a low current), one can say that the skywire thickness does not affect the scattered gains a great deal so that a comparison between different results can safely be made. At 1546 kHz a similar behaviour was noted, as follows. For the case without the skywire the scattered field produced by the detailed model with a wire radius of 0.2 m was approximately 0.8 dB larger than the one obtained for the same tower with a wire radius of 0.1 m and 0.25 dB different from the results of the simpler model. For the case with the skywire the discrepancy between the gains produced by the detailed model but with different radii was 0.9 dB, and the difference between these and the simpler model was 0.8 dB and 0.2 dB respectively. From these analyses, it was concluded that the triangular-frame computational tower model of Figure 3 is indeed a good choice.

The effect of a perfectly conducting ground may be taken into account by introducing the system's image into the thin-wire model. The problem becomes more complicated when a distributed ground of finite surface impedance is considered. Such a ground could not be simulated using the computer program available, so that only ground effects localized around the tower footings could be considered by representing each footing with a lumped impedance. Figure 8 shows an approximate representation for a tower ground connection, where ρ_o is the radius of the tower footing. Monteath [6] derived an expression for the change in input impedance Z'- Z when perfectly-conducting ground is replaced with ground having finite conductivity, where Z' and Z are respectively the input impedance in the finite and infinite conductivity cases. The expression is a function of the tangential magnetic field at ground level and the surface impedance. Since the magnetic fields for the towers are unknown an exact solution cannot be obtained for Z' - Z. So, instead, a "worst case" situation for re-radiation is assumed. This case is obtained if one assumes that the current distribution on the tower is the same as that of a thin vertical monopole antenna one quarter of a wavelength high and therefore having a current maximum at ground level. The surface impedance η is a function of the radius ρ and is given by

$$\eta = 0 \text{ for } \rho < \rho_o$$
$$= \eta_1 \text{ for } \rho > \rho_o$$

where η_1 is a constant (see Figure 8).

For the quarter-wavelength antenna and the above surface impedance the change in input impedance is

$$Z' - Z = \frac{\eta_1}{4\pi}\left[e^{-2j\beta_o\ell}\,\mathrm{Ei}\{-2j\beta_o(r_o-\ell)\} + e^{2j\beta_o\ell}\,\mathrm{Ei}\{-2j\beta_o(r_o+\ell)\}\right]$$

where $\ell = \lambda/4$ is the antenna height.

The values of Z' - Z were calculated for $\sigma = 11.5 \times 10^{-3}$ mhos/m, $\epsilon_r = 20$, $\rho_o = 0.144$ m. The results obtained for each tower leg were: for 1151 kHz, Z' - Z = 20.7 + j 13.4, and for 1546 kHz, Z'- Z = 23.8 + j 14.6. The impedance for the tower was then calculated by considering the impedances of the four legs as being in parallel. The values obtained were 5.17 + j 3.34 and 5.95 + j 3.66 at 1151 kHz and 1546 kHz respectively.

The clay pigeon tower is the isolated steel tower situated directly in the main beam. Due to its position so close to the antenna it is strongly illuminated and therefore it has quite large induced currents. This tower is 24.4 m in height and 6 to 7 m wide. Four computational models were considered, the first and second having configurations shown in Figure 3, with heights of 30.0 and 24.4 m respectively. The third and fourth models are depicted in Figure 9 with 6 and 7 m widths respectively. Table 4 shows the total base currents induced in each of the tower models. From this table one can see that, for the latter three lower models the current has approximately the same magnitude, and this value is lower, by as much as 30% at 1151 kHz and 40% at 1546 kHz, than that for the first model. However, the actual clay-pigeon tower had three fairly extensive metal shooting platforms near the top, the effect of which would be to raise the effective height, so it was judged that model # 1 would be the best representation to use.

The relevant part of the power line was taken to extend over a region with a 1 km radius. Figure 10 shows the towers' positions with respect to the antenna array for a radius of 2.5 km. The route PFB is located mostly on the main lobe and therefore all of it was included in the model. The route PMD, although located across the back lobe, was also considered in part by including PMD 26 to PMD 29, plus PF 70; the clay pigeon tower is also shown. The computational model of the power line extended for about 3600 meters in total length.

Calculations Using the Specified Antenna Array Currents

The first set of calculations was done for the antenna array with the originally specified base current distribution. All towers were modelled similarly and no footing impedances were included. The power line tower base current magnitudes shown in Figures 11 and 12 were observed to be highest at the towers PFB 4 to 6 at 1151 kHz and PFB 3 to 6 at 1546 kHz. The lowest currents at 1151 kHz occur from PMD 26 to PFB 3 and PFB 7 to PFB 9. The lowest currents at 1546 kHz occur from PMD 26 to PFB 2 and PFB 7 to PFB 9. These current distributions appear reasonable, to judge from Figures 13 and 14 in which the total and scattered gain patterns have been plotted with the power line and clay pigeon tower locations superimposed. From the graphs one can see that the low currents were obtained for those towers which are either in the back-lobe direction or located farthest from the antenna array. The computed total gains are also plotted in rectangular coordinates in Figures 15 and 16, which include the effects due to a finite ground conductivity as represented by the values of footing impedance already discussed. With footing impedances included, a small decrease in the maximum currents was observed at 1151 kHz (Figure 11), but no appreciable changes in the currents were observed at 1546 kHz (Figure 12). As for the ground effects on total gain, it was noted that at 1151 kHz the minor lobe peaks were changed by less than ½ dB (Figure 15) while at 1546 kHz no effect was noticeable. These results show that the tower footing impedances have little effect on the system's total gain, so that, for the calculations to follow, the computer model did not include footing impedances.

Frequency Sensitivity

The second set of calculations was done for the array with the specified base currents but for frequencies of 1151 ± 5 and ± 10 kHz, and 1546 ± 5 and ± 10 kHz. The scattered gains were calculated and compared with the results for 1151 kHz and 1546 kHz. It was found that the scattered field magnitude did not change significantly but all the scattered lobes were shifted by angles of about 10°. The total gains were also computed and the results for the ± 10 kHz cases are shown in Figures 17 and 18. These results show changes of the order of 2 dB in minor lobe levels, changes which are large enough to indicate the importance of multi-frequency computations in the analysis of re-radiation problems.

Calculations Using the Adjusted Antenna Array Currents and Comparison with Measured Data

The adjustment of the antenna array base currents during commissioning has already been described, the purpose of the adjustment being to satisfy the protection requirements without resorting to detuning of the power line. After the adjustment, there followed a short period of time in which some drift in the system phasing occurred. Then, the array base currents were recorded and a set of far-field measurements taken by IBA. These currents, comprising the "adjusted" set already described, were used in the calculation of the radiation patterns shown in Figures 19 and 20. The same figures also show the measured data. Agreement at both frequencies between theory and experiment is seen to be excellent over the main lobe and fairly good in the minor lobes. It is clear from the calculations and measurements that a small angular shift in the minor lobes would result in the protection levels being exceeded.

Conclusions

The agreement between theory and experiment is evidence that moment-method thin-wire computational methods are useful in analyzing the re-radiation from power lines and lattice towers adjacent to directional MF antenna arrays.

The frequency sensitivity of the re-radiated field has been analyzed, showing that in this case there is a quite noticeable variation over ± 10 kHz. This establishes the importance of checking frequency sensitivity in all re-radiation calculations.

Ground effects which are localized near the tower bases have been estimated and included in the calculations as equivalent base impedances. In this case, ground effects proved to have a negligible effect on the re-radiated field, but this conclusion does not necessarily apply to other situations where resonances in power line cells might be significantly reduced in amplitude by ground effects.

This work demonstrates a logical method for building up an electromagnetic computational model for a power line. The model employs a minimum of struts to represent accurately a complex lattice tower, thereby minimizing the costs of performing the re-radiation computation.

The practical example studied is a "borderline case" in which power line re-radiation is strong enough (in relation to protection requirements) to necessitate curative measures in the form of antenna array adjustments, but it is not so strong as to require the attachment of detuning devices to the power line. Therefore this description of such a borderline case could be useful to others who must decide how to classify and solve existing or potential re-radiation problems of their own.

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Table 1 - Antenna Parameters

SPECIFICATION*		1151 kHz		1546 kHz	
		ERP	Direction	ERP	Direction
Groundwave service area	ERP to central London Minimum ERP at ± 80°	+14 dBkW 0 dBkW	160° ETN 80° to 240°	+20 dBkW +5 dBkW	160° ETN 80° to 240°
Co-channel protection	Maximum ERP Maximum ERP	-10 dBkW -5 dBkW	301° to 316° 324° to 348°	0 dBkW +5 dBkW	261° to 265° 315° to 348°

* An ERP of 0 dBkW represents a field strength of 300 mV/m at 1 km from the antenna, under lossless propagation conditions.

Table 2 - Antenna Array Base Currents and Equivalent Base Generator Voltages at 1151 kHz

(Currents are relative, with respect to one mast current having an arbitrary reference value)

Mast	Specified Currents	Voltages	Adjusted Currents	Voltages
1	0.100/0°	-5.88 +j49.9	0.0302/236°	13.0 - j6.08
2	0.345/121°	-79.7 - j23.3	0.100/0°	5.60 +j23.2
3	0.347/248°	48.0 - j37.2	0.101/130°	-16.2- j7.36
4	0.127/13°	0.128 +j13.8	0.0358/256°	3.35 - j1.60

Table 3 - Antenna Array Base Currents and Equivalent Base Generator Voltages at 1546 kHz

(Currents are relative, with respect to one mast current having an arbitrary reference value)

Mast	Specified Currents	Voltages	Adjusted Currents	Voltages
1	0.100/0°	86.6 + j128	0.0690/262°	73.5 - j69.7
2	0.175/106°	-196 + j13.1	0.100/0°	38.4 +j107
3	0.130/210°	30.9 - j111	0.0850/106°	-81.2+j1.68
4	0.0358/305°	27.3 + j11.9	0.0320/211°	11.9 - j26.2

Table 4 - Total Induced Base Currents in Various Computational Models for the Clay Pigeon Tower

(The specified antenna base currents have been assumed: see Tables 2 and 3)

Model No.	Current Magnitude at 1151 kHz	Current Magnitude at 1546 kHz
#1	2.09 mA	5.41 mA
#2	1.45 mA	3.25 mA
#3	1.38 mA	3.22 mA
#4	1.49 mA	3.52 mA

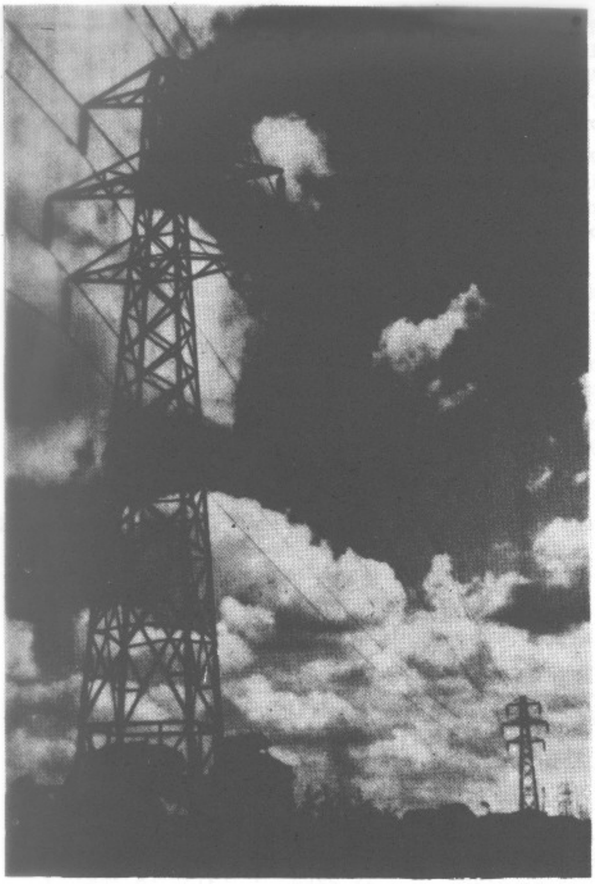

Fig.1 Typical tower found along power line.

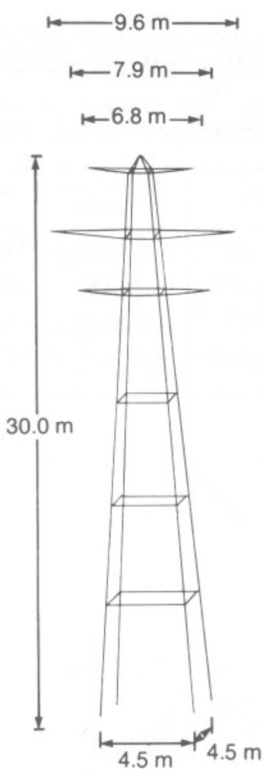

Fig.2 Detailed computational model of power line tower.

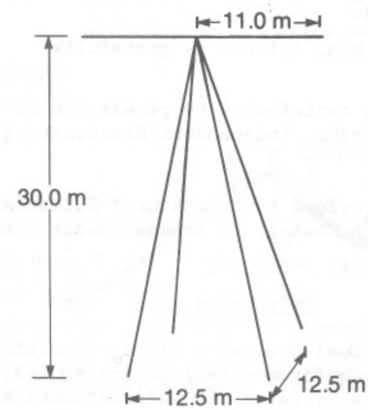

Fig.3 Equivalent simplified tower model (6 segments).

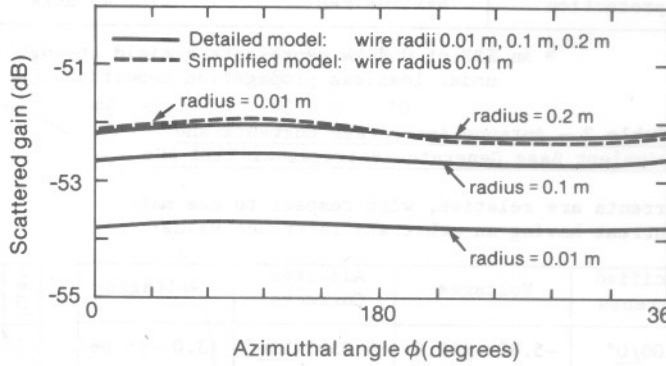

Fig.4 Scattered gain at 1151 kHz for the detailed and simplified tower models without skywire.

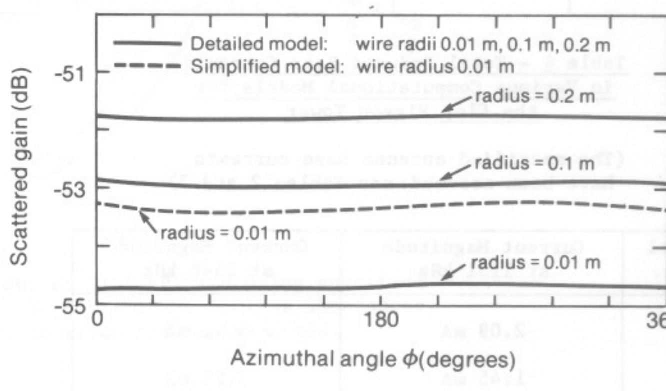

Fig.5 Scattered gain at 1151 kHz for the detailed and simplified tower models with skywire.

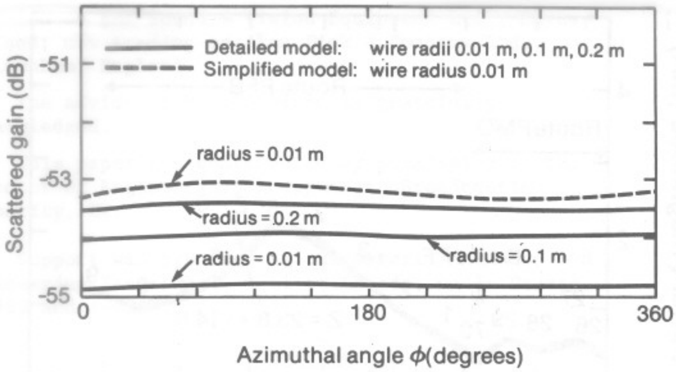

Fig.6 Scattered gain at 1546 kHz for the detailed and simplified tower models without skywire.

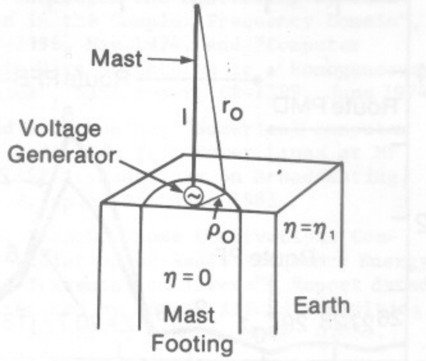

Fig.8 Power line tower ground connection: this is the situation analyzed to determine lumped base impedance.

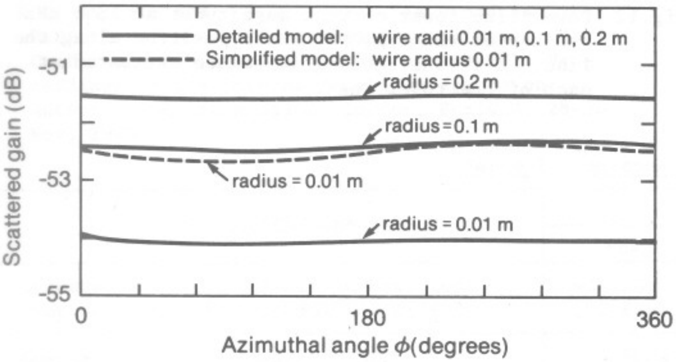

Fig.7 Scattered gain at 1546 kHz for the detailed and simplified tower models with skywire.

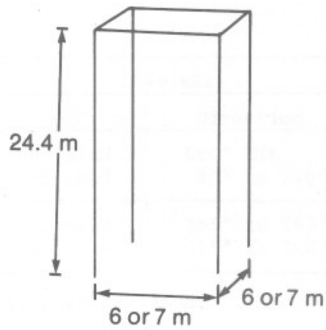

Fig.9 Third and fourth clay pigeon tower models (8 segments).

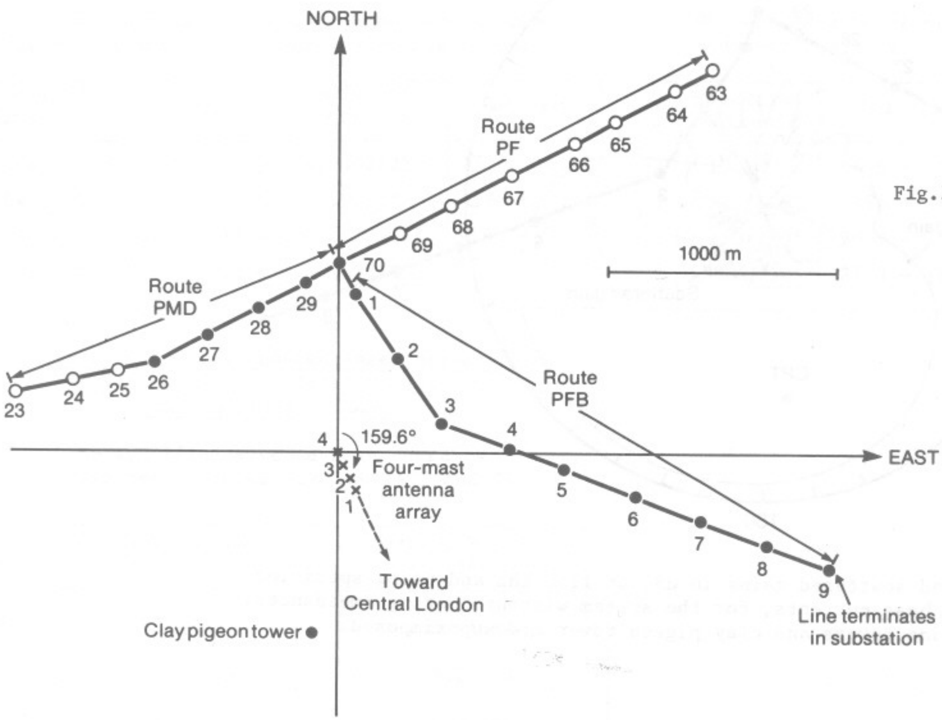

Fig.10 Layout of power line towers and clay pigeon tower relative to antenna array. Solid dots indicate towers included in computational model.

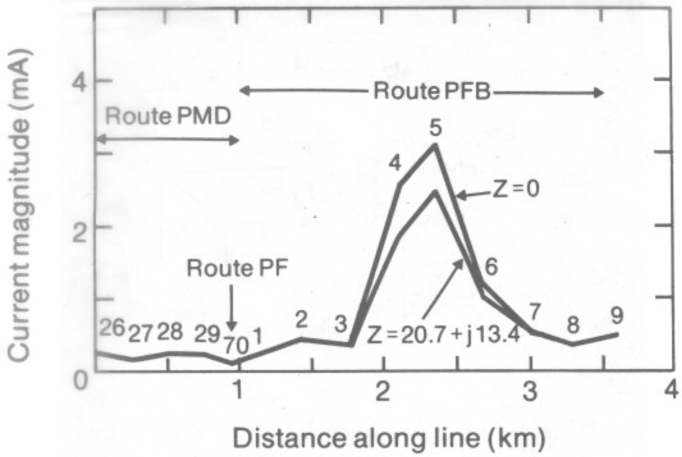

Fig.11 Power line tower current magnitudes at 1151 kHz for one of the legs vs. tower position along the line. Z is the footing impedance estimated at each of the tower legs.

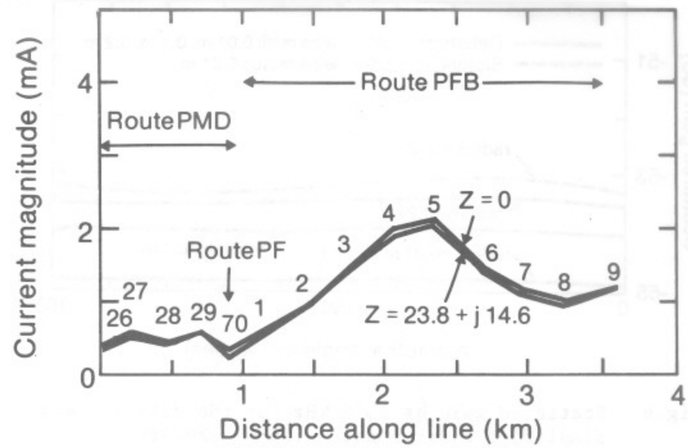

Fig.12 Power line tower current magnitudes at 1546 kHz for one of the legs vs. tower position along the line. Z is the footing impedance estimated at each of the tower legs.

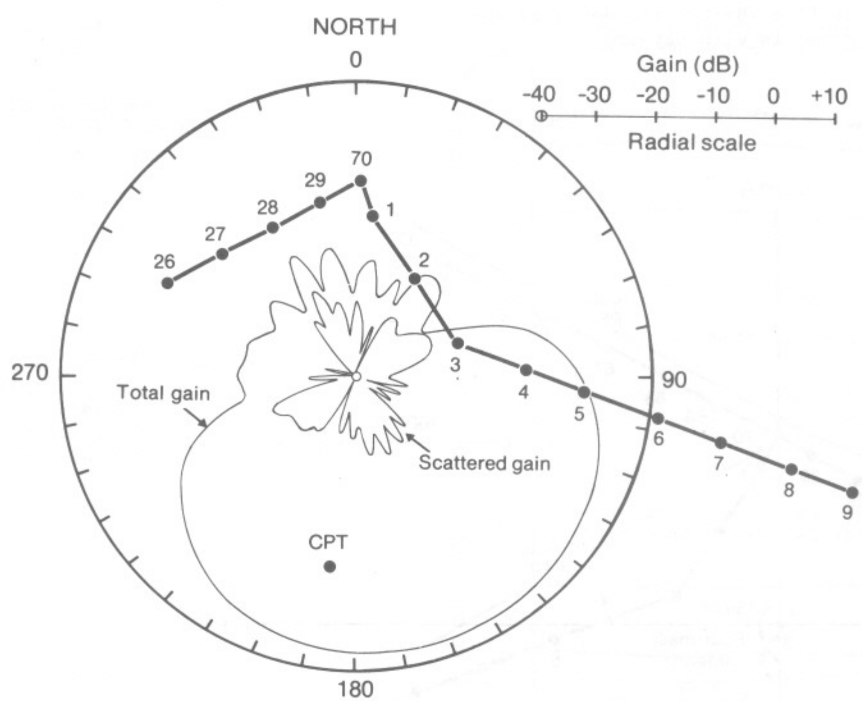

Fig.13 Total and scattered gains in dB, at 1151 kHz and using specified antenna base currents, for the system without footing impedances. Power line towers and clay pigeon tower are superimposed.

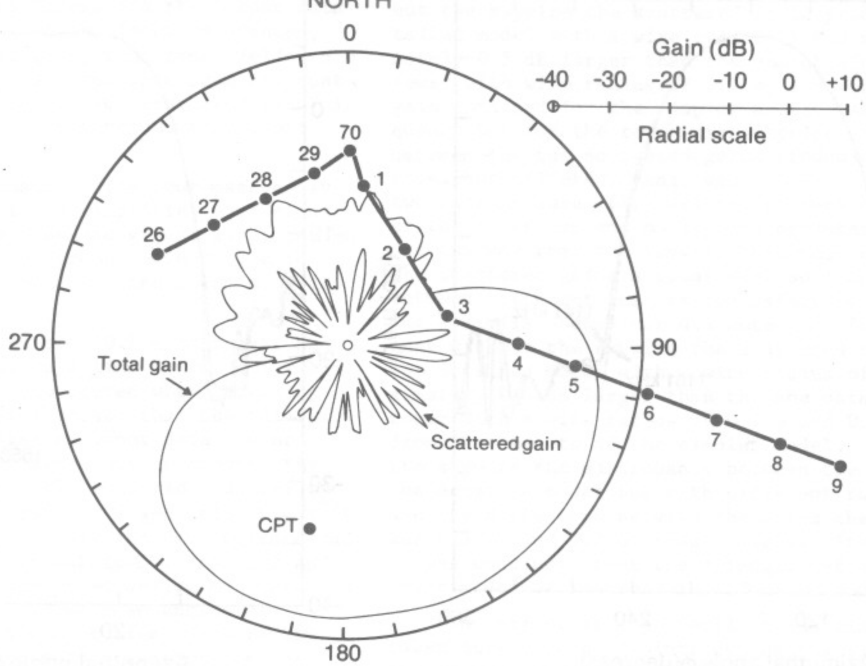

Fig.14 Total and scattered gains in dB, at 1546 kHz and using specified antenna base currents, for the system without footing impedances. Power line towers and clay pigeon tower are superimposed.

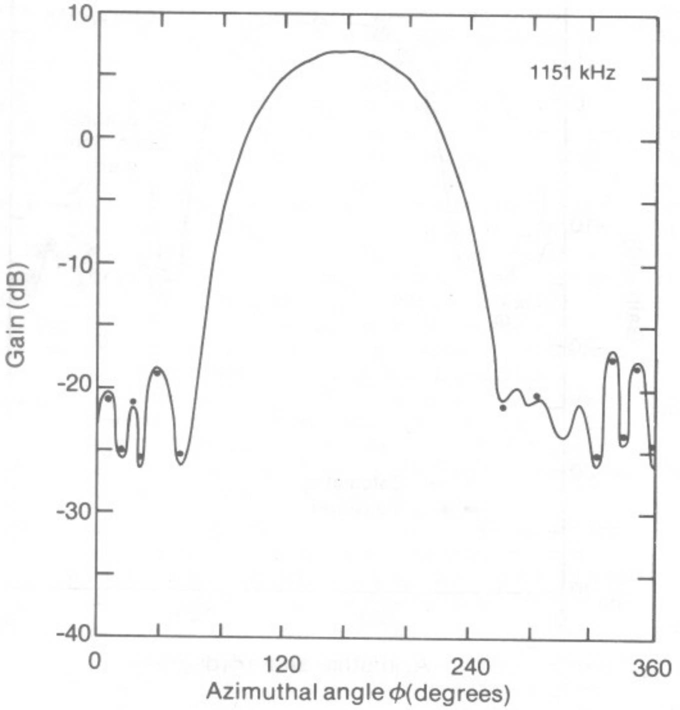

Fig.15 Total gain computed at 1151 kHz, neglecting footing impedances and using specified antenna base currents. Dots indicate influence of including footing impedances on height of minor-lobe maxima and minima.

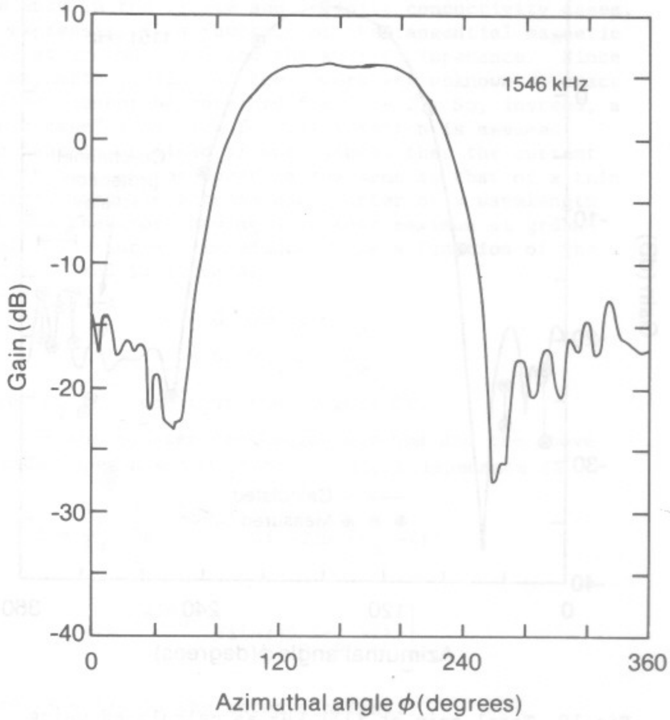

Fig.16 Total gain computed at 1546 kHz, neglecting footing impedances and using specified antenna base currents. The introduction of footing impedances had a negligible effect at this frequency.

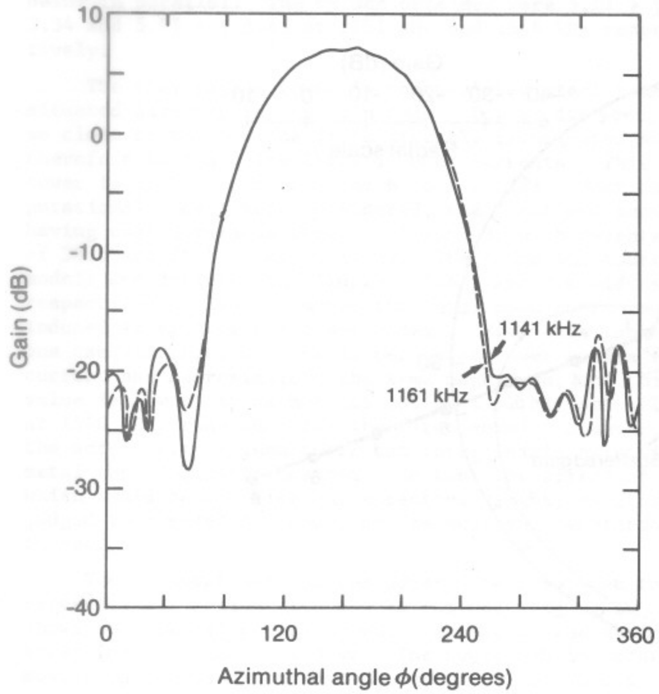

Fig.17 Total gain computed at 1151 ± 10 kHz, neglecting footing impedances and using specified antenna base currents.

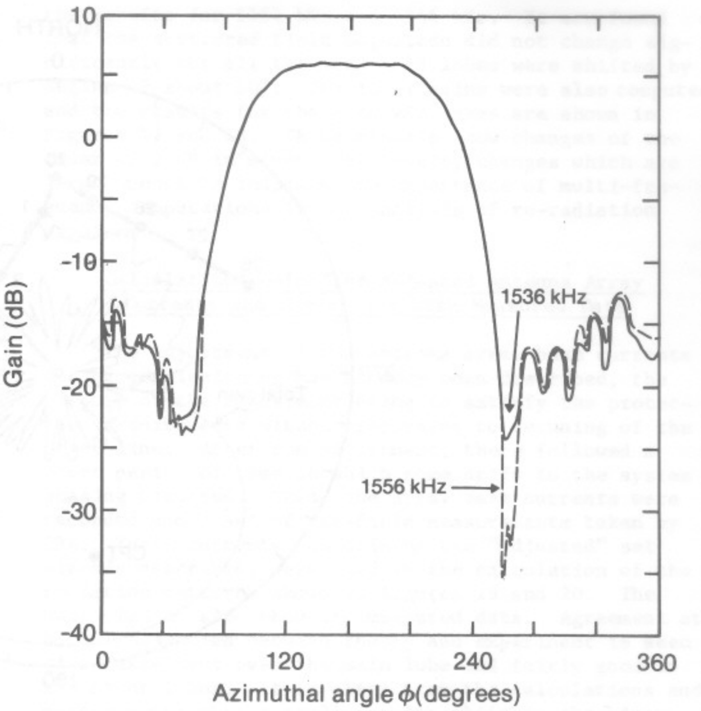

Fig.18 Total gain computed at 1546 ± 10 kHz, neglecting footing impedances and using specified antenna base currents.

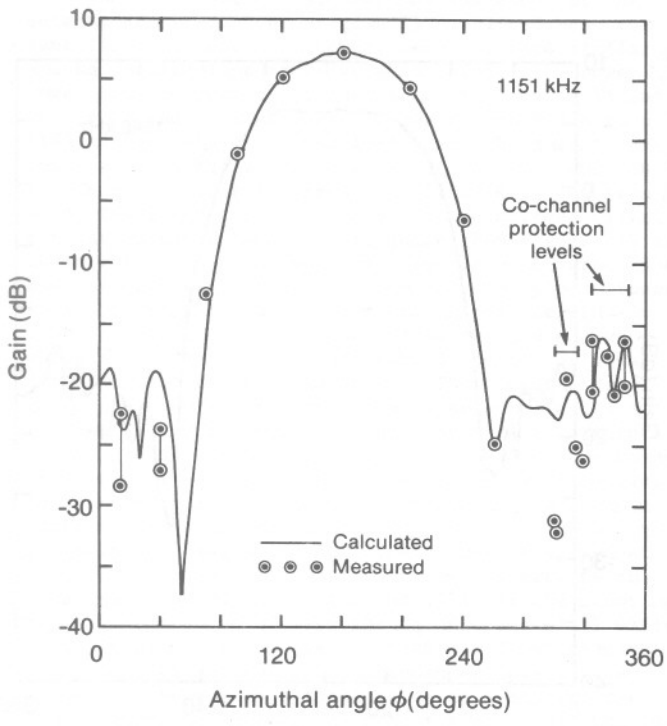

Fig.19 Total gain at 1151 kHz as calculated using adjusted antenna base currents (solid line) and as measured (points). Co-channel protection levels are indicated.

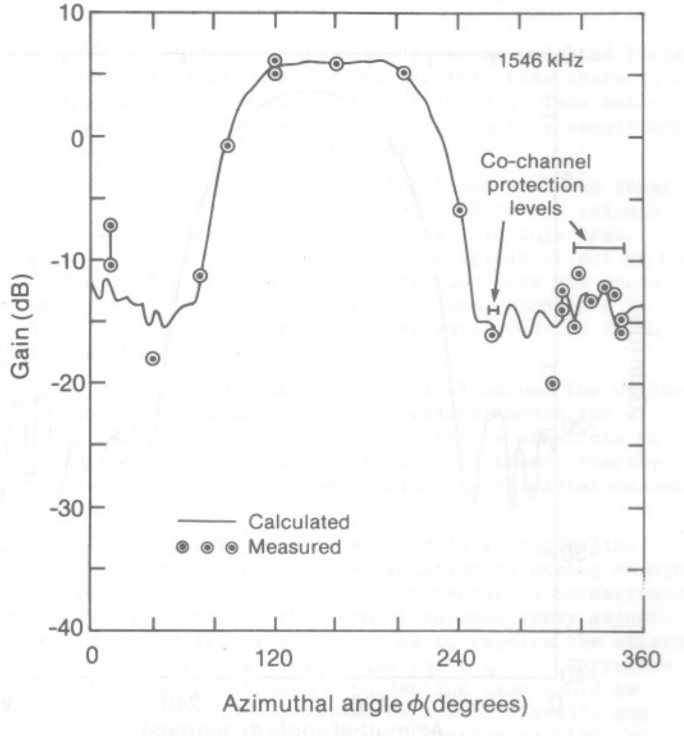

Fig.20 Total gain at 1546 kHz as calculated using adjusted antenna base currents (solid line) and as measured (points). Co-channel protection levels are indicated.