VLF/LF Transmitting Antennas

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1. Introduction

VLF transmitting antenna design is a specialized field of engineering that requires the combined skill of radio, civil and mechanical engineers. The antenna systems used for this band (15-30 kHz) are enormous structures; vertical radiators with very extensive top-loading (non-radiating top-hats), necessary because the electrical height of practical towers is small. For tower heights of 300-450 metres (1000-1500 feet) the electrical heights are only fifteen to forty-five one thousands of a wavelength.

Various types or classes of antennas are presently in operational use. Some of the common types are: inverted-L antennas; T-antennas; multi-wire diamond antennas and paralleled combinations of diamonds; down leads from long catenaries with mountain top support (e.g. the USN Jim Creek, WA station); and the fjord mountain antenna, Narvik, Norway are employed. There are about as many configurations as there are antennas [Watt, 1967; Belrose, 1983].

Three very large VLF antennas are more or less scaled versions of each other. These are the USN stations at Cutler, ME and North West Cape, Australia; and the NATO VLF station at Anthorn, England. The top-loading consists of 6-diamond shaped wire panels, see Fig 1, supported by 13-towers of heights 243 - 390 metres high.

While indeed a high radiation efficiency is achieved (> 80% for the USN antennas operating in the 20-30 kHz band), for a new installation, in the authors view, this is not a good antenna design for the following reasons:

1) There are too many tall grounded towers;

2) Even for the largest antenna (the NWC antenna) the effective height of the antenna system is only about one-half the average height of the 13 towers. The decrease is attributed to the sag on the top loading structure, and to the many grounded towers with their extensive guy systems;

3) The top-loading contains many wires, too many wires for places where wind loading is a problem, and too many wires to ice up in a Canadian environment;

4) The star like configuration results in six sharp points, and while this forms a nice snow-flake-like pattern viewed from above, sharp points should be avoided, because of corona problems with the high transmit powers employed. It is clear that precautions were taken to avoid corona, note the large corona rings (Fig. 2);

5) The operational bandwidth, except for the largest, the NWC, Australia antenna, is less than that required for 4-channel MSK (a 200 Hz bandwidth is required). The NWC Australian antenna system is a very large installation. The outer ring of towers for this station are on a diameter of 2.5 kilometers. The problem with bandwidth is particularly a problem for the smallest of the three antenna systems Anthorn. In fact Anthorn employs bandwidth resistors, resulting in a loss in radiated power, in order to realize even a 100 Hz bandwidth.

2. A Need to Overview Antenna Design Concepts

The purpose of a study recently carried out at the Communications Research Centre was to search for new concepts, or revisit old ones; e.g. multiple tuning, an early concept [Alexanderson, 1920], to improve the radiation efficiency and bandwidth of VLF/LF antennas. During the course of the study the author had the opportunity to visit the German Navy VLF Station at Rhauderfehn, near Hanover, Germany. This station employs eight 352.5 m umbrella top-loaded antennas. Each antenna is tuned and separately fed. Since the spacing between the antenna elements is small with respect to a wavelength, the eight elements radiate "in phase", and the far field radiation pattern is omni-directional. In effect this antenna system is a "radiation coupled multiple tuned antenna array". This configuration intrigued the author, and so even prior to his visit to the station he decided to carry out a detailed study (by numerical and experimental modeling) of a simplified version of such an antenna system, for comparison with a more conventional multiple tuned antenna system.

During the course of the study, five antenna types were considered, some of which were modeled in more detail then others. These were:

1) Conventional antenna systems, like the Anthorn/Cutler/NWC Australia VLF antennas;
2) A single tall umbrella top-loaded radiator;
3) A transmission-line radiator;
4) Radiation coupled multiple tuned antenna arrays (similar in principle to the Rhauderfehn VLF antenna); and
4) Multiple-tuned folded unipole type of antenna arrays (to be described).

Multiple tuned-antenna systems is a principle subject of my paper.

3. Antenna Fundamentals

The input impedance of an electrically short top-loaded vertical radiator $Z_a = R_a - j X_a$. This is the impedance that must be tuned and matched to the characteristic impedance of the transmission feeding the antenna, and to the transmitter output impedance. The antenna resistance R_a (sometimes labeled R_b to indicate that the antenna is base fed) is the sum of the radiation resistance R_r and the ground loss resistance R_g, referenced to the feed point. The resistance R_c of the tuning coil or helix must also be included, and this further increases the antenna system resistance $R_{as} = R_a + R_c$.

The radiation resistance R_r is an important parameter, since the radiated power is

$$P_r = I_a^2 R_r$$

where I_a is the antenna current.

The radiation efficiency η is equal to

$$\eta = \frac{P_r}{P_t}$$

where P_t is the transmitter power.

Since R_r is small for conventional VLF antennas, typically less than 1 ohm, the loss resistances must be small with respect to the radiation resistance for an acceptable radiation efficiency. The loss resistances are the ground loss resistance R_g, and the RF resistance of the tuning coil or helix R_c.

$$\eta = \frac{R_r}{R_r + R_g + R_c} = \frac{R_r}{R_{as}}$$

where R_{as} is the antenna system resistance.

The antenna system bandwidth, for VLF/LF antennas, when the antenna's base reactance $X_a >> R_{as}$ is

$$BW_{as} = \frac{f}{Q_{as}} = \frac{R_{as} f}{X_a}$$

since $Q_{as} = \frac{X_a}{R_{as}}$

This formula is an approximation and valid only if the antenna is electrically small and its operating frequency f is low compared to the resonant frequency f_0 of the antenna system. The general formula is

$$BW_{as} = \frac{R_{as} f \, [1 - [\frac{f}{f_0}]^2]}{X_a}$$

This is the bandwidth of the antenna system. When connected to a transmitter the operating bandwidth is increased by a factor of 2. When a signal source (an RF amplifier) is required to deliver power to a load (the antenna system), the power transfer will be a maximum when the load impedance is the complex conjugate of the source impedance. Matching therefore reduces the antenna system Q by a factor of two, and so doubles the bandwidth. However, the the bandwidth calculated above from circuit theory, is the 3dB bandwidth. A more practical operational bandwidth of the antenna system is less than this; more typically the antenna's bandwidth is increased by a factor of 1.5. Hence the operational band width

$$BW_{op} = 1.5 \times BW_{as}$$

An alternative definition of bandwidth useful for numerical modeling is the predicted bandwidth for an arbitrary VSWR, say 1.5:1. This bandwidth is calculated for the numerical model by change of frequency. VSWR is measured with respect to the resonant antenna system impedance. Since the transmitter's RF amplifier is conjugately matched to its load, the antenna system, the operational bandwidth is twice the antenna system bandwidth.

Another important parameter is antenna potential. The base voltage for an electrically short antenna is

$$V_b = I_a X_a$$

The maximum potential existing on the antenna due to potential build-up from its standing-wave potential-distribution pattern is

$$V_{as}(max) = \frac{V_b}{\cos\theta}$$

where θ = electrical height of the antenna system at the operational frequency f

$$\theta = \frac{f}{f_o}\, 90^o$$

4. Tools For Antenna Modeling

The numerical modeling studies employed the numerical electromagnetic codes NEC-3 and MININEC. Menu driven versions of MININEC, ELNEC and MN are easier to use---we used ELNEC [Belrose, 1992]. The experimental modeling studies were conducted by fabricating a detailed model of the antenna, sometimes including insulated guys, using a scale factor of 1000 for VLF antennas. That is towers 300 meters in height scale to a modeled rods 30 centimeters high, and a full scale frequency of 25 kHz scales to 25 MHz.

4.1 Measuring Antenna System Impedance

The experimental models were placed on a 30 metre diameter elevated ground plane (Fig. 3), so that the instruments to measure impedance and the effective height of an antenna under test could be deployed from beneath the wire grid ground plane (Fig. 4). To measure impedance either a Hewlett-Packard RF Impedance Analyzer Model 8505A or a HP Network Analyzer Model 4194A was employed. The latter instrument was used with a probe (a HP 41194A) so that the impedance could be measured right at the base of the model antenna; or the effect of the measurement coaxial cable could be taken into account using the former instrument.

The modeled antennas were very small with respect to the size of the ground plane, but the radius of the ground plane (15 metres) was not large with respect to the wavelength at the modeling frequency (wavelength 12 metres for a frequency of 25 MHz). Edge effects, because the ground plane was finite affect particularly the measured resistance. The effect on measured reactance is small, since the effective capacity of the ground plane is very large with respect to the capacity of the antenna system. But there is another problem with modeling electrically short antennas. Since the base capacity of the antenna system at the model frequency is small, the base insulator capacity of the model becomes important.

4.2 Measuring Antenna System Radiation Resistance

The radiation resistance is not so easily measured. We have used three methods. Whatever method is employed, measurements have to be made with great precision to achieve accuracy, since the radiation resistances are small (for conventional VLF antennas < 1 ohm).

The three methods that we have used are:

4.2.1 Antenna under test as a Receiver

The effective height of electrically short antennas, but not tuned antennas such as a multiple tuned antenna array, can be determined by measuring the open circuit voltage of the antenna under test (AUT), using the antenna as a receiving antenna. A signal was radiated (using a Hewlett Packard Model 3335 Tracking Synthesizer) from a small loop antenna at the edge of the ground plane. The open circuit voltage was measured using a HP Level Meter Model 3586C with a HP 1124 active probe. The effective height is determined by a comparison with the measured open circuit voltage for an antenna of known effective height. We used a 1-metre whip as the reference antenna.

The input impedance of the probe must be known. In our case the HP active probe had input impedance of 1 MΩ in series with a 10 pf capacity.

The open-circuit voltage of an antenna is

$$V_{oc} = h_e\, E_i\ \mu V$$

where h_e is the effective height of the antenna (in metres); and E_i is the incident field strength (in μV/metre).

The reference antenna was a 1 meter whip, whose effective height is known (0.5 m), and so the effective height of the antenna under test can be determined from the difference between the open-circuit voltages of the antenna under test compared with the reference antenna.

The problem with this technique is that the precision of measurement has to be very great, and all parameters have to be accurately measured and taken into account. The reference antenna's capacity was small (our's was 12.4 pf---calculated value); hence the feed through capacity of the base insulator for this reference antenna becomes important (our feed through insulator capacity was 4.6 pf). Any error in the measurement of h_e is squared, since

$$R_r = 160\,\pi^2 \frac{h_e^2}{\lambda^2} \text{ ohms}$$

We have estimated that the accuracy in determining R_r using this method of measurement was something better than a factor of two.

4.2.2 Antenna under test as a Transmitter

A second method is to use the antenna under test as a transmitting antenna. The field strength for a particular power input is measured in the far field, and compared with the field strength for a reference antenna, e.g. a quarter wave whip. This measurement technique is a good one if the model frequency is high. For a scale factor of 1000, and a full scale frequency of 25 kHz, the model frequency is 25 MHz, and a quarter wave whip while larger than at VHF frequencies is still a reasonable size. There are however, errors with this method. Field strength can be measured with an accuracy of ± 1 dB, and so the difference in field strength is measured with a precision of ± 2 dB. Power radiated varies as field strength squared (see below). Since we are trying to measure radiation resistance, antenna current must be measured, and P_r is proportional to I_a^2. Even with great care the uncertainty in determining R_r can be as great as a factor of two.

If the scale factor is 100, the model frequency is 2.5 MHz. The modeled antenna cannot be placed on the elevated ground screen, and a quarter wave whip is unreasonably large. We carried out a series of model measurements using a scale factor of 100.

In this case we measured absolute field strength, and so it was necessary to measure field strength as a function of distance, over say 2 kilometers. From the field strength vs. distance curve, one can deduce the effective ground conductivity of the field site; and, knowing this, one can estimate (using an appropriate theoretical formulation for ground wave propagation) the unattenuated field strength E_u at 1 kilometer. And, since

$$P_r\text{ (kW)} = 1.111 \times 10^{-5}\, E_u^2 \text{ mV/m}$$

we can determine the radiated power. Again, antenna current must be measured to determine the radiation resistance. This method is quite accurate, since the field strength is determined from a series of measurements, rather than a spot measurement, but it is tedious to do.

Any estimation of the radiation efficiency using this method is low, in fact very low since the ground conductivity should also be scaled. For average ground, conductivity 3 mS/m for the full scale antenna site, the ground conductivity for the modeling site should be 3 S/m. Since the radial ground system cannot be modeled, resonant quarter wavelength elevated radials can be used for the model, since a 3- or 4- elevated radial wire ground system is equivalent to 120 buried radials [Christman, 1989].

5. A Mini-Study of Conventional Antennas

First let us consider several conventional antennas:

1) The Anthorn/Cutler/NWC type;
2) A single umbrella top loaded radiator (Fig. 5); and
3) A transmission line radiator (Fig. 6), which is an antenna system that has been investigated by the author [Belrose, 1983] in previous years. This antenna type was revisited as a part of the present study. The transmission line radiator is an inverted-L type in which the horizontal arm is bent into a multi-side-polygon, or a spiral, of length necessary for resonance.

5.1. A Basic Antenna Element- a Single Inverted-L

The multiple tuned antenna systems which we will be considering here were made up from basic elements, inverted-L type antennas (Fig. 7). This is a commonly used antenna type, which is easy to construct. Therefore the investigation began with a short study of inverted-L antennas.

For our study we supposed that:

1) the vertical radiator was a square or triangular tower 304.8 m high, 4 - 5 m on a side; and
2) the horizontal top loading was a 457.2 m long square cage of four conductors, where the square is 15.24 m on a side. The construction of the horizontal cage and its support by the towers could be similar to that used for EHV (500 KV) power transmission lines.

5.1.1 Idealized Inverted-L

An idealized inverted-L, a base insulated tower with no end support tower is sketched in Fig. 8a. In Fig. 9 we compare the measured antenna resistance R_a and reactance X_a vs. frequency for an inverted-L experimentally modeled, having scaled dimensions as above, with theoretical values (radiation resistance R_r and reactance X_a) calculated by: 1) a transmission line type of analysis, c.f. Belrose [1983]; and by 2) by ELNEC. Theory and experiment are considered to be in good agreement. The differences are thought to be due to the difficulty with experimental modeling, when such a large scale factor is used; and with the fact that the antenna is mounted on a ground plane of finite size (an elevated ground screen 30 m in diameter). For example, the calculated reactance at 25 MHz corresponds to an antenna capacity for the model of 11 pf, and the difference between this reactance and the measured reactance amounts to a difference of 2.3 pf, which can be attributed to the base insulator capacity for the model. The differences between calculated radiation resistance and measured antenna resistance are attributed to effects associated with the finite size of the ground plane. Although the ground screen looks to be very large with respect to our small model, its radial dimension is only 1.25λ at 25 MHz. It is well known that the resistance of a monopole is modified by currents reflected from the edge of a ground plane of finite size.

5.1.2. Effect of Grounded Towers

The idealized antenna had no end support tower, and no sag on the horizontal arm of the antenna (Fig. 8a). We have investigated the effects of grounded support towers and sag on the horizontal arm by numerical and experimental modeling. Fig. 8b is an inverted-L with an end support tower. The current induced to flow on the grounded support tower, according to ELNEC, is opposite in phase to the current on the radiator. This effect reduces the effective value of the antenna's radiation resistance and reactance. The sag on the horizontal arm further reduces the radiation resistance.

If two towers are employed (Fig. 8c) to support a cage antenna, this further reduces the radiation resistance and reactance.

These effects are summarized in Table 1.

5.1.3. Cage Feed for a Grounded Tower

An arrangement discussed by Belrose [1983] which eliminates the need for an insulated-base tower, a decided advantage if feasible, cf. Fig. 10, is to feed a cage of wires that surround a grounded tower. In fact this method of feed was used for the USN VLF antenna at Northwest Cape Australia. This method of feed (confirmed by experiment and performance at full scale) works well for LF/MF radiators, where the electrical height of the tower is large, large compared with practical antennas at VLF, and the radiation resistance is several ohms, or more. However, according to NEC-3, when the electrical height of the tower is small [Royer, 1991], the 'transmission line' induced current on a grounded tower surrounded by a 9-wire cage (Fig. 8d) reduces the radiation resistance by an intolerable amount (Table 1).

While the antenna's reactance is reduced, which is desirable, the radiation resistance is reduced by a large factor. This means that the ground loss resistance for the same radiation efficiency must be proportionally reduced; and the antenna's bandwidth is less. Thus, unfortunately, this method of feed should not be used at VLF where the highest possible value for the radiation resistance is desired from the point of view of efficiency and bandwidth.

5.2. The Anthorn/Cutler/NWC Type of Antenna

The Cutler and Anthorn antennas are in effect 6-inverted L type antennas fed in parallel, each with a diamond shaped top-loading structure. The antenna system is supported by 13 towers. The NWC antenna uses cage feed with a grounded center tower (a 48-wire cage).

Anthorn is the smallest and the NWC antenna system the largest. The Anthorn antenna is an example of the problem with this type of antenna if its size (in wavelengths) too small. The measured radiation resistance for this antenna at the operating frequency of 19 kHz is only 0.08 ohm (we comment below on factors affecting radiation resistance for this type of antenna); the antenna system resistance including bandwidth resistors is 0.18 ohms; and the antenna reactance -j 85 ohms. The self-resonant frequency 50.1 kHz. The radiation efficiency is 44-percent and the antenna's bandwidth is 100 Hz. Note that the antenna employs bandwidth resistors. Since the antenna is built on land that is partly under water at high tide, the ground loss resistance is very low and the bandwidth is small. Bandwidth resistors are used to achieve a 100 Hz bandwidth [Cook, private communications, 1991].

Why is the radiation resistance so small? For uniform current on a driven tower of height that of the center tower of the Anthorn antenna (228 m), and if there was no sag on the top loading, and if the antenna was supported by insulated towers, the radiation resistance at 19 kHz would have been 0.33 ohms. The difference between this value and the actual measured value is because: the top loading is insufficient for there to be uniform current on the down-lead; there is a significant sag of the top-loading structure; the grounded towers carry out of phase currents and this effect decreases the antenna system radiation resistance and the antenna's reactance. The effect of the grounded center tower is particularly significant. The center tower supports the driven ends (Fig. 1) of the diamond panels and the 6-downleads that are fed.

In Fig. 11 we show a skeleton model for this type of antenna---skeleton because the diamond panels are made up from perimeter and center wires only, to simplify the numerical model. For this case study the diameter to the open ends of the diamond panels was 1000 meters, and the height of the panels 300 meters. The frequency was 25 kHz. As can be seen by the density of wires at the center of the model, each diamond panel has its own down-lead and all panels are fed in parallel. Table 2 shows the effect of the grounded towers.

The effect of the grounded towers is to reduce the antenna's radiation resistance and the antenna's reactance. The phase of the current on each of the grounded towers is -180^o wrt the current on the radiating downleads. The current on the grounded center tower is significant. With a current of 1 ampere flowing on each down-lead (antenna current 6-amperes), the current on the grounded tower is 0.7 amperes. However radiation due to the current distribution on this tower is partially screened by the six down-leads (on a 15m radius about the center tower).

5.3 Umbrella Top Loaded Antenna

Umbrella top loading, see Fig. 5, has been studied by Belrose [1983] and Hansen [private communications, 1988]. The design procedure given by Belrose was a numerical/graphical method, based on experimental modeling studies. Hansen has written a computer programme for use with an IBM compatible PC (ANT 1) based on other model studies

The important parameters for an umbrella top loaded antenna are: the height of the tower h; the number n of active top loading wires (12 is a reasonable number); the tangent of the angle θ between the top loading wire and the tower (1.4 is reasonable but 1.0 has been employed); and the height at which the umbrella wires are broken by an insulator divided by the height of the tower (s/h).

The capacitive reactance is decreased by the use of umbrella wires (or active guys), and as s/h increases the capacitive reactance decreases. As s/h increases the radiation resistance at first increases, and then decreases. The radiation resistance is a maximum when $s/h \approx 0.3$. This is because current on the umbrella wires has a component opposite in phase wrt current on the tower.

For $f = 20$ kHz, $h = 609.6$m, $n = 12$, tangent $\theta = 1.4$, and $s/h = 0.7$, the antenna's impedance is

$Za = 0.83 - j\ 158$ ohms

For a helix Q-factor = 2000, and a ground loss resistance $R_g = 0.25$ ohms, the antenna system resistance $R_{as} = 1.16$ ohms, and the radiation efficiency $\eta = 72$ percent. The self resonant frequency f_o of the antenna system is calculated to 39.3 kHz, and so the operational bandwidth of the antenna is 163 Hz. For a transmitter power of 1000 kW, the antenna voltage is high. The end voltage where the umbrella wires are broken by an insulator is 210 kV.

Reducing the height of the tower will reduce the radiation efficiency and bandwidth, and increase the antenna's reactance and antenna voltage (Table 3). A tall tower with an extensive umbrella-hat is required for VLF.

5.4 Transmission Line Radiator

The transmission line antenna, see Fig. 6, has been studied by Belrose [1983]. This antenna was revisited as a part of the present study. A resonant antenna was thought to be a good feature. Since the antenna could be "tuned" by the addition of an end capacitor, it was thought that this could provide a way to dynamically tune the antenna in synchronism with the frequency shift keying for MSK, if its bandwidth was too small. That is the "end" capacity could be switched in synchronism with the frequency shift keying. However, after a detailed experimental/numerical modeling study, it was concluded that this type of antenna was not a useful antenna for high power VLF transmission for the following reasons:

1) A number of towers would be needed, eight or more, to support an extensive top-loading cage;
2) since the antenna system is in effect "quarter wave resonant" the end voltage would be very high for a transmitter power of 1000 kW, and the end tuning capacitor would have to withstand this voltage; and

3) this type of antenna system does not lend itself easily to frequency agility.

6. Multiple Tuned Antenna Systems

As noted above multiple tuning has been used since the beginning of radio, for improving the radiation efficiency of early VLF antennas, where the most adverse conditions of low radiation resistance and high base reactance are encountered, and some extreme measures were necessary to obtain acceptable antenna radiation efficiencies, c.f. Alexanderson [1920]. While the basic principles were understood, little use has been made of multiple tuning since these early antenna systems fell into disuse, until recently, because of the high cost of multiple helix tuning coils, and matching and phasing circuitry, inside physically large copper or aluminum screened tuning huts.

The early history of multiple tuning is summarized in Table 4.

6.1 Radiation Coupled Antenna Systems

The German Navy VLF antenna system at Rhauderfehn, Germany (Figs. 12, 13, 14, 15) is multiple tuned. It comprises eight 352.5 m umbrella top loaded antennas, Figs. 12 and 13. Each antenna is separately fed, and the 8-elements of the antenna array are coupled through radiation.

Our antenna model consisted of four inverted-L antennas, see Fig. 7a, each element tuned with an identical base loading coil. A single inverted-L antenna by itself, with the base loading used, resonated at 25.12 MHz. The impedance (Z, θ) as measured at the base of one of the elements of the coupled antenna system is graphed in Fig. 16. Notice that in the frequency range 23-28 MHz the antenna's reactance was measured to be zero ($\theta = 0$) at five frequencies in this band, 24.15, 24.24, 24.7, 26.3 and 26.815 MHz.

The theoretical impedance curve was calculated by ELNEC, in a like manner with the experiment. That is a base load reactance was chosen such that a single inverted-L antenna was resonant at 25.12 MHz, and this inductance was used as a base load for each of the 4-elements of the multiple tuned antenna system. The resistance associated with these base loads was chosen such that the calculated antenna's impedance at the highest resonant frequency was in agreement with the measured value (at the corresponding resonant frequency). Clearly there is a good qualitative agreement between theory and experiment. The differences are attributed to difficulties with experimental modeling as discussed above, and the simplicity of the numerical modeling.

The multiple resonant frequencies were somewhat unexpected. They are due to the complex interactions between multiple tuned antenna elements that are closely coupled, not because of a misstuning of the elements in the experimental model. It is interesting to note that with 4-towers tuned, there were 5 resonant frequencies; and with 2-towers tuned there were 3 resonant frequencies. It is speculated that with 8-towers tuned, like for example the Rhauderfehn antenna, there would be 9 resonant frequencies. However, according to ELNEC only the two highest resonant frequencies are of practical importance, since for these the antenna's radiation efficiency is high. The radiation efficiency is low for the other 3 resonant frequencies. And, only the highest resonant frequency (26.815 MHz for the model) would be used practically, since VLF antennas are 'current fed.' Therefore in practice such antenna systems should be tuned by incrementally increasing the helix reactances from the high frequency side (minimum inductance) to achieve resonance. It is not known whether this is the tuning procedure used for the German Navy VLF antenna, Rhauderfehn.

However, it should be noted, that for our model studies only one tower was fed. The Rhauderfehn VLF station employs eight towers, and each tower is fed. We have not investigated the frequency response of a radiation coupled antenna system with all towers fed.

6.2 Folded Monopole Type

Two approaches can be taken to achieve a wider bandwidth: increase the effective diameter of the radiator; or multiple tune several vertical towers (or down-leads) sharing a common top-hat. Both approaches are taken in the antenna system to be described.

Let us now consider four inverted-L antennas arranged in the manner just discussed, but with their ends connected, see Fig. 7b. This configuration is more typically like a conventional multiple tuned antenna system where two or more down leads share a common top-load, excepting for the simplicity of the top-loading structure. The antenna to be described is in effect a multiple tuned double folded unipole. The base tuning is an essential part of the antenna system, since this establishes equal and in-phase currents on the vertical elements. The current is zero at the center of the antenna system, as it was at the end of a single inverted-L. It is interesting to note that the antenna can in effect 'be tuned' in the course of the numerical modeling study by changing the loads to achieve the deepest overhead null in the vertical plane pattern.

For the experimental model, each element of the multiple tuned antenna system was tuned with an identical base loading coil. As for the radiation coupled multiple tuned antenna discussed above, each inverted-L antenna, by itself, with the base loading inductance used, resonated at 25.5 MHz. The measured impedance vs. frequency for this antenna is plotted in Fig. 17. For this multiple tuned antenna, in the frequency range 23-28 MHz, there was only one resonant frequency, 27.2 MHz. Theoretically, according to MININEC, loads of j 652 ohms would be required to tune the antenna to 27.2 MHz, and such a load would tune a single inverted-L to 24.56 MHz.

In accord with early theory the radiation resistance with multiple tuning R_{rr}^{MT} is equal to $n^2 R_r$, where R_r , is the radiation resistance of a single element, n the number of elements, and R_{rr}^{MT} is the radiation resistance with multiple tuning. But this equation does not take account of the mutual inductances between the vertical elements of the multiple tuned antenna, which in effect lower the effective capacity of the antenna system. A larger load inductor must be used to tune to a given frequency, and the increase in the radiation resistance is less. Writing

$$R_{rr}^{MT} = k\, n^2 R_r \ ,$$

for our experimental model k = 0.87.

The loss resistance associated with each inductor R_c appears at the terminals of the driven element as n $R_{c,}$ and this same factor n applies for the ground loss resistance R_g attributed to each element of the antenna system. But the effective ground loss with multiple tuning should be less than for single tuning, since with multiple tuning the ground loss is distributed over n times the area. The radiation efficiency can therefore be significantly increased.

The above analysis is for the antenna modeled. That is the antenna is multiple tuned but only one leg is fed. If all four legs are fed the effective radiation resistance attributed to each element is R_{rr}^{MT} divided by four.

7. A Comparison between Performance (Measured and Predicted) for Multiple Tuned Antennas vs. Single Tuned Antennas

In Table 5 we compare the operational performance of two types of multiple tuned antenna systems: 1) the German Navy radiation coupled multiple tuned antenna system (measured performance); and 2) a multiple tuned double folded unipole (predicted performance); with 3) the largest antenna of conventional design in the world, the US Navy antenna system at North West Cape, Australia. The comparison is made at a frequency of 20 kHz.

The predicted radiation efficiency for the double folded unipole multiple tuned antenna system compares favorably with the Northwest Cape antenna, which is the largest VLF antenna in the world, excepting the antenna voltage is high, and the antenna's bandwidth is too narrow for 4-channel MSK. The high value of radiation resistance, 2.3 ohms, which at first sight might seem to be unacceptably high, is due to the fact that all towers excepting for one, the center support tower, radiate in-phase and contribute to the total radiation field. Since the radiation resistance is high, ground loss resistance becomes less important for comparable radiation efficiencies, and in the design of such antenna systems, it would be possible, for example, to use fewer radials in the ground system, to in effect trade radiation efficiency for bandwidth, but still achieve a reasonable radiation efficiency.

When we compare the radiation resistance for multiple tuned antennas with single tuned antennas, we must specify how the multiple tuned antenna was fed. The radiation resistance for the multiple tuned double folded unipole is the source value with four tower fed. This method of feed is operationally convenient, since four transmitters could be used. Hence it would be possible, but with retuning, to remove one or more transmitters for service, with a corresponding decrease in radiated power. The predicted value for the radiation resistance is in more in accord with the 1.9 ohms for the Rhauderfehn antenna, then with other antennas in the world.

If one tower is fed, and the other three towers are grounded through their tuning helixes, the radiation resistance associated with the fed tower would be four times that shown, viz. 9.2 ohms; an unheard of value for VLF!

While the multiple tuned folded unipole antenna has limitations when compared with the largest VLF antenna in the world, the

USN NWC, Australia antenna, let us be clear what we are comparing. The NWC antenna comprises 13 towers, and the diameter of the outer ring of towers is 2.5 kilometers. The double folded unipole multiple antenna comprises 5-towers on a diameter of 914 metres. Clearly, now that we know how to design such an antenna system, we could optimize its characteristics. For example, lengthening the horizontal arms of the antenna will decrease the reactance needed to tune the antenna, and the antenna voltage; and increase the radiation resistance. But additional towers would be needed to support the longer top-loading spans. Finally it should be noted that the comparison was made at 20 kHz. Increasing the operational frequency will result in improved performance.

8. Concluding Remarks

The Folded Unipole type of multiple tuned antenna has a number of attractive features:

1) Its configuration lends itself to a relatively simple mechanical construction;

2) There is a minimum of wire structure in the air, which is subject to environmental stress, such as wind and icing;

3) Since the structure is in effect a system of closed loops sleet melting is made easy;

4) All of the towers contribute to the radiated field (with the exception of the center tower), and since currents on grounded support towers oppose the current on the radiating towers this is a distinct advantage;

5) As is well known with multiple tuning, since current is collected at 2-, 3-, or 4-downleads, depending on design, the radiation resistance is high, and less attention needs be given to reducing the ground loss resistance to a very low value. It is speculated that less wire would be needed in the total ground system;

6) The maximum voltage on the antenna, in contrast with conventional VLF antennas, occurs at the center of the antenna system, at a place where in effect the antenna does not "end". Thus corona problems associated with high powers are minimized; and

7) The theoretical bandwidth far exceeds that for any known VLF antenna system of comparable size and having a similar number of towers.

However, the antenna voltage is high, and several (2, 3 or 4) very large helix inductors are required to tune and phase the antenna. It should be noted that this study is still ongoing. Other configurations for the top-loading structure one under consideration.

This antenna offers an attractive alternative to conventional design for a LF antenna. Here, the length of the top loading elements is more practical, and can be significantly longer in electrical length. Grounded support towers could be used to support a wire cage antenna structure (i.e. down leads could also be cages). A three- or four-element multiple tuned antenna system could be suspended from 4- or 5-grounded towers. While, as noted above, this reduces the antenna's radiation resistance and the antenna's reactance, this configuration lends itself to a practical antenna design.

Acknowledgments

This study was sponsored by the Canadian Department of National Defence. The author benefited from a visit to the German Navy VLF station near Rhauderfehn, and from discussions with Karl Ruf, Telefunken-System Technik, Ulm (Donau), Germany about this unique VLF antenna system. The author thanks Peter Bouliane, who built and meticulously measured the antenna parameters for the experimentally modeled antennas.

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Table 1

Effect of support towers, and of physical and feed arrangement on the impedance, according to MININEC, of an inverted-L antenna: height 304.8 mm, diameter 6.35 mm; with 457.2 mm horizontal cage, diameter 10.6 mm; frequency 25 MHz

Configuration	Reference Sketch	Impedance
Base fed, no end support tower	Fig. 2a	0.6 - j 577
Base fed, grounded end support tower*	Fig. 2b	0.52 - j 562
Cage inverted-L radiator suspended between two grounded towers	Fig. 2c	0.35 - j 482
Cage fed grounded tower no end support tower	Fig. 2d	0.125 - j 255

* For a realistic model, with suspended top-loading cage hanging under its own weight, the base impedance Za = 0.4 - j 549

Table 2

Skeleton Cutler/Anthorn/NWC Antenna System

Configuration	Antenna's Impedance	Base Currents on Towers* Outer Ring/Inner Ri (center tower)
No Towers	$0.85 - j\ 200$	
12 Towers (No center Tower)	$0.55 - j\ 179$	$0.085/0.089 \angle -180^{\circ}$
13 Towers	$0.45 - j\ 163$	$0.077/0.0805 \angle -180^{\circ}$ $(0.7 \angle -180^{\circ}$

* Antenna current $6.0 \lfloor 0^{\circ}$ amperes.

Table 3

Predicted performance for an Umbrella-Type Antenna

Reference parameters:
$f = 20$ kHz
$n = 12$
tangent $\theta = 1.4$
$s/h = 0.7$
$P_t = 1000$ kW
Helix Q-factor = 2000

Tower Height (Metres)	R_r ohms	R_g ohms	$-j\ X_a$ ohms	BW_{op} Hz	η %	f_o kHz	$V_{as(max)}$ kV
304.8	0.21	0.25	398	46	31	78.7	533
457.2	0.46	0.25	242	88	55	52.5	321
609.8	0.83	0.25	150	163	71	39.3	210

Table 4

Multiple Tuning: Early History

Alexanderson [1920]	Briefly described by Laport [1950]
German VLF Goliath antenna, Kalbe, Germany, mid 40s. Measured data available [Watt, 1967]. Station moved after the war to Gorki, USSR.	Three interconnected hexagonals with 3 insulated 200m central towers, and 15 grounded 170m towers, the three central support towers were tuned, the center down lead was also tuned and fed (in effect this gives 4-down-leads tuned).
Canadian Department of Transport LF transmitter at Beaconsfield, QC (near Montreal)--late 40s - early 50s.	Diamond antenna with four tuned down-leads.
LF Broadcast transmitter Donebach/Odenwald, Germany [CCIR 1966-69 Doc. X 57].	Folded monopole, 3 - 200m towers uniformly spaced about a central tower, tops joined by a 10m flat wire system, all towers tuned (BW 6 kHz achieved at 155 kHz).
USN Stations Annapolis, MD (1941) and Lualualei, Hawaii (1947) [Watt 1967].	12 parallel wires supported by 7-182.9m grounded towers, two down-leads tuned one fed.
Unique antenna system for short (LF/VLF application)/low profile (HF mobile application) [Ray, 1972; Ma and Fitzgerrell, 1977].	Multiple tuned type, but an additional feature was the method of feeding the flat-top; by a wire running up the center of the grounded towers (loading coils said to be effectively in series at the top of the towers but physically placed at ground level).
German Navy VLF Station at Rhauderfehn, nr Hannover, Germany (operationally in use).	8-352.5m umbrella top-loaded antennas, each antenna tuned and separately fed (author visited the station in June 1989).

Table 5

A comparison between performance of two multiple tuned VLF antennas with the USN NWC VLF antenna, which is the largest antenna in the world.

Reference parameters:
$f = 20$ kHz
$P_t = 1000$ kW
Helix Q-factor = 2000

Antenna	R_r ohms	R_g ohms	$j X_a$ ohms	BW_{op} Hz	η %	$V_{as}(max)$ kV
NW Cape Australia	0.25	0.033	38	163	87	123
Rhauderfehn, Germany, Eight umbrella antennas multiple tuned, radiation coupled.	1.9	0.15	490	120	85	124
Multiple Tuned Double Folded Unipole	2.3*	0.25	796	106	78	247

* Four inverted-L type antennas, ends electrically connected, four 457.2 m towers tuned and fed, with 457.2 m horizontal arms and grounded center support tower. If only one tower is fed the radiation resistance would be 9.2 ohms, and the associated ground loss resistance 1 ohm.

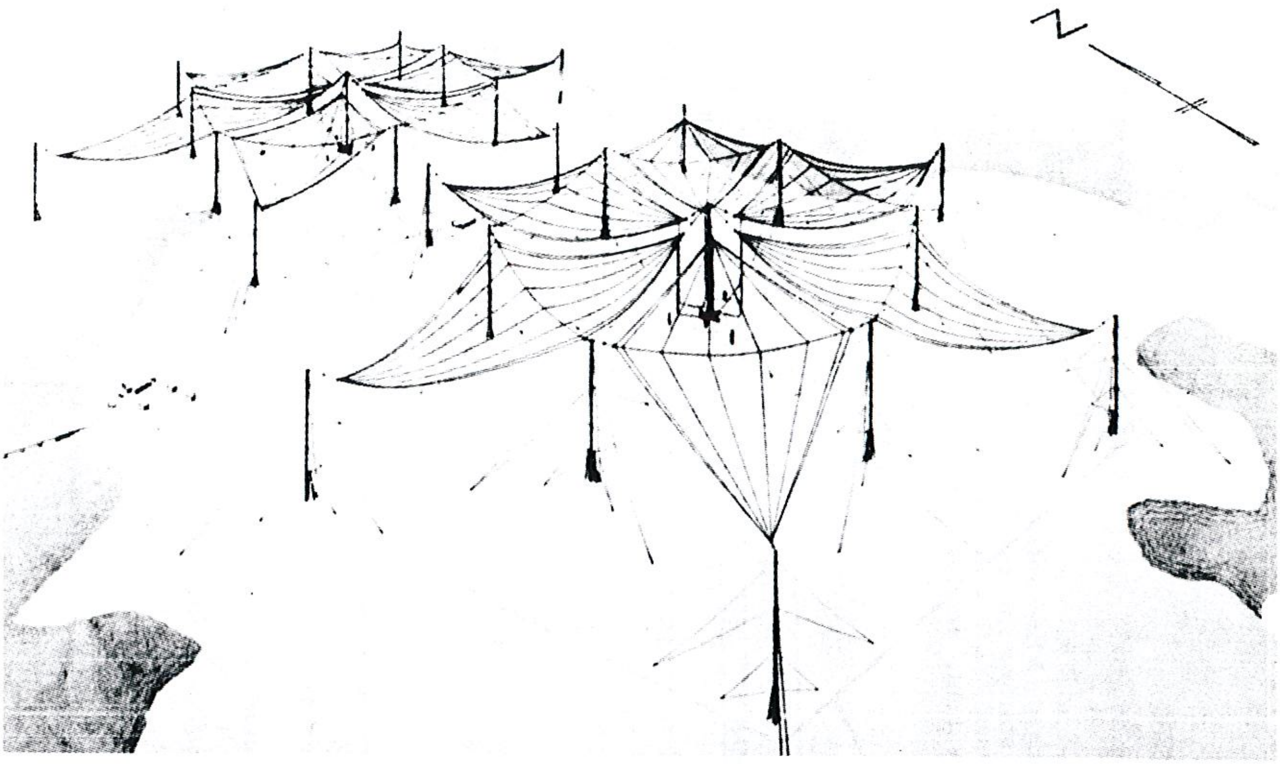


Fig. 1 Pictorial view of the USN Cutler, Maine, VLF antenna [after Watt, 1967].

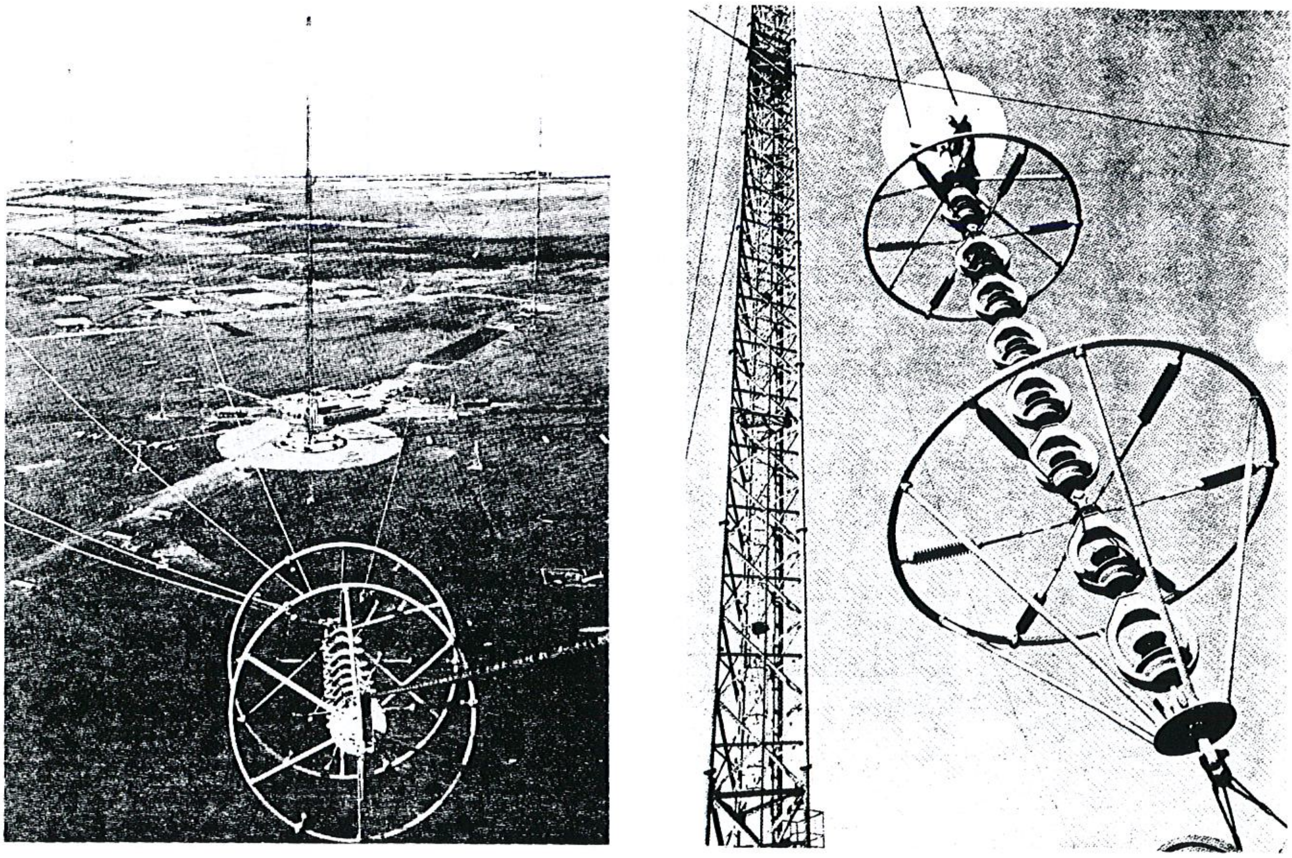


Fig. 2 Bird's eye view from an outer tower of the NATO Anthorn, England, VLF antenna, looking toward the center tower. Antenna insulator strings are 9-metres long and fitted with large coronal rings. Note the engineer at the top for size comparison.

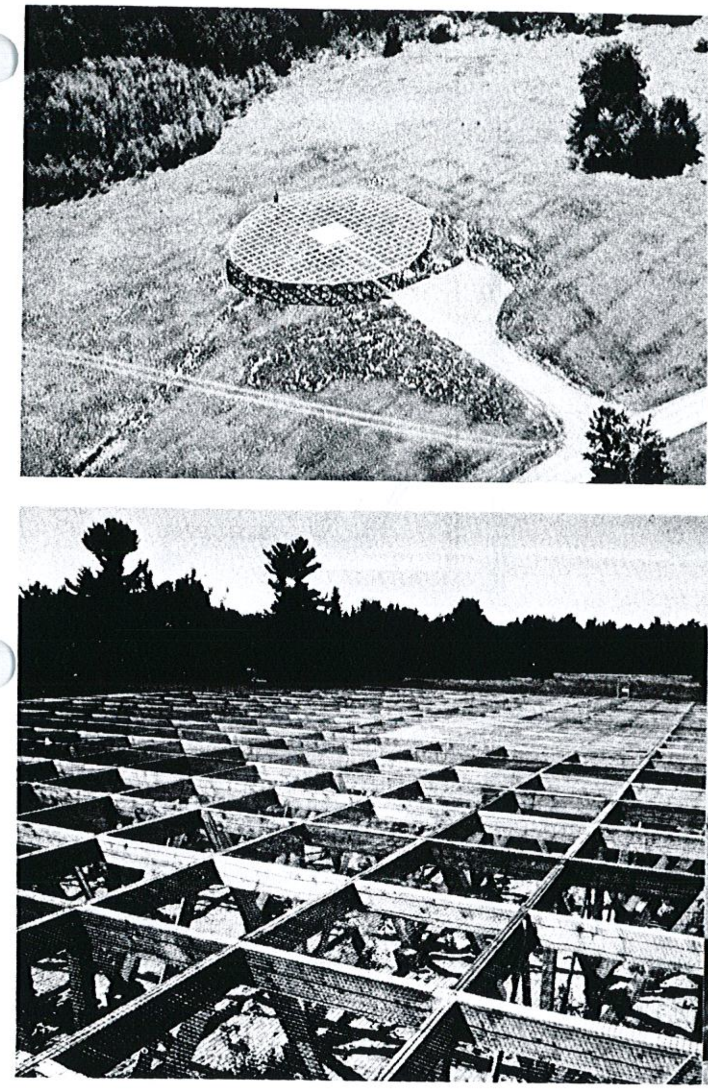
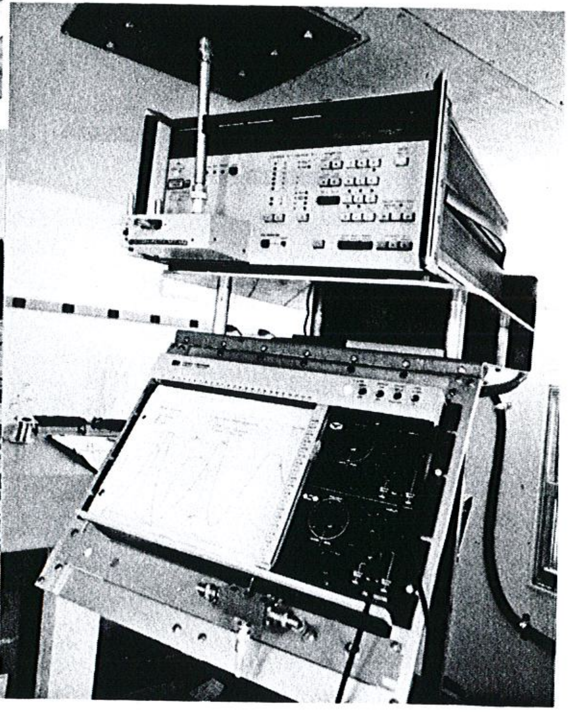


Fig. 3 Left: Aerial view and close up view of the CRC 30-metre elevated ground plane for experimental antenna modelling studies.

Fig. 4 Below: Instruments to measure antenna system characteristics are deployed directly beneath the modelled antenna system, and below the ground plane.



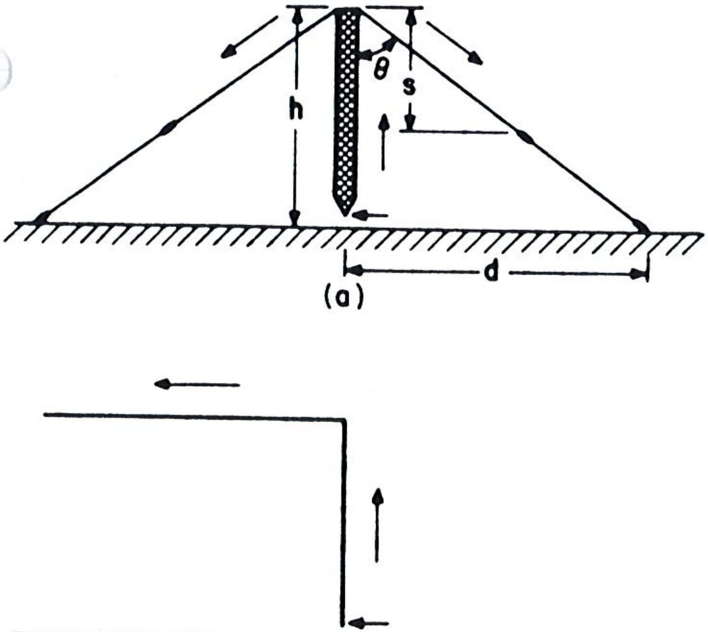


Fig. 5 Sketches illustrating phasing of currents on umbrella and inverted-L type radiators. Note that for the inverted-L currents on the top-load do not interfere with currents on the radiator, but this is not the case for the umbrella antenna.

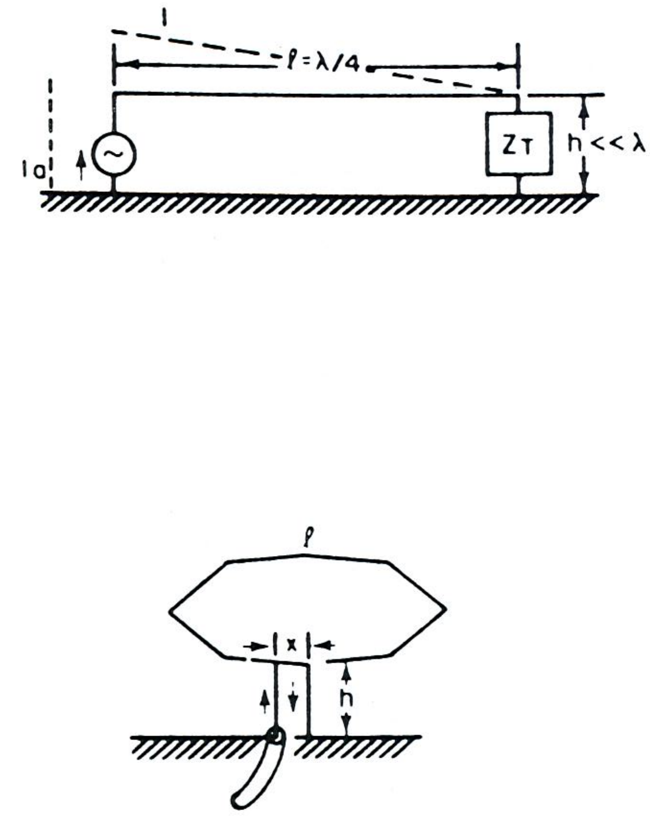


Fig. 6 Sketches for a transmission-line radiator (h << λ/4). The sketch below shows a practical method of matching and feeding a grounded radiator [after Belrose, 1983].

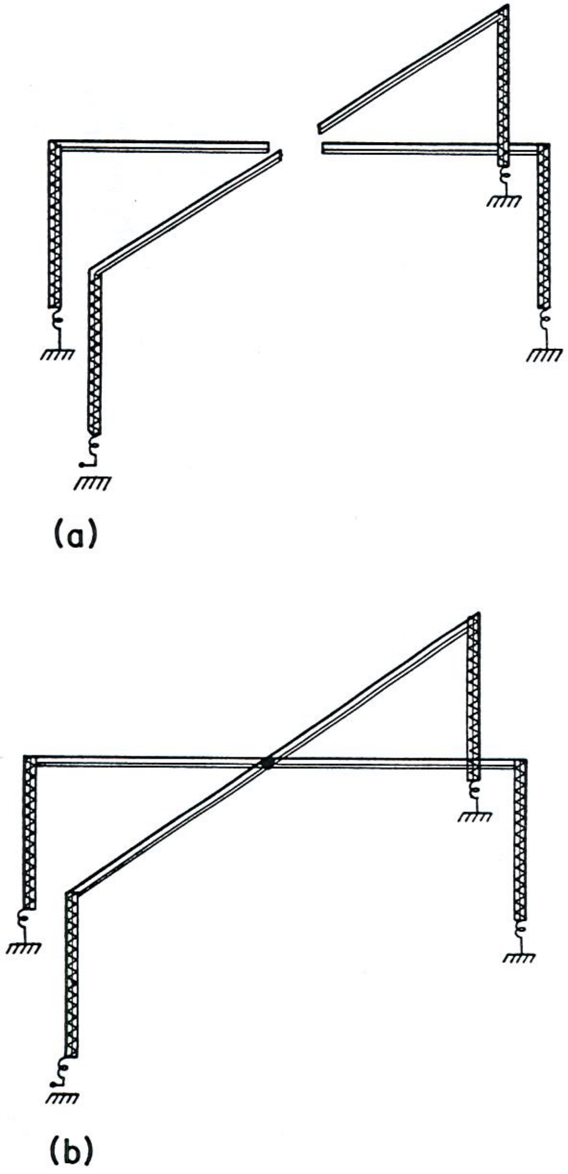


Fig. 7 Sketches of multiple-tuned antenna systems: a) radiation coupled; b) double folded unipole.

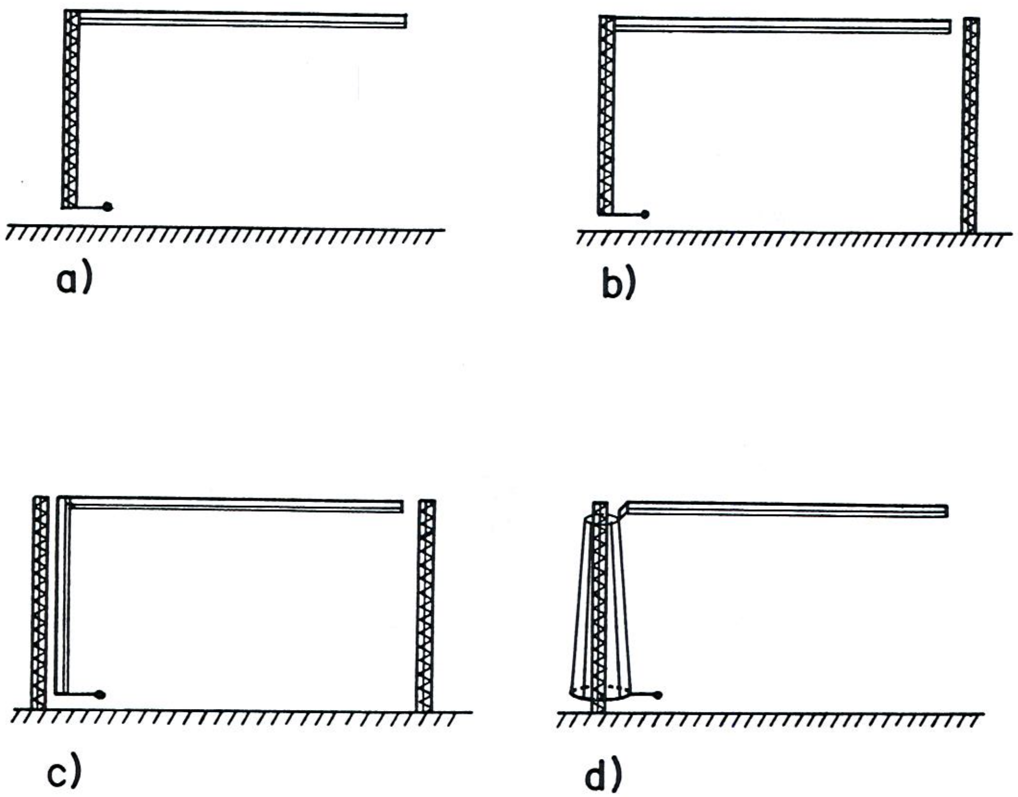


Fig. 8 Sketches for inverted-L type antennas: a) idealized radiator (no end support tower); b) with end support tower; c) cage type inverted-L with two support towers; and d) grounded tower with cage feed.

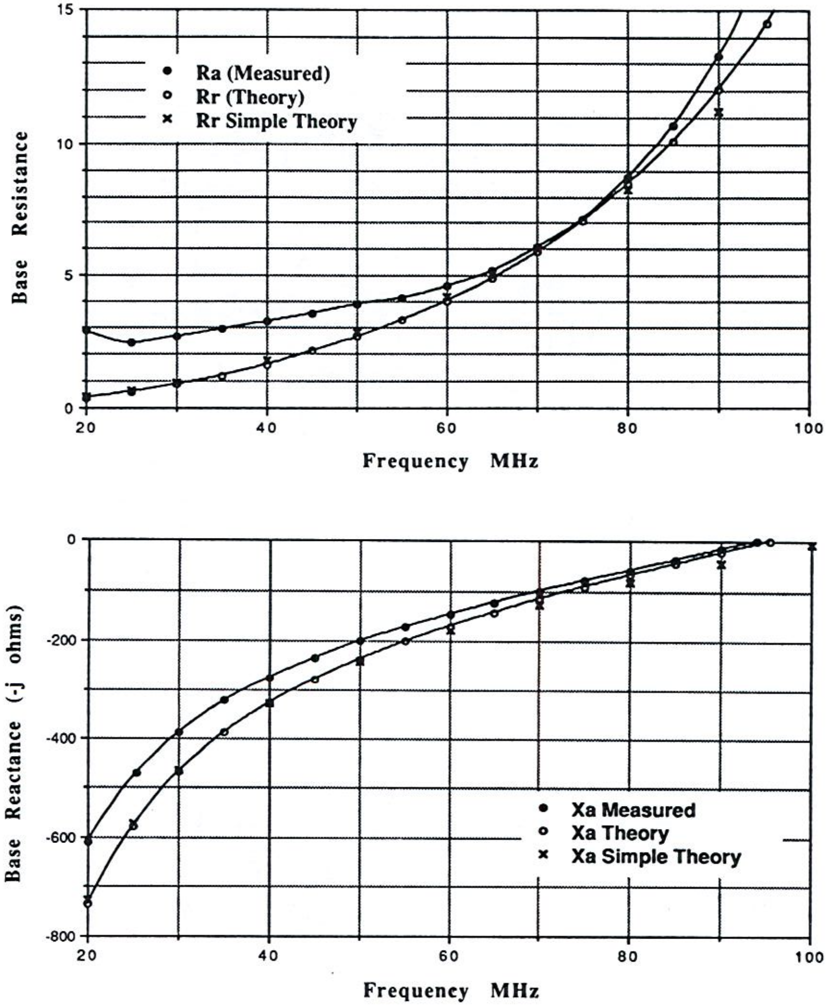


Fig. 9 Measured and predicted impedance vs frequency for a modelled inverted-L antenna with no end support tower (Fig. 8(a)'s antenna).

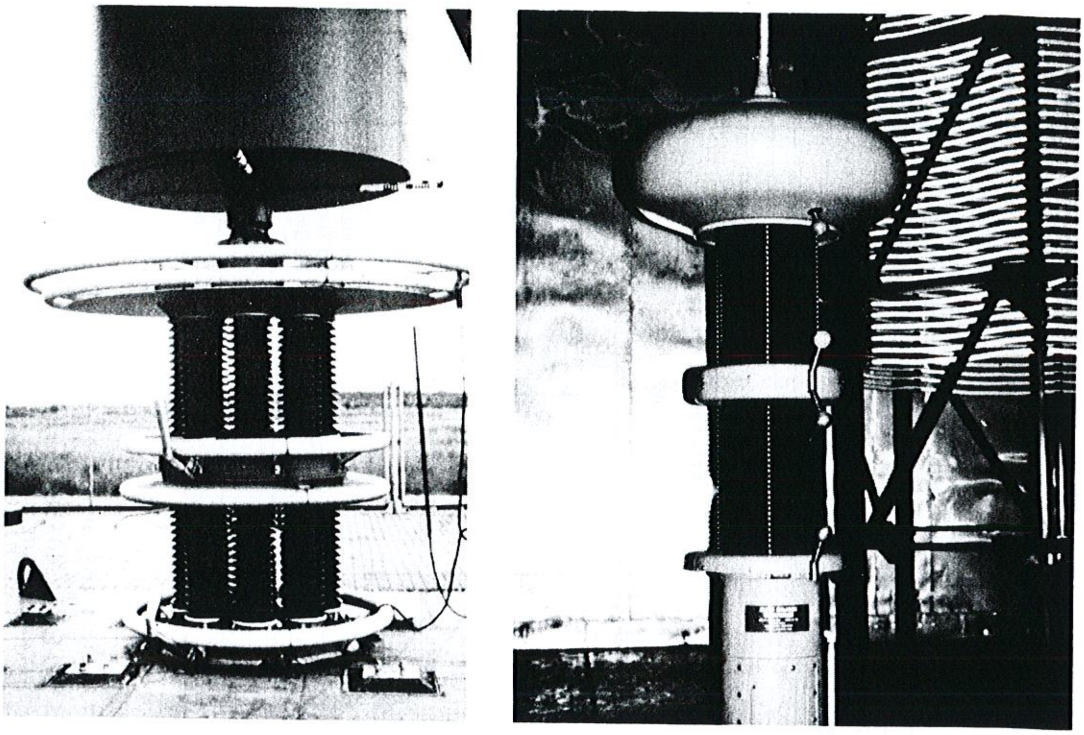


Fig. 10 Photograph of the base insulator for one element of the German Navy Rhauderfehn, FRG, VLF radiation coupled antenna system; and view inside one of the tuning huts. The tower lighting transformer is in the foreground, the main tuning helix in the background. In the case of a grounded tower neither the base insulator or the lighting transformer would be needed.

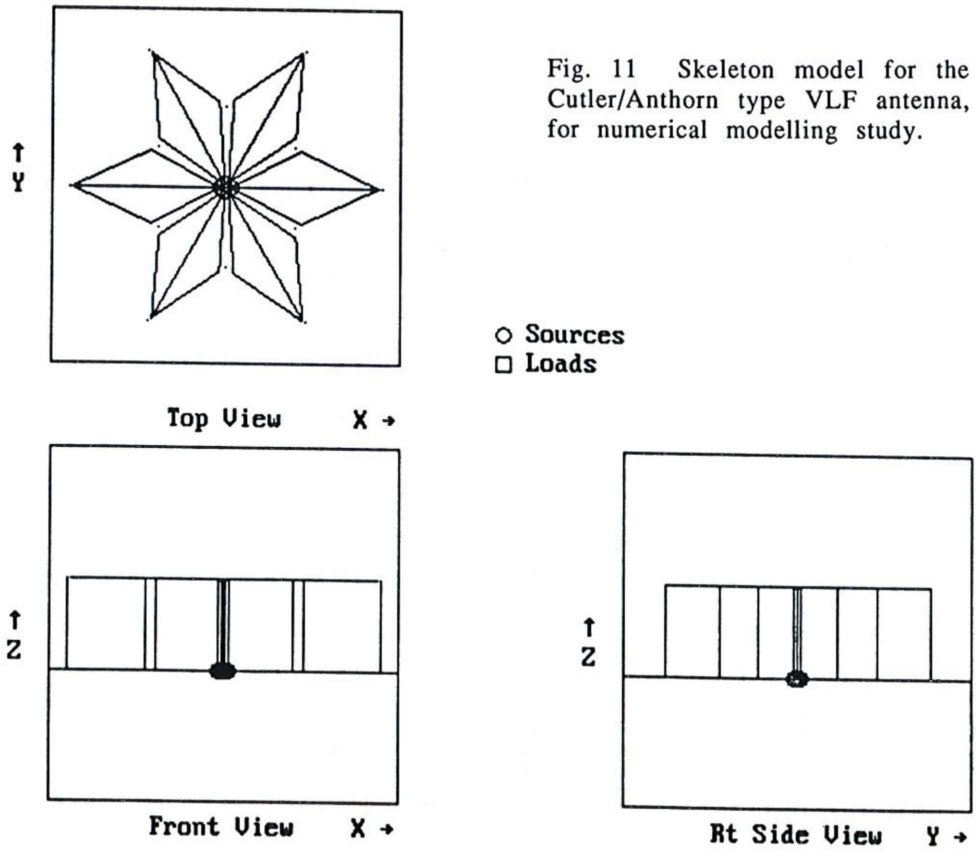


Fig. 11 Skeleton model for the Cutler/Anthorn type VLF antenna, for numerical modelling study.

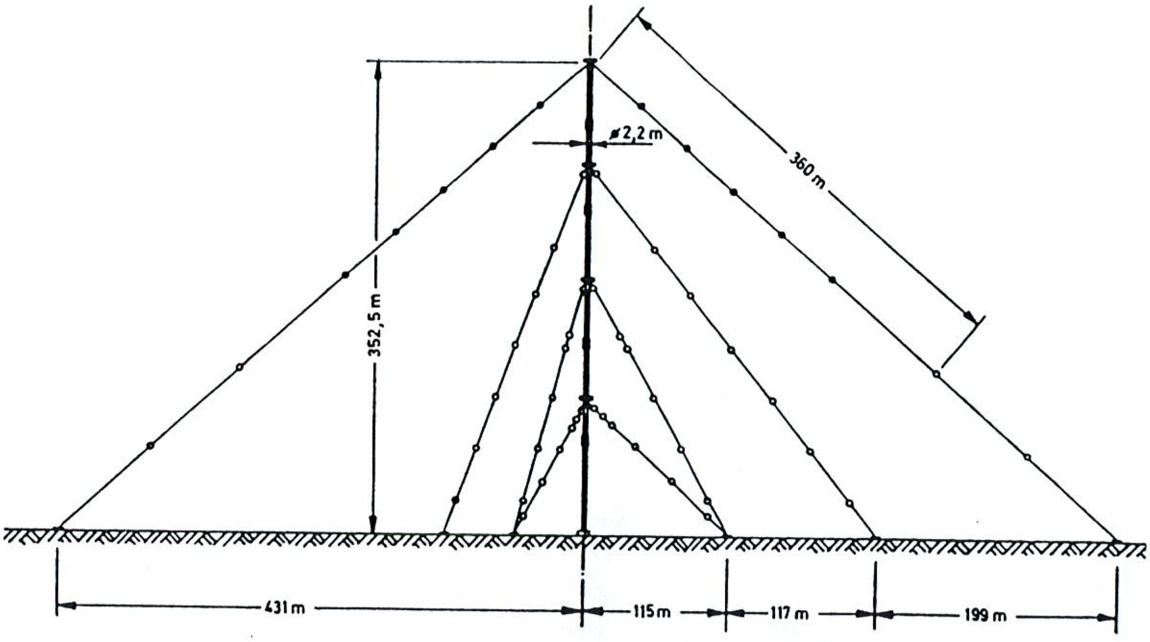


Fig. 12 Sketch of one of the Rhauderfehen umbrella antennas.

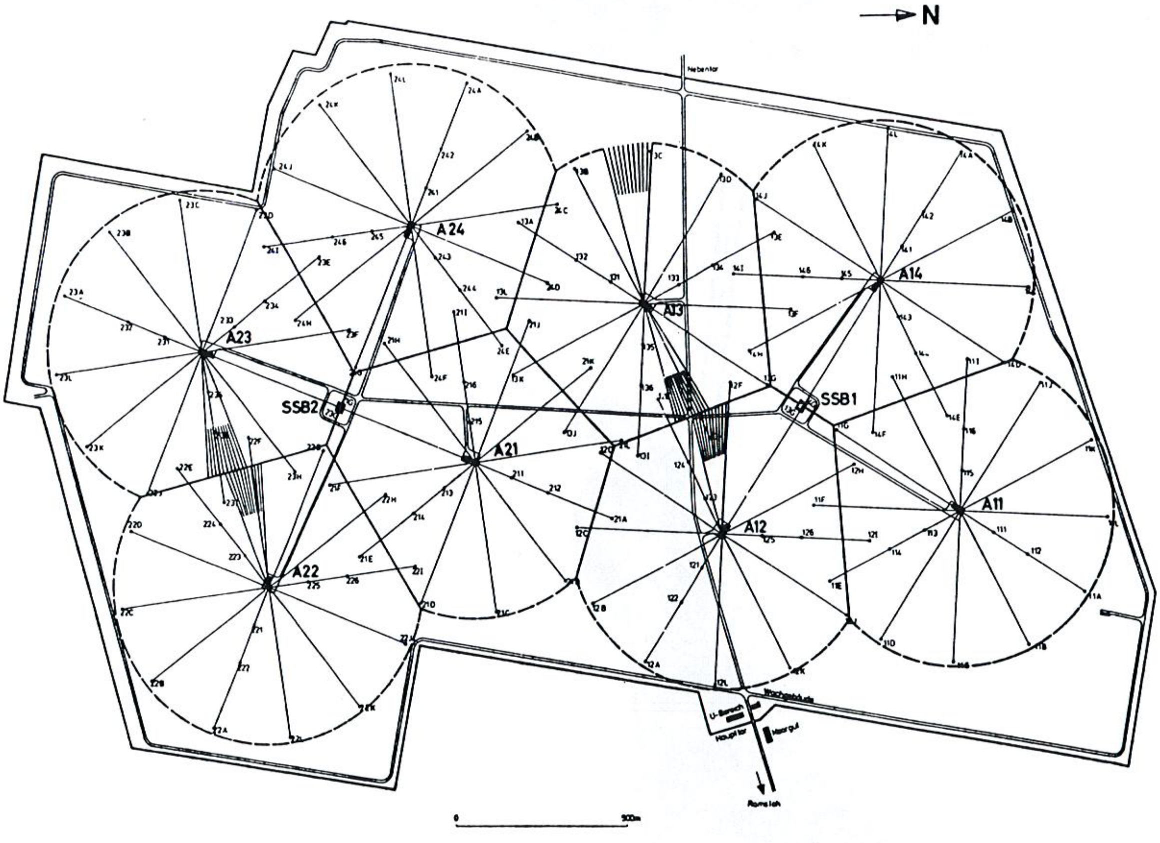


Fig. 13 Site plan for the Rhauderfehn VLF antenna system, showing the position of the towers and arrangement of radial ground system for the eight umbrella antennas.

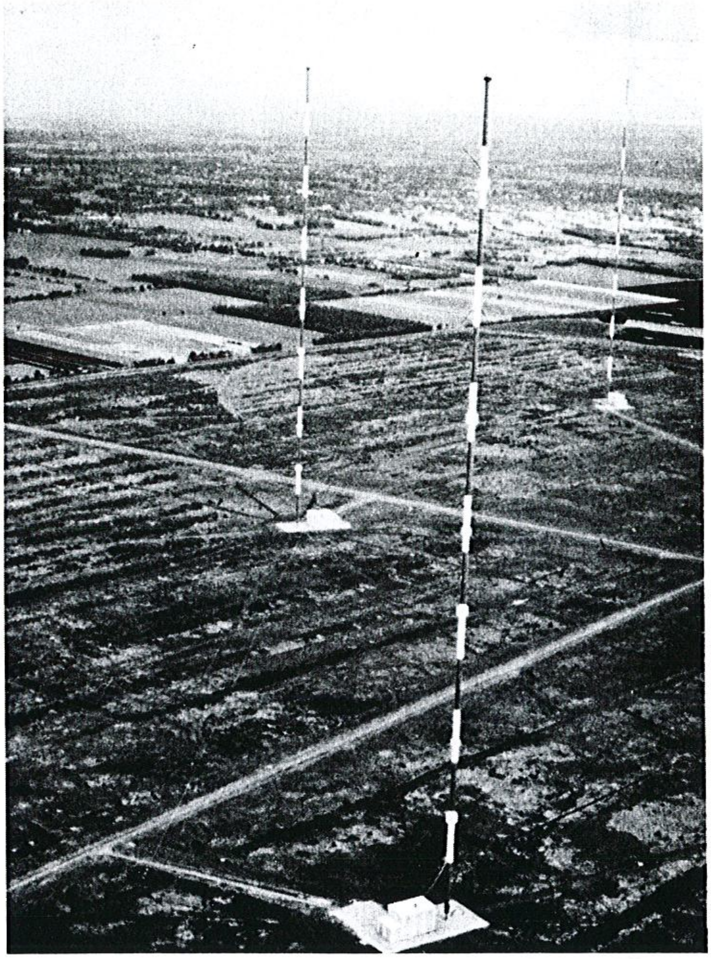
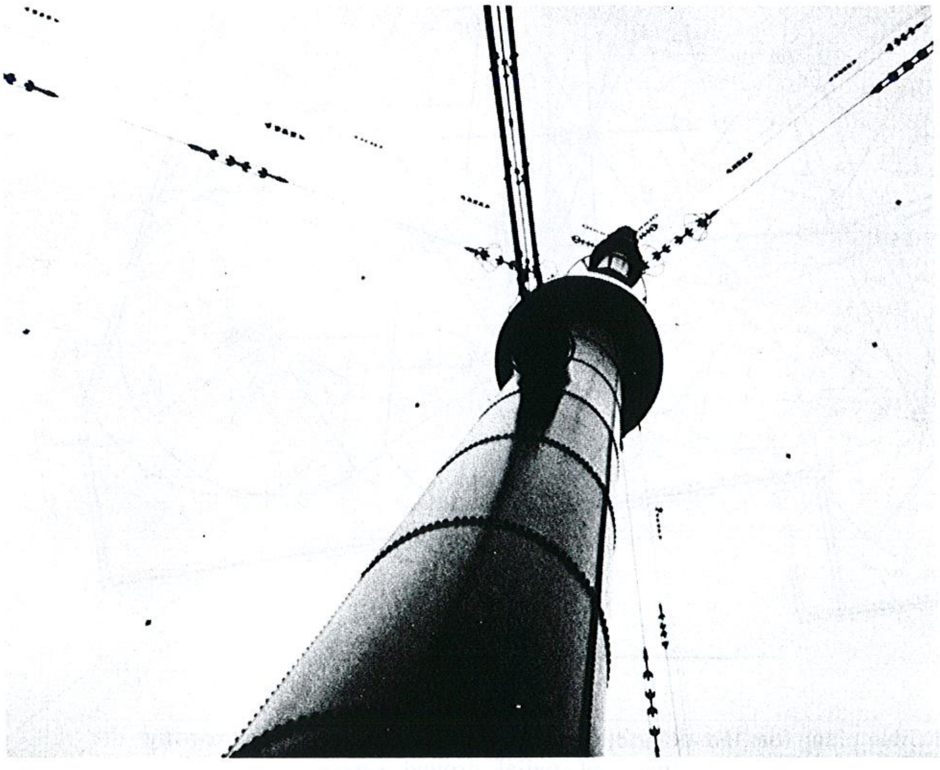


Fig. 14 Photograph of three of the Rhauderfehn towers taken from the top of one of the towers. The tuning huts can be clearly seen, as well as, for the near tower, the antenna lead to a feed through insulator feeding through the roof of the antenna tuning hut.

Fig. 15 View looking up from the base of one of the Rhauderfehn towers. The antivibration segment can be clearly seen, as well as the antenna feed cage (the heavy conductor that appears to be coming in from the top of the photograph).



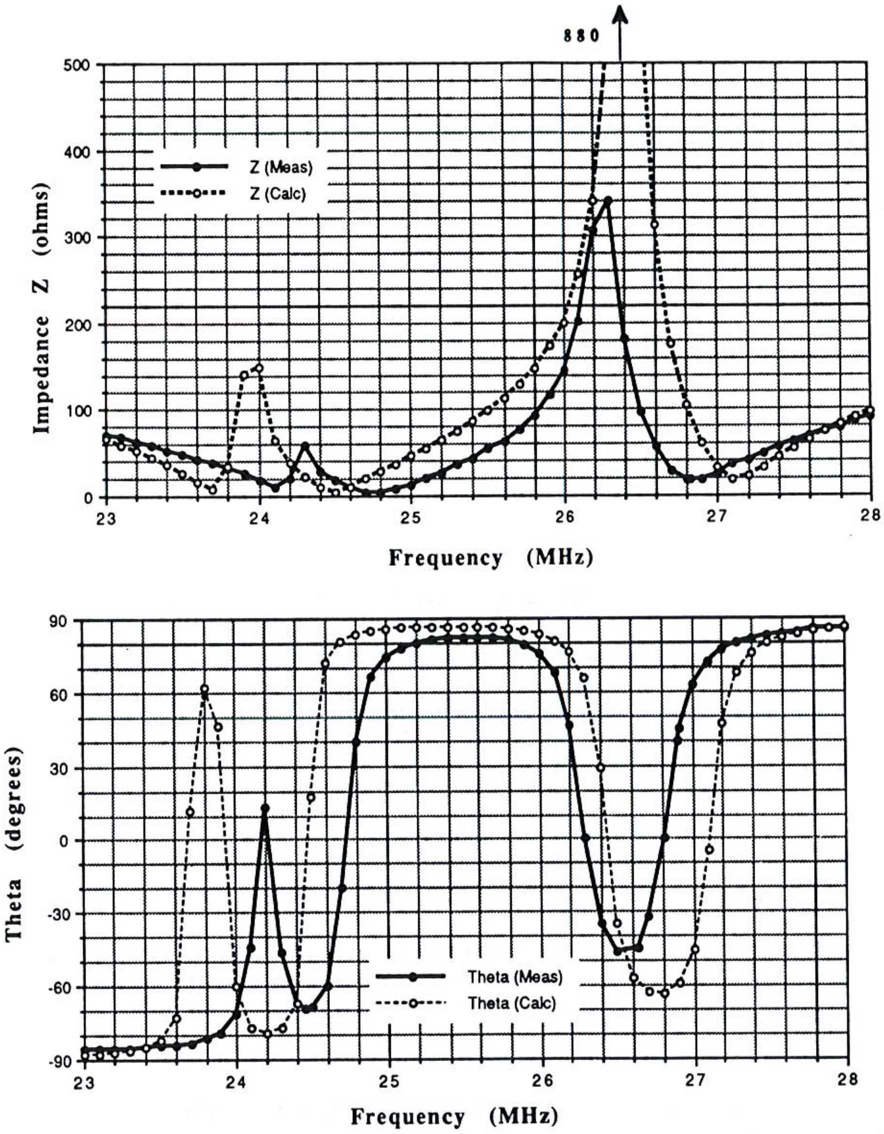


Fig. 16 Measured and calculated impedance (Z, θ) vs frequency for modelled VLF radiation coupled antenna system (Fig. 7a's antenna).

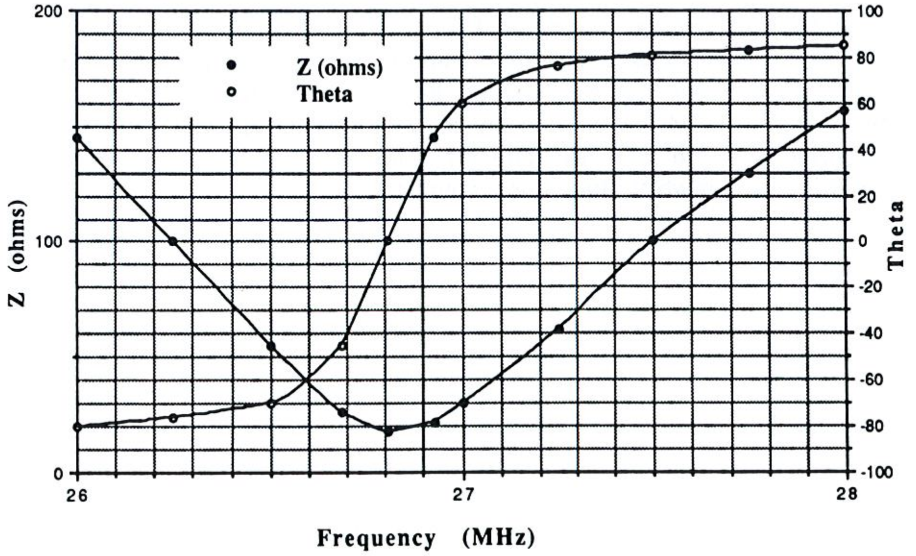


Fig. 17 Measured and calculated impedance (Z, θ) vs frequency for double folded unipole antenna system (Fig. 7b's antenna).

Discussion

V. LAMMERS (US)

In addition to keeping the ratio of radiation resistance to ground loss resistance high for best signal transmission, what can you do by improved grounding to achieve a low take-off angle.

AUTHOR'S REPLY

Improved grounding will not help to achieve a low take-off angle (or efficient coupling into the waveguide mode of propagation). I discussed this briefly in my introductory overview. In the case of MF, where one can certainly describe the propagation via a wave-hop mode, I argued that the ground more thar fifty wavelengths in front of the antenna was important in achieving a low take off angle. At 3.75 MHz this distance is 4 km; at 25 kHz (if this concept still has meaning) this distance is 600 km!! Ideally a VLF/LF transmitter should be on an island remote from land, or have the ocean in the preferred direction of propagation. However, as I noted ground of high conductivity can be found in the prairie provinces of Canada.

U.S. INAN (US)

What you just described is also valid for MF Broadcast antennas, which have ground systems underneath essentially vertical monopoles. The purpose of the ground plane is to increase efficiency rather than control the radiation pattern.

AUTHOR'S REPLY

What you have said is only partly correct. The ground system controls and stabilizes the self impedance of the individual antenna elements, and it plays a significant role in stabilizing the antenna's azimuthal pattern, which is important for critical antenna arrays. Some critical broadcast antenna systems have used elevated radials (elevated near the center) or insulated radials, to help stabilize the pattern in the different seasons.

Concerning the desire to achieve a low angle of radiation, we are concerned here with skywave, which is usually considered a nuisance for broadcasters. The MF Broadcast service relies on ground wave, in fact particular attention is sometimes taken to reduce the skywave, and so reduce the interference problem during nighttime hours. The null on the horizon, characteristic of vertical antennas, is a null with respect to the launch of skywave. The total field strength does not have a null in the direction of the horizon -- this is the range of angles in which the ground wave is found.