RECOMMENDATION ITU-R BS.1386-1*

LF and MF transmitting antennas characteristics and diagrams**

(Question ITU-R 201/10)

(1998-2001)

The ITU Radiocommunication Assembly,

considering

a) that Recommendations ITU-R BS.705 and ITU-R BS.1195 are defining respectively HF and VHF, UHF broadcasting antenna diagrams together with other relevant information;

b) that the diagrams published in this Recommendation should be easy to be understood and used by the planning and designing engineers, while retaining all necessary useful information;

c) the experience gained with the previous editions of Recommendations on antennas;

d) that the characteristics of the LF and MF antennas as contained in Annex 1 to this Recommendation have a wide application,

recommends

1 that the formulae as illustrated by sample diagrams and contained in Annex 1 to this Recommendation together with the corresponding computer programs should be used to evaluate the performance of LF and MF transmitting antennas; particularly for planning purposes.

NOTE 1 – Part 1 of Annex 1 gives comprehensive and detailed information on the theoretical characteristics of LF and MF transmitting antennas.

Computer programs have been developed from the theory to calculate the radiation patterns and gain for the various included antenna types.

The real performance of antennas encountered in practice will deviate to a certain extent from its analytically calculated characteristics. To this purpose Part 2 gives advice about this deviation on the basis of the results of a comprehensive set of measurements carried out by various administrations with modern techniques.

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* Radiocommunication Study Group 6 made editorial amendments to this Recommendation in 2002 in accordance with Resolution ITU-R 44.

** Chapter 2 of Part 2 of Annex 1 should be brought to the attention of the International Electrotechnical Commission (IEC).

ANNEX 1

CONTENTS

PART 1 – LF AND MF TRANSMITTING ANTENNA CHARACTERISTICS AND DIAGRAMS

1 Introduction

Efficient spectrum utilization at LF and MF demands for both omnidirectional and directional antennas whose characteristics and performance should be known as accurately as possible. Therefore, a unified approach to evaluate the antenna gain and radiation pattern should be made available to the engineer both for national planning and for international coordination. In the past the former CCIR responded to such a requirement by preparing Manuals of Antenna Diagrams (ed. 1963, 1978 and 1984), which included graphical representations of the radiation patterns of some of the most commonly used antenna types at MF and HF. For the sake of simplicity, the patterns were calculated assuming a sinusoidal current distribution and using computer facilities as available at that time. Today modern antenna theories and powerful computing means allow the planning engineer to determine the antenna characteristics with far better accuracy and perform the relevant calculation on low cost computers.

The application of digital techniques to sound broadcasting at LF and MF is envisaged in the near future and relevant studies are already being carried out by the ITU-R. The advantages of such techniques combined with the propagation characteristics at LF and MF in comparison to broadcasting at VHF (such as larger coverage areas and more stable reception in mobile conditions, etc.) will make the new services not only more spectrum efficient but also more attractive from the economical point of view. However, the introduction of digital techniques to broadcasting at LF and MF, will put an emphasis on the use of advanced planning tools, such as the calculation of the antenna patterns, to be made available to future planning Conferences as well as to assess more precisely the performance of existing transmitting systems. This Recommendation has been developed to respond timely to such requirements providing, as in the case of the companion Recommendations ITU-R BS.705 and ITU-R BS.1195, that the associated computer program to be used to perform the relevant calculations.

2 Radiation patterns and gain calculation

2.1 General considerations

An LF-MF antenna system may consist of a single element or an array of radiating elements. Radiation patterns of an antenna system can be represented by a three-dimensional locus of points. The three-dimensional radiation pattern is based on the reference coordinate system of Fig. 1, where the following parameters can be defined:

- θ: elevation angle from the horizontal ($0° \leq \theta \leq 90°$)
- φ: azimuth angle with respect to the North direction, assumed to coincide with the y-axis ($0° \leq \varphi \leq 360°$)
- r: distance between the origin and distant observation point where the far field is calculated.

2.2 Radiation patterns

In the reference coordinate system of Fig. 1, the magnitude of the electrical field contributed by an antenna is given by the following expression:

$$|E\,(\theta,\varphi)| = K\,|f(\theta,\varphi)| \tag{1}$$

where:

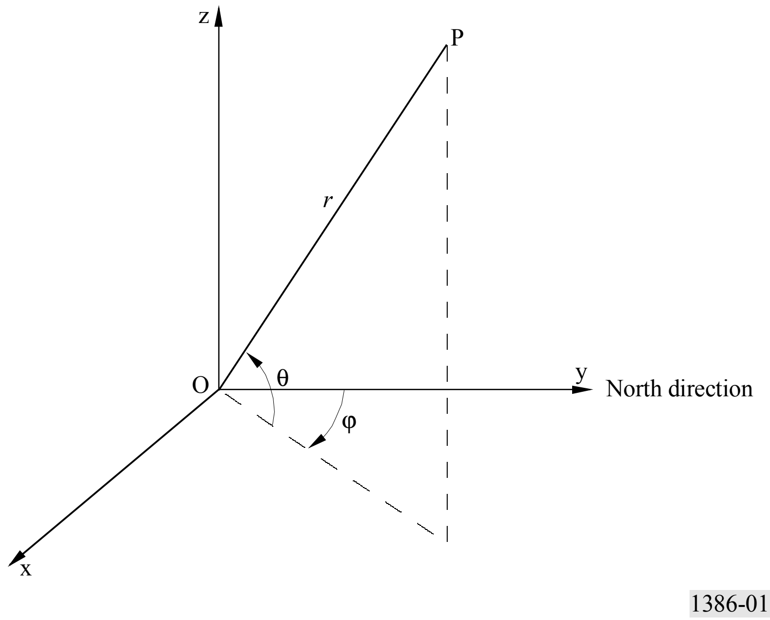
- $|E\,(\theta,\varphi)|$: magnitude of the electrical field
- $|f(\theta,\varphi)|$: radiation pattern function
- K: normalizing factor to set $|E\,(\theta,\varphi)|_{max} = 1$, i.e. 0 dB.

Expressing the total electrical field in terms of its components in a spherical coordinate system, gives:

$$|E\,(\theta,\varphi)|^2 = |E_\theta\,(\theta,\varphi)|^2 + |E_\varphi\,(\theta,\varphi)|^2 \tag{2}$$

FIGURE 1

Reference coordinate system



2.2.1 Graphical representation

A set of particular sections of the radiation pattern at specific elevation angles (azimuthal patterns) and at specific azimuthal angles (vertical patterns) is used to describe the full radiation pattern. The most important sections are the azimuthal patterns at the elevation angle at which the maximum cymomotive force (c.m.f.) occurs and the vertical pattern at the azimuthal angle at which the maximum c.m.f. occurs. These are referred to as the horizontal radiation pattern (HRP) and the vertical radiation pattern (VRP) respectively.

2.2.2 Tabular representation

A tabular representation of the full antenna pattern may be found to be a useful application when antenna data is integrated into a planning system. A resolution which is considered suitable for such a purpose consists of pattern values evaluated at each 2° for elevation angles and each 5° for azimuthal angles.

2.3 Directivity and gain

The directivity, *D*, of a radiating source is defined as the ratio of its maximum radiation intensity (or power flux-density) to the radiation intensity of an isotropic source radiating the same total power. It can be expressed by:

$$D = \frac{4\pi \left|E(\theta,\varphi)\right|^2_{max}}{\int_0^{2\pi}\int_{-\pi/2}^{\pi/2} \left|E(\theta,\varphi)\right|^2 \cos\theta \, d\theta \, d\varphi} \tag{3}$$

When equation (1) is applied, D can be expressed in terms of the normalized radiation pattern function of the source, $|f(\theta,\varphi)|$:

$$D = \frac{4\pi \left| f(\theta,\varphi)_{max} \right|^2}{\int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \left| f(\theta,\varphi) \right|^2 \cos\theta \, d\theta \, d\varphi} \tag{4}$$

The above definition of directivity is a function only of the shape of the source radiation pattern.

The antenna efficiency is defined as a ratio of radiated power, P_{rad}, to the power at the input of antenna P_{input}:

$$\eta = \frac{P_{rad}}{P_{input}} \tag{5}$$

The antenna gain, G, is expressed as a ratio of its maximum radiation intensity to the maximum radiation intensity of a reference antenna with the same input power.

When a lossless isotropic antenna is taken as the recommended reference antenna, the gain, G_i, is expressed by:

$$G_i = 10 \log_{10} D \qquad \text{dB} \tag{6}$$

Other expressions used are the gain relative to a half-isotropic antenna, G_{hi}, that is:

$$G_{hi} = G_i - 3.01 \qquad \text{dB} \tag{7}$$

and the gain, G_v, relative to a short vertical monopole:

$$G_v = G_i - 4.77 \qquad \text{dB} \tag{8}$$

2.4 Effect of the ground

Using the assumptions given in § 2.1, and also the assumption that the antenna is located in the coordinate system of Fig. 1, where the x-y plane represents a flat homogeneous ground, the far field produced at the observation point P(r, θ, φ), including the ground reflected part, can be derived as follows.

If the incident radiation on the ground is assumed to have a plane wavefront, the following two different cases can be considered.

a) horizontal polarization;

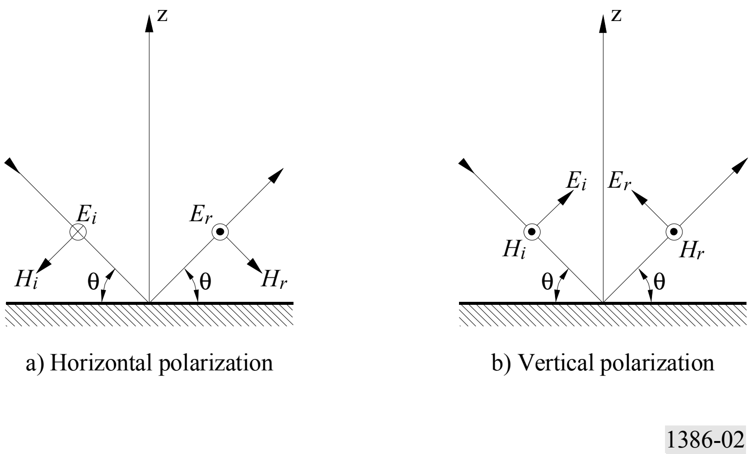
b) vertical polarization.

In the case of *horizontal polarization*, the incident (direct) electric vector is parallel to the reflecting x-y plane (and hence perpendicular to the plane of incidence, i.e. the plane containing the direction of propagation and the perpendicular to the reflecting surface, as shown in Fig. 2a)).

In the case of *vertical polarization*, the incident electric vector is parallel to the plane of incidence while the associated incident magnetic vector is parallel to the reflecting surface, as shown in Fig. 2b).

FIGURE 2

Wave reflection on imperfect ground



2.4.1 Wave reflection on imperfect ground

The total far-field components above ground in Fig. 2 can then be expressed as follows:

a) *Horizontal polarization*

$$E_h = E_i\,(r_1) + E_r\,(r_2) = E_i\,(r_1) + R_h\,E_i\,(r_2) \tag{9}$$

where:

E_h: total horizontal component

r_1: direct distance between the antenna and the observation point

r_2: distance from the image of the antenna to the observation point

E_i: direct electric field

E_r: reflected electric field

R_h: complex reflection coefficient for horizontally polarized waves defined as:

$$R_h = \frac{\sin\theta - \left[(\varepsilon - \cos^2\theta) - \mathrm{j}\,\dfrac{18\,000\cdot\sigma}{f_{\mathrm{MHz}}}\right]^{1/2}}{\sin\theta + \left[(\varepsilon - \cos^2\theta) - \mathrm{j}\,\dfrac{18\,000\cdot\sigma}{f_{\mathrm{MHz}}}\right]^{1/2}} \tag{10}$$

and

θ: grazing angle

ε: relative permittivity (or dielectric constant) of the ground

σ: conductivity of the ground (S/m)

f_{MHz}: operating frequency (MHz).

b) *Vertical polarization*

$$E'_h = E_i(r_1) - R_v E_i(r_2)$$
$$E_v = E_i(r_1) + R_v E_i(r_2) \tag{11}$$

where:

E'_h: total horizontal component

E_v: total vertical component

R_v: complex reflection coefficient for vertically polarized waves defined as:

$$R_v = \frac{\left[\varepsilon - j\frac{18\,000 \cdot \sigma}{f_{\text{MHz}}}\right]\sin\theta - \left[(\varepsilon - \cos^2\theta) - j\frac{18\,000 \cdot \sigma}{f_{\text{MHz}}}\right]^{1/2}}{\left[\varepsilon - j\frac{18\,000 \cdot \sigma}{f_{\text{MHz}}}\right]\sin\theta + \left[(\varepsilon - \cos^2\theta) - j\frac{18\,000 \cdot \sigma}{f_{\text{MHz}}}\right]^{1/2}} \tag{12}$$

2.5 Antenna designation

In consideration of the variety of LF-MF antenna systems, a suitable antenna designation based only on the electrical length might not be feasible. Therefore, such a designation will have to be implemented on a case-by-case basis.

3 LF-MF antenna systems

3.1 General considerations

LF and MF antennas have in general few radiating elements. The height and the spacing of these elements are not restricted to λ/2. The radiation pattern of these antennas is a function of:

– radiating element cross-section;
– frequency of operation;
– earth system and ground characteristics;
– number of elements and their spacing;
– height of elements above the ground;
– orientation;
– feeding arrangement;
– characteristics of environment.

3.2 Radiating element cross-section

Various radiating structures are in common use, such as self-supporting towers, guyed masts and wire elements. Therefore, the cross-section and, as a consequence, the current in the radiating element vary considerably, affecting its radiation pattern and gain. In the case of radiating towers or masts, triangular or square cross-section are in common use, whilst wire structures are characterized by circular cross-sections. To simplify the calculation of LF-MF antenna patterns and gain for planning purposes, each element of the antenna system is assumed to have the same cross-section. In addition the calculation procedure developed according to the theory included in Annex 1, automatically transforms any triangular or square section into an equivalent circular cross-section.

Input parameters to the calculation procedure

– Type of cross-section (T, S, C)

  Triangular (T), square (S) or circular (C)

– Cross-section dimension (m)

  The section side or, in the case of circular section, its diameter is to be specified.

3.3 Frequency of operation

The operating frequency of a given antenna system has an impact on the resulting radiation pattern. In some cases a given structure is used to operate on more than one channel or may be used to radiate on a channel different from the design frequency. In this case the pattern has to be evaluated at the actual operating frequency to get consistent results.

Input parameters to the calculation procedure

– Frequency (kHz)

  (A default value of 1 000 kHz is included).

3.4 Earth system and ground characteristics

As mentioned in § 2.4, antenna systems at LF-MF are normally placed on an imperfect ground whose characteristics in terms of reflection coefficients, are specified by the dielectric constant and conductivity of the ground. However, efficient antenna systems at LF-MF require an earth system. An ideal earth system would consist of a perfectly conducting circular surface surrounding the base of the antenna.

In practice an earth system is realized by a network of radial conductors of suitable length and diameter that can only be an approximation of an ideal perfectly conducting surface.

The length of radials varies from 0.25 λ to 0.50 λ and the number of radials varies from 60 to 120, whilst their diameter is of the order of a few mm. A typical earth system configuration consists of a circular mesh of 120 wires 0.25 λ long having a diameter of 2.7-3 mm. As usual it is necessary to optimize systems both from the technical and economical point of view.

In the case of directional vertical antennas (see § 3.2.2) each radiating element is normally provided with an individual earth system suitably connected to the others.

To simplify the calculation of LF-MF antenna patterns and gain for planning purposes, the earth system is assumed to be represented by a circular wire network centred on the base of the radiating element. In the case of arrays of radiating elements it is also assumed that the earth system parameters of each of the radiating elements are the same.

Input parameters to the calculation procedure

The following input parameters are needed to evaluate the radiation pattern on imperfect ground:

– Dielectric constant
  (A default value of $\varepsilon = 4$, is included)
– Ground conductivity (S/m)
  (A default value of $S_0 = 0.01$ S/m is included)

The following additional input parameters are needed when an earth system is present:

– Earth system radius (m)
  (A default value of 0.25 λ at the default calculation frequency is included)
– Number of wires of the earth system
  (A default value of 120 wires is included)
– Earth system wire diameter (mm)
  (A default value of 2.7 mm is included).

3.5 Omnidirectional antenna types

3.5.1 Vertical monopoles

A basic radiator at LF-MF is the vertical monopole consisting of a vertical radiating element erected on an earth system. The vertical monopole can be realized by a self-supporting structure or by a guyed mast and can be fed in various ways i.e. by suitably selecting the feeding point height on its vertical structure. The base-fed vertical monopole is one of the most common feeding arrangements.

The radiating element cross-section may vary considerably according to various design approaches. Self-radiating towers show triangular or square sections with side lengths of the order of 5-10 m and recent realization of cage radiators have even larger cross sections.

The vertical monopole height normally ranges from 0.1 λ to 0.625 λ according to various operational requirements (see Part 2).

The base-feed impedance depends both on height and section of antenna. Increasing the section will lower the reactance and increase the bandwidth.

The vertical monopole provides an omnidirectional pattern on the azimuthal plane. However the associated vertical pattern is always significantly affected by the ground constants as well as by other physical parameters, e.g. the electrical antenna height, etc.

The presence of an earth system does not significantly affect the geometrical shape of the pattern, but it significantly affects the efficiency.

3.5.2 Types of vertical monopoles

Vertical monopoles with electrical heights in the range 0.15 λ to 0.3 23 can be easily realized at LF-MF by base-fed radiators (masts or towers) with insulated bases. Also grounded-base constructions with a bottom-fed wire cage (folded monopole or shunt feed) can be used. In many cases relatively short radiators are top loaded to increase the electrical length.

– *Short monopoles*

For economical reasons short monopoles (i.e. with electrical heights considerably less than $\lambda/4$) are normally used at lower frequencies. It should be noted that the use of this kind of antenna for high power transmitters may cause high voltages.

– *Quarter-wavelength monopoles*

This type of radiator, having an electrical height of approximately $\lambda/4$, is well-suited when ground wave service is needed out to a relatively short distance only and sky wave service should begin as close as possible to the transmitting site.

– *Anti-fading antennas*

At LF and MF, fading of the received broadcast signal occurs when the ground-wave field strength has an intensity of the same order of magnitude of the sky-wave field strength. The resulting signal amplitude at the receiver will vary according to their relative phase difference which is affected by the propagation conditions.

Fading can be reduced by controlling the amount of sky-wave power radiated in the desired service area. This control can be achieved by selecting vertical monopoles with electrical heights in the range from 0.5 λ to 0.6 λ. In this case the vertical radiation pattern shows minimum and minor side lobes in the angular sector from 50° to 90° where radiation will be directed to the ionosphere.

3.6 Directional antennas

Directional antenna systems are widely used to:

– limit radiation toward the service area of other stations to reduce interference;

– concentrate radiation toward the desired coverage area;

– achieve higher gain.

At LF-MF the most common directional antenna systems consist of arrays of vertical radiators in two basic arrangements:

– arrays of vertical active elements;

– arrays of vertical passive elements (in combination with one or more active element).

Arrays of passive elements in combination with more than one active element are less frequently encountered in practical applications.

3.6.1 Arrays of active vertical elements

Arrays of vertical active elements are realized by a number of suitably spaced vertical radiators. The desired horizontal pattern directivity depends upon: spacing between the radiators, feeding current amplitude and phase of each element and feed location of each element.

By controlling these parameters it is possible to obtain a wide variety of patterns, even in the simple case of a two-element array. However, higher gains and directivities (and front-to-back ratios) are achieved with arrays with more than two elements at the price of a more complex and expensive realization.

The vertical pattern of an array of vertical radiators will depend on the height of the elements, the ground system, the terrain characteristics, etc.

The radiating elements composing the array can be fed in various ways as previously mentioned, the most common and economical approach being the base-fed configuration.

It is to be noted that the arrays of vertical active elements offer a definitely better control of the resulting directional patterns in comparison to the arrays of vertical passive elements due to the possibility of a more accurate control of the current in each element. However this advantage is achieved at the price of a more complex and expensive feeding arrangement.

Finally it is to be mentioned that whilst the most common approach is to arrange the vertical radiator bases along a line in the horizontal plane, other configurations are common.

An array of four elements having their respective bases located at the corners of a square on the horizontal plane can provide a steerable main lobe of radiation by suitable control of the feeding arrangement. An approximately omnidirectional pattern can also be achieved.

A few examples of patterns of these antenna systems, calculated applying a sinusoidal current distribution, have been included in previous ITU publications [see Manual of Antenna Diagrams, 1978]. However, the calculation procedure described in this Recommendation allows for the evaluation of the radiation pattern of arrays of vertical elements having whatever relative position in the horizontal plane and heights as shown in Fig. 3. It is also possible to take into account radiating elements not base-fed, by specifying the feeding point height.

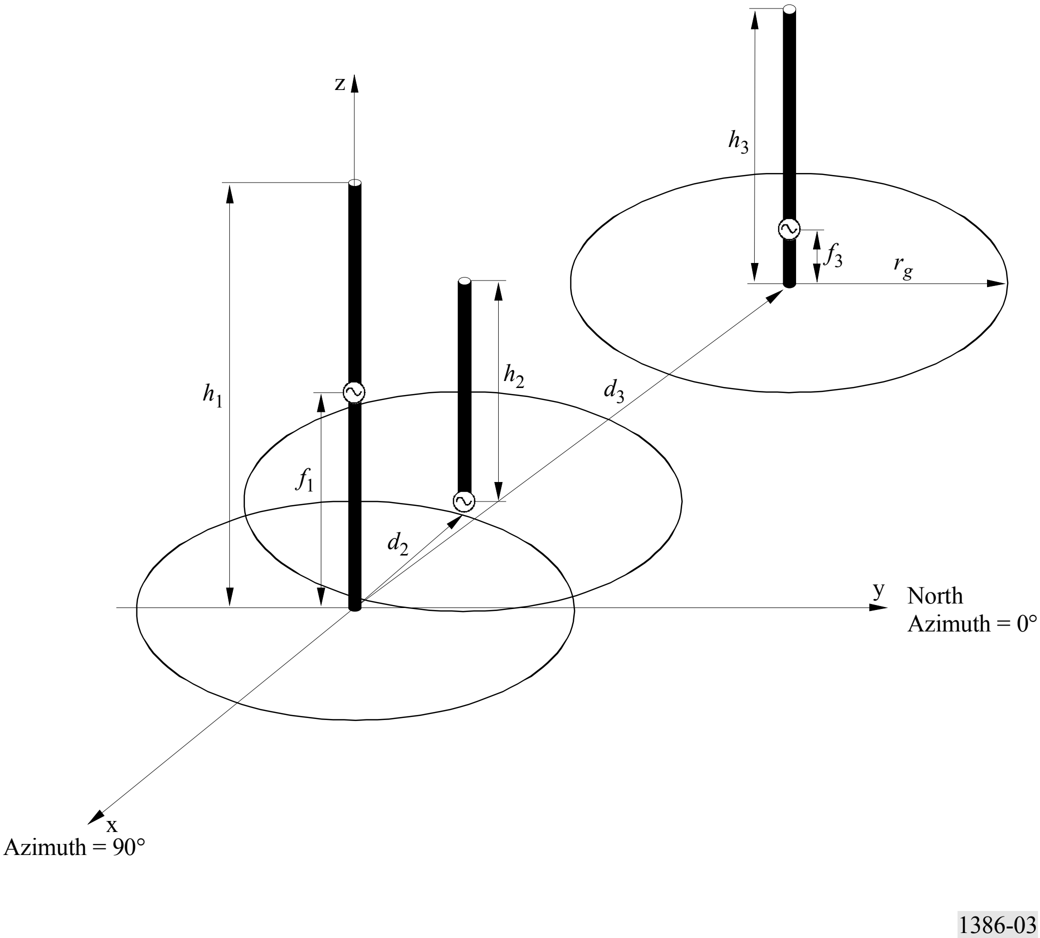
Input parameters to the calculation procedure

With reference to Fig. 3, the following input parameters are needed by the calculation procedure:

– Height of each radiating element (m)
– Distance (m) of each element
  (From element No. 1 considered as the origin of the coordinate system)
– Azimuth angle (degrees) of the line from element No. 1 to each other element
  (Referred to the North direction coinciding with the y-axis)
– Feeding point height of each element (m)
– Feeding voltage amplitude (%)
  (Expressed as a percentage for each element)
– Feeding voltage phase (degrees)
  (Referred to the phase of the voltage applied to element No. 1, assumed to be 0°).

FIGURE 3

Arrays of active vertical elements



3.6.2 Arrays of passive vertical elements

These represent the most economical approach to achieve directional azimuth patterns at the cost of a more cumbersome adjusting procedure.

They are in general realized by an active (base-fed or centre-fed) element with one or more passive element(s) suitably spaced on the horizontal plane. The desired horizontal directivity depends upon the placement of the radiators and the passive reactance placed at the feed point of each passive radiator.

By controlling these parameters it is possible to obtain a wide variety of azimuthal patterns, even in the simple case of a two-element array. However, higher gains and directivities (and front-to-back ratios) are achieved with arrays with more than one passive element at the price of a more expensive realization. It is to be noted that the overall gain of the array does not increase linearly with the number of radiators, so that arrays with many radiators may not represent an economical solution to specific high gain requirements.

The active element can be fed in various ways as previously mentioned, the most common and economical approach being the base-feeding arrangement.

It is to be noted that arrays of vertical passive elements need an efficient control of the current amplitude and phase of the passive elements to achieve the desired azimuth pattern. Once the placement of the elements has been fixed, the only way to realize such control is by inserting a suitable reactance at the feed point of the passive element. While the desired theoretical value of such reactance can easily be determined, a non-negligible amount of on-site adjustment may be needed to achieve the desired effect in practice.

Finally it is to be mentioned that for specific (low-power, low-directivity) applications, it is possible to use one or more guy ropes as passive radiators in a single mast antenna system, provided that a suitable base reactance is introduced.

These now widely used arrays were not included in the previously mentioned ITU publications due to the difficulty of correctly calculating the currents induced in the passive elements when applying the sinusoidal current distribution method. The calculation procedure described in this Recommendation allows their feed point reactance to be taken into account (assumed, for simplicity, to be lossless).

Furthermore, as in the previous case, the fed element (considered to be placed at the origin of the coordinate system shown in Fig. 1) may have a variable feeding point height and the various passive elements may be located in whatever mutual position in the horizontal plane, as shown in Fig. 4.

Input parameters to the calculation procedure

With reference to Fig. 4, the following input parameters are needed by the calculation procedure:

– Height of each radiating element (m)

– Distance (m) of each element
  (From the active element No. 1 considered as the origin of the coordinate system)

– Azimuth angle (degrees) of the line from element No. 1 to each other element
  (Referred to the North direction coinciding with the y-axis)

– Feeding point height of the active element (m)

– Base reactance of the passive elements (Ω)
  (Both positive and negative values can be entered).

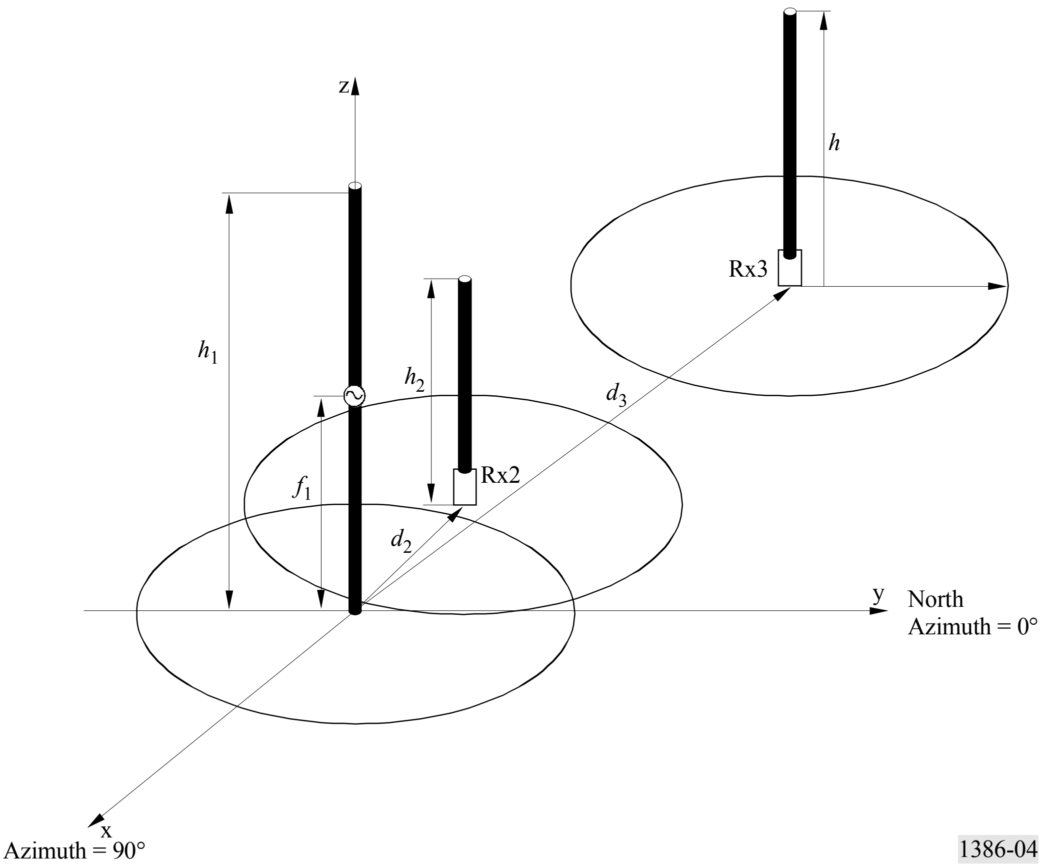
3.7 Other types of antennas

Electrically short antennas generally have low radiation resistance, poor efficiency, high capacitive reactance and high *Q* (hence narrow bandwidth). A capacitive top-loading of such antennas improves all these characteristics. In general, top-loading can be realized in two different ways. One way is by adding on the top of the mast a number of horizontal wires so that the mast and the wires form a so-called "T" shaped radiating structure. A second type of top-loaded structure is the "umbrella" antenna, which is made of a number of radial wires connected to the top of the vertical mast and inclined downwards.

The radiation patterns in horizontal and vertical planes are very similar to those of a vertical monopole.

FIGURE 4

Arrays of passive vertical elements



3.7.1 T-antennas

T-antennas consist of a suitably fed vertical radiator, connected at its upper end to the centre of a horizontal element conveniently supported at its ends. Base feeding of such a radiating element is most common.

This type of antenna is sometime used, especially at LF, for applications where the horizontal element (often called a capacity hat) is used to obtain a more uniform current distribution along the main vertical element. The horizontal element often consists of one or more short horizontal wires as shown in Fig. 5. If the length of the horizontal radiator is short compared to wavelength the T-antenna can be assumed to be non-directional. It should be noted that the radiation polarization of this antenna is principally vertical with a small horizontal component.

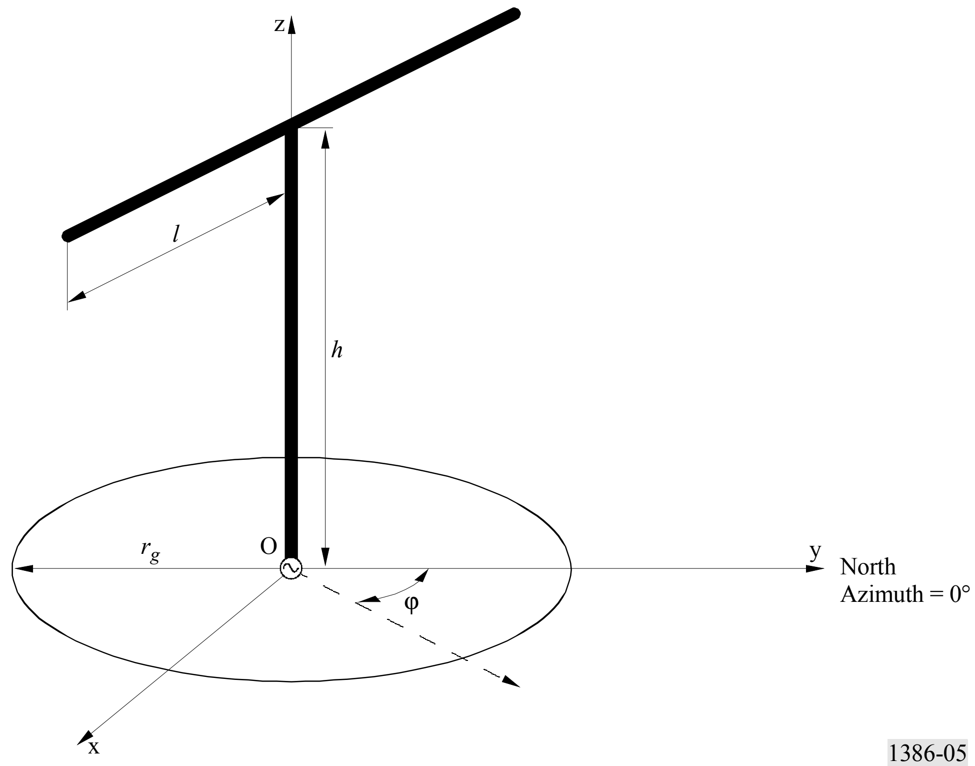
Input parameters to the calculation procedure

With reference to Fig. 5, the following input parameters are needed by the calculation procedure:

– Vertical element height (m)
– Horizontal element half-length (m)
– Azimuth of the direction normal to the horizontal element referred to the North (degrees).

FIGURE 5

T-antenna



3.7.2 Umbrella antennas

The umbrella antenna basically consists of a short vertical radiator which is suitably fed, the base feeding being the usual arrangement. In order to improve the antenna's efficiency by increasing the radiation resistance, the typically short physical height of the vertical radiator is electrically increased by capacitively top loading the radiator. This is done by connecting the upper end of the vertical radiator to a number of radiators of equal length, sloping downwards at equal angles with respect to the vertical. These sloping radiators, evenly distributed azimuthally, constitute a cone (or umbrella) on top of the vertical radiator. The sloping radiators are conveniently supported and insulated at their lower ends, as shown in Fig. 6.

If the cone has a dimension which is small compared to a wavelength (typically 0.1 λ) and a sufficient number of radiators (in general not exceeding 8) constitute the cone, the "umbrella" antenna can be assumed to be non-directional.

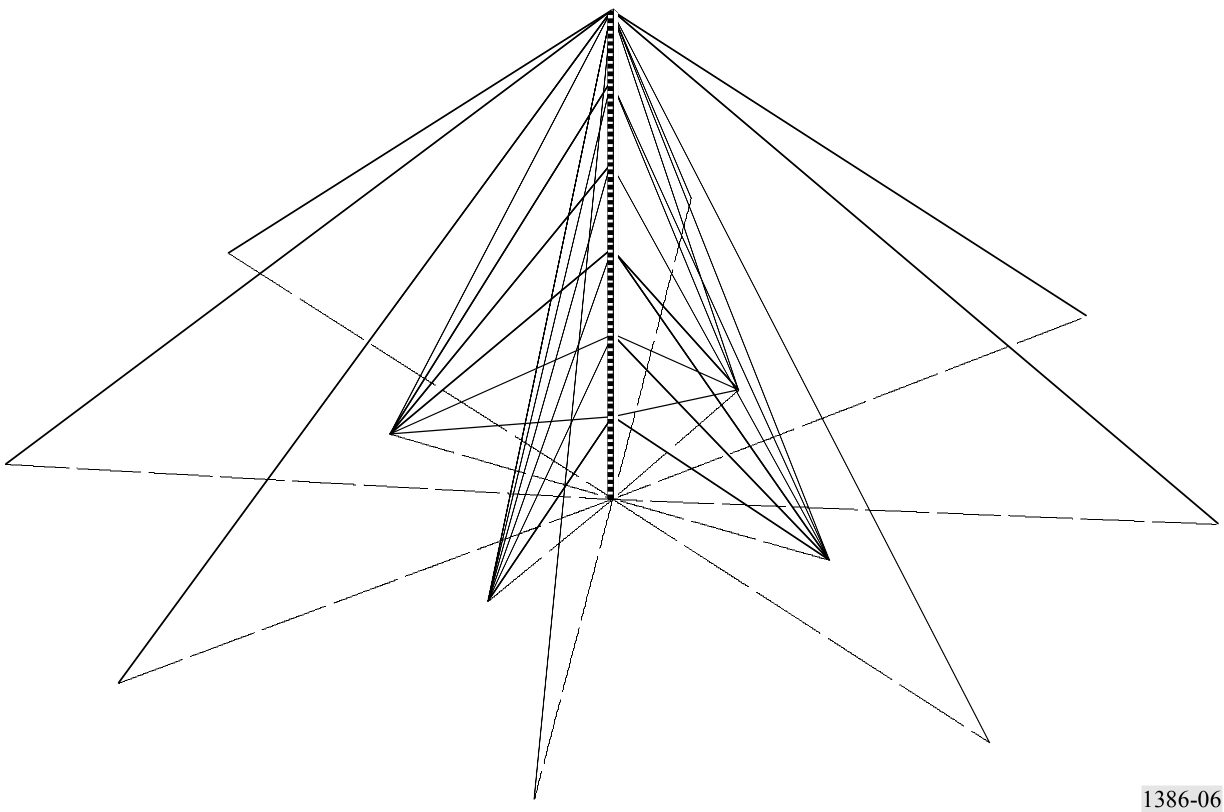
Input parameters to the calculation procedure

With reference to Fig. 6, the following input parameters are needed by the calculation procedure:

– Vertical element height (m)
– Number of radials
– Radial length (m)
– Slope of the radials with respect to the vertical element (degrees).

FIGURE 6

Umbrella antenna



3.7.3 Angle radiator cage antennas

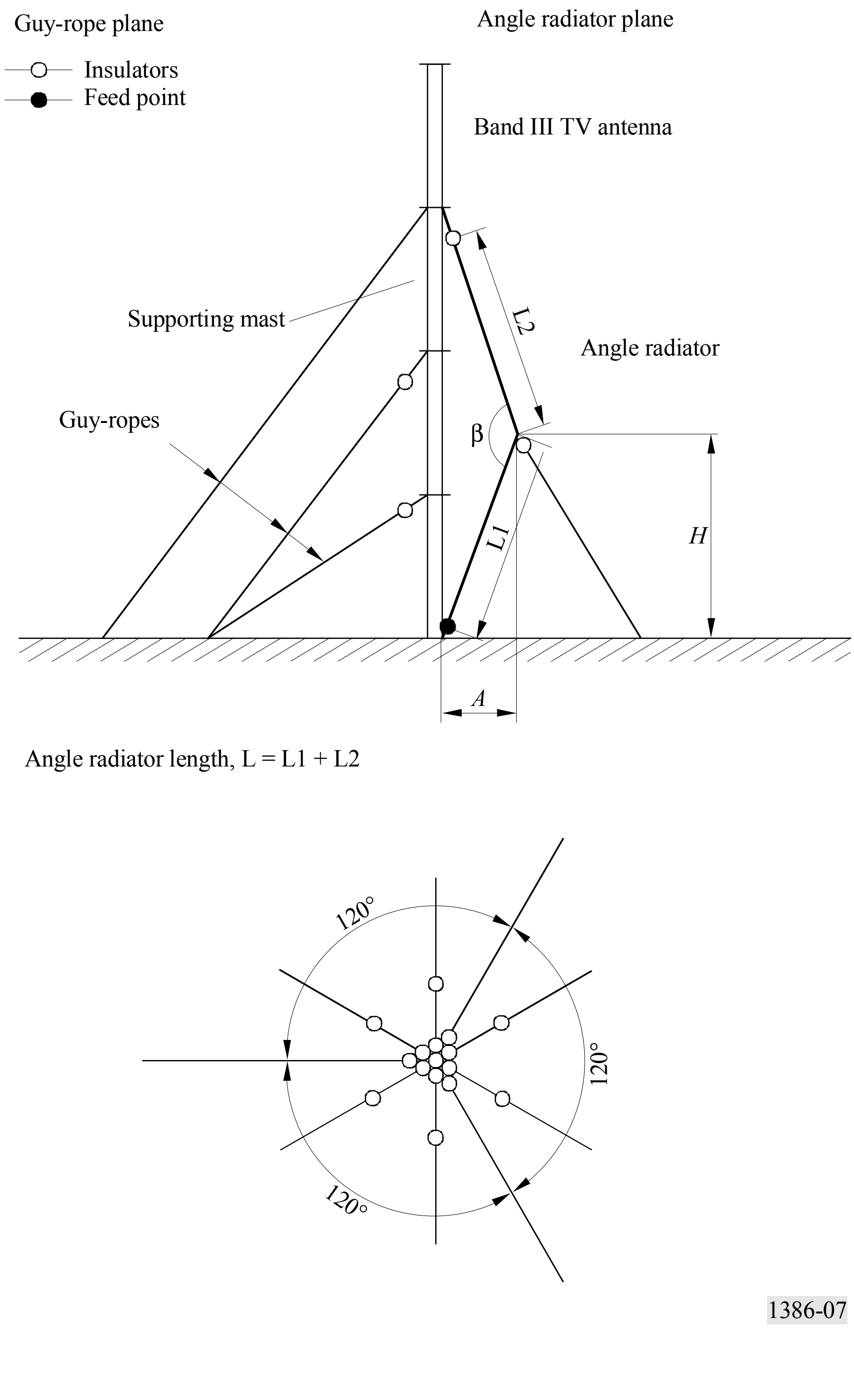
The most important design feature of this antenna type is the possibility that omnidirectional or directional patterns can be achieved by specially arranged angle radiators suspended by one single high, grounded supporting mast only. This type of antenna system permits undisturbed radiation of various frequency bands with diverse radiation diagrams from a single basic support. It can be formed by combining an MF transmitter antenna with an existing VHF/UHF tower.

This antenna type is designed so that the supporting structure does not affect the electromagnetic radiation characteristics. Hence, the angle radiators are arranged and shaped for a relatively loose coupling to the mast with its guy ropes. Figure 7 shows a model of an angle radiator antenna combined with a supporting mast. The angle radiators (three or six) are positioned around the mast, between the guy-ropes, with equal angular spacing. The base of each angle radiator is attached to an insulated conductive ring, suspended around the mast base. At their outer extremities the angle radiators are supported by additional suspension ropes. These points of attachment must also be insulated.

FIGURE 7

Angle radiator cage antenna

Top and front view of a 230 m support mast with three sets of guy-ropes



The guy-ropes of MF vertical mast radiators are coupled electromagnetically with the radiating element. Their influence on the radiation characteristics is highly critical if any non-insulated section of the guy-rope system has an electrical length, which is exactly or approximately equal to $\lambda/4$. To minimize this influence, the guy-ropes are usually divided into insulated sections no longer than λ/10. The supporting mast and the guy-ropes of the structure are purely passive elements. To optimize the radiation pattern the induced currents on the non-insulated guy-ropes can be influenced by their distance from the angle radiators. Only in specific cases when the supporting mast is λ/2 or 3 λ/4 a high partial separation by insulators of the guy-ropes is necessary.

Various design parameters can be adjusted to optimize the impedance matching and radiation patterns. In this context the azimuth distance of the angle radiators between the guy-ropes and the radial distance from the supporting mast are of utmost importance. These are defined by the position of the outer extremity of the angle radiators, determined in terms of its radial distance, *A*, from the mast and its height above ground, *H* (see Fig. 7). Further influential factors are the overall electrical length, L, of the angle radiators, and the element angle, β (see Fig. 7).

Input parameters to the calculation procedure

With reference to Fig. 7, the following input parameters are needed:

– Number of angle radiators: *N*
– Angle radiator length: L = L1 + L2
– Radial distance of the outer extremity of the angle radiator from the mast: *A*
– Height above ground of the outer extremity of the angle radiator: *H*
– Element angle, β: fixed by the height of the feedpoint and the height of the point of attachment of the top rope to the mast.

The ripple of omnidirectional pattern depend on antenna design and may lie between less than 0.2 dB and about 2.5 dB.

To create directional MF radiation patterns three methods can be adopted:

Method 1: Grounding only one of several angle radiators.

Method 2: Additional passive radiators.

Method 3: Feeding one angle radiator with different current in amplitude and phase relative to the other equal-phased radiators.

However, a specific irregularity has to be taken into account. Normally, for AM modulation a bandwidth of ±4.5 kHz is used. At the cut-off frequencies a variation of the radiation pattern can be observed, especially in the sector of limited radiation. In this area the variation in field strength exceeds ±6 dB when using Method 1 or 2. As a consequence, the receive signal would be deteriorated by an additional distortion factor. At least an additional distortion of about 3% occurs when the asymmetrical sideband deflection is 6 dB, and there would be a phase difference of 10°. The deterioration of the receive signal can be avoided, essentially by double feeding the antenna system with a power splitting network (Method 3). In this case, two more parameters are available to adjust the radiation pattern: the magnitude and phase current variation of the feed network.

Additional input parameters to the calculation procedure for directional patterns
Amplitude and phase of the network currents: – For one angle radiator – For the other equal-phased angle radiators.

For an implemented antenna installation the angle radiators are fed with equal amplitude and phase during the day service to get an omnidirectional pattern. For the night service a radiation reduction of 12 dB in one direction is achieved by feeding one angle radiator out of phase and amplitude relative to the other equally phased angle radiators. The input impedance is matched for a standing wave ratio of $s < 1.2$ over a bandwidth of ±4.5 kHz.

The calculation of angle radiator antenna characteristics can be carried out with the numerical electromagnetic code I_NAC_3. As the calculation algorithm comprehensively described in § 5 of Annex 1, where an early version of the MININEC programme is applied, this code is also based on the direct integration of Maxwell's equations by the method of moments, and the underlying theory corresponds with the numerical algorithm based on the well-known and publicly available NEC-4 (GNEC) code. It is expected that the calculation results will be similar.

4 Calculation of radiation patterns and gain

4.1 General considerations

There are two inter-related aspects that make a unified approach to calculate antenna patterns extremely important:

– national broadcasting station planning and design;

– conformity of the station parameters to international frequency plans.

These factors lead to the development of a unified calculation procedure able to:

– be applicable to several broadcasting antenna types;

– as far as possible, calculate pattern values directly (not interpolate);

– display pattern calculation results both in graphical and numerical form.

4.2 Currently available analytical approaches

Several mathematical approaches with various difficulty levels are presently available to solve the antenna pattern equations. They can be basically grouped as follows (in order of increasing accuracy):

– sinusoidal current distribution theory,

  where the radiating element cross-section is neglected;

– non-sinusoidal current distribution theory,

  where the current in the radiating elements depends on their length and cross-section;

– numerical integration methods,

  where the radiating structure is decomposed into thin short elements, the current distribution in each element is assumed to have an elementary given function, and the overall current distribution, impedances and radiation pattern are obtained by the integration of Maxwell's equations.

ANNEX 1

TO PART 1

The calculation procedure

1 Main objectives

Before selecting any particular calculation procedure, it is necessary to consider the particular purpose that it should fulfil, i.e. the calculation of antenna parameters to be used for planning. Therefore the following two basic calculations are to be performed:

– *antenna pattern* (with gain values relative to the maximum);

– *directivity gain* (not including losses).

2 Main constraints

The selected calculation procedure should be:

– easy to be implemented on small computers;

– sufficiently accurate for the above objectives;

– highly interactive with unskilled operators;

– fast enough if to be integrated into a planning system;

– homogeneously and easily applicable to all considered antenna types;

– needing a limited number of input parameters.

3 Comparative analysis of available approaches

Table 1 summarizes the results of a comparison of the various methods, listed in § 4.2 of Part 1, as a function of their conformity with the above constraints, when applied to the calculation of LF-MF antenna patterns:

TABLE 1

Comparison of calculation methods

Requirement	Sinusoidal	Non-sinusoidal	Numerical
Implementation on small computers	YES	YES	YES(1)
Accurate for planning	NO(2)	NO(3)	YES
Interactive with unskilled operators	YES	YES	NO(4)
Fast for integration in a planning system	YES	YES	YES(5)
Generalized and easy application to all antenna types	NO(6)	NO(6)	YES
Need for minimum number of input parameters	YES	NO	NO

(1) With some limitations presently available small computers may run numerical methods.

(2) Inaccuracies arise when thin wire approximation is no longer applicable.

(3) Inaccuracies arising when an earth system is present may be unacceptable.

(4) A suitable user interface can be implemented to ensure high interactivity, see below.

(5) Although time-consuming procedures are to be used, fast implementation in planning systems can be envisaged, see below.

(6) Generalized application to all the envisaged LF-MF antenna types may not be practical resulting in cumbersome analytical developments.

From Table 1 it appears that the sinusoidal current distribution method applied in the past by the former CCIR, may not represent the best approach, since to get sufficiently accurate results by the application of the sinusoidal current distribution theory, the following basic conditions are to be met:

– the radiating elements are thin (negligible section) perfectly conducting wires;

– the currents in the radiating elements are sinusoidal;

– mutual effects between radiating elements are neglected;

– the radiating structure is situated on a flat, homogeneous imperfectly conducting ground.

The above conditions are seldom respected in the case of LF-MF antennas, where the radiating element cross-section is often non-negligible (for instance in the case of self-radiating masts or towers) and the mutual effects between the elements cannot be neglected (for instance in the case of passive vertical elements, etc.). Furthermore the application of the sinusoidal current distribution theory to antenna other than vertical or horizontal arrays may result in complicated algorithms depending on the particular antenna's geometry.

On the other hand the non-sinusoidal current distribution theory, whilst resulting in a more accurate definition of the antenna parameters, has the same drawbacks. Its generalized application to the various antenna types encountered in LF-MF may prove to be complicated.

4 The numerical method

This method was selected as the preferred approach. However, the basic numerical method was to be considerably re-arranged in order to satisfy the requirements listed in Table 1. The resulting procedure appears to meet the constraints listed in § 2. The only condition to be checked is the feasibility of it being directly integrated into a planning context. If this condition will not be met, the procedure can still be applied to derive a set of tabulated values with suitable resolution (as indicated in § 2.2.2 to Part 1), to be interpolated in planning. In a personal computer environment, the calculation procedure has been implemented by an integrated software package having a high degree of interactivity with the operator realized by the following characteristics:

– menu-driven commands;

– video mask data entry;

– wide use of high-resolution graphics;

– tabulated data output addressable to console and/or printer;

– calculation results stored in files for retrieval.

5 The calculation algorithm

The numerical methods are based on the direct integration of Maxwell's equations through a number of different approaches extensively described in current literature. The procedure selected in this Recommendation is an early version of the MININEC programme which was developed in the past. The underlying theory can be summarized as follows: A well-known relation derived from the Maxwell's equation in the case of circular cross-section wires is:

$$\mathbf{E}_{inc} \cdot \mathbf{s}(s) = \nabla\varphi \cdot \mathbf{s}(s) + j\,\omega\,\mathbf{A} \cdot \mathbf{s}(s) \tag{13}$$

where

$\mathbf{E}_{inc}$: incident electrical field radiated by a current density, **J**, flowing in a wire radiator

φ: scalar potential (function of position) on the wire radiator

A: vector potential on the wire radiator

$\mathbf{s}(s)$: unit vector parallel to the wire radiator axis

ω: $2\pi f$

with f: frequency of calculation.

It can be shown that:

$$\varphi = -\frac{1}{j\,\omega\,\mu\,\varepsilon}\ \nabla \cdot \mathbf{A} \tag{14}$$

where:

μ: magnetic permeability

ε: dielectric constant

and

$$\mathbf{A} = \frac{\mu}{4\pi} \iiint_{\upsilon} \mathbf{J}\rho / r \, \mathrm{d}u \tag{15}$$

where:

- ρ: charge density
- r: distance from each point on charge distribution to the observation point
- υ: volume of the wire radiator.

In the case of circular section, c, wires equation (14) becomes:

$$\varphi = \frac{1}{4\,\pi\,\varepsilon} \int_c q(s)\, k(s - s')\, \mathrm{d}s'$$

where:

$$k(s - s') = \frac{1}{2\,\pi} \int_{-\pi}^{\pi} \frac{e^{-\mathrm{j}kr}}{r} \, \mathrm{d}\varphi \tag{16}$$

and $q(s)$ is the linear charge density, i.e.:

$$q(s) = -\frac{1}{\mathrm{j}\,\omega} \frac{\mathrm{d}I}{\mathrm{d}s} \tag{17}$$

Equation (13), which is the one to be solved for our purposes, can be put in the general form:

$$v = F(i) \tag{18}$$

where:

- v: known excitation (voltage applied to the antenna)
- i: unknown response (current in the antenna)
- F: a known linear (integral) operator.

The objective is to determine i when F and v are specified. The linearity of the operator makes a numerical solution possible. In the moment method the unknown response function is expanded as a linear combination of N terms and written as:

$$i(s) \approx c_1\, i_1(s) + c_2\, i_2(s) + \cdots\cdots + c_N\, i_N(s) = \sum_1^N c_n\, i_n(s) \tag{19}$$

Each c_n is an unknown constant and each $i_n(s)$ is a known function usually referred as a basis or expansion function having the same domain of the unknown function, I. Using the linearity of the operator, F, equation (18) can be re-written:

$$\sum_1^N c_n\, F(i_n) = I \tag{20}$$

The selection of the basis functions plays a fundamental role in any numerical solution and it is normally performed among basis functions which allow for an easy evaluation of $F(i_n)$, the only task remaining then is to find the unknown constants c_n.

Sub-domain functions (which are non-zero only over a part of the domain of the function $i(s)$ which corresponds to the surface of the structure) are the most commonly used since they do not require a prior knowledge of the function they must represent.

A straightforward approach is to subdivide the structure into N equal non-overlapping segments, as shown in Fig. 8, and select the pulse function, shown in Fig. 9 as the basis function.

FIGURE 8

Segmentation of the antenna's structure

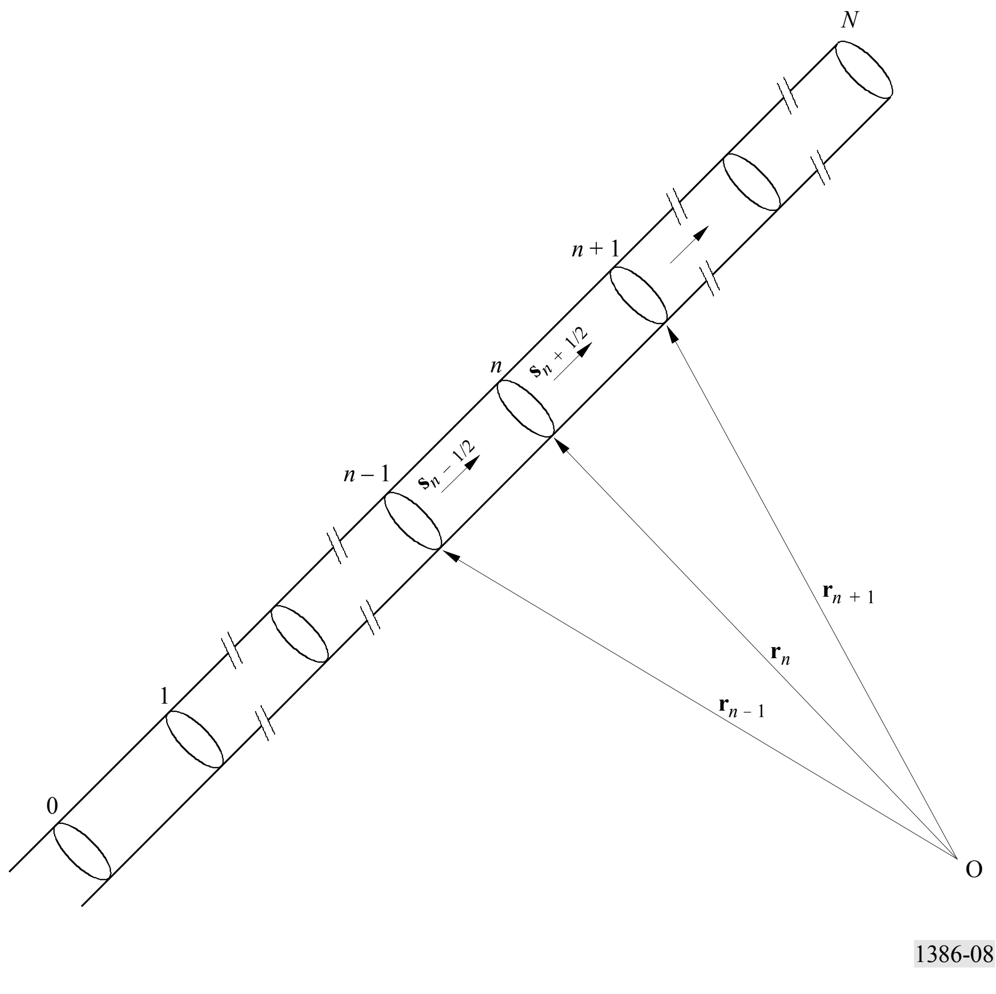
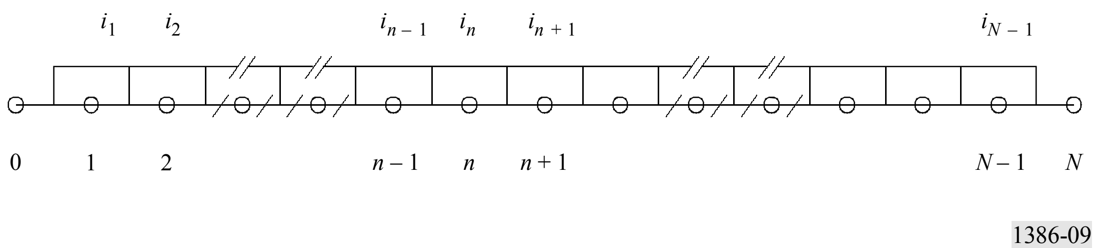


FIGURE 9

Pulse functions



This approach allows one to considerably simplify the calculation algorithm and computation time, while maintaining an acceptable accuracy. In Fig. 8 the vectors $\mathbf{r}_0$, $\mathbf{r}_1$,..........., $\mathbf{r}_{N+1}$ are defined with respect to the reference coordinate system.

The unit vectors parallel to the wire axis for each segment shown are defined as:

$$\mathbf{s}_{n+1/2} = (\mathbf{r}_{n+1} - \mathbf{r}_n) \Big/ |(\mathbf{r}_{n+1} - \mathbf{r}_n)| \tag{21}$$

The n-pulse function, $i_n(s)$, used in the present approach is then defined as:

$$i_n(s) = \begin{cases} 1 & \text{for } s_{n-1/2} < s < s_{n+1/2} \\ 0 & \text{otherwise} \end{cases} \tag{22}$$

where the points $s_{n+1/2}$ designate the segment mid-points at:

$$s_{n+1/2} = (s_{n+1} + s_n) / 2 \tag{23}$$

and

$$\mathbf{r}_{n+1/2} = (\mathbf{r}_{n+1} + \mathbf{r}_n) / 2 \tag{24}$$

Assuming s_m as the observation point for both the vectors $\mathbf{E}_{inc}$ and $\mathbf{A}$, equation (13) can be expanded as:

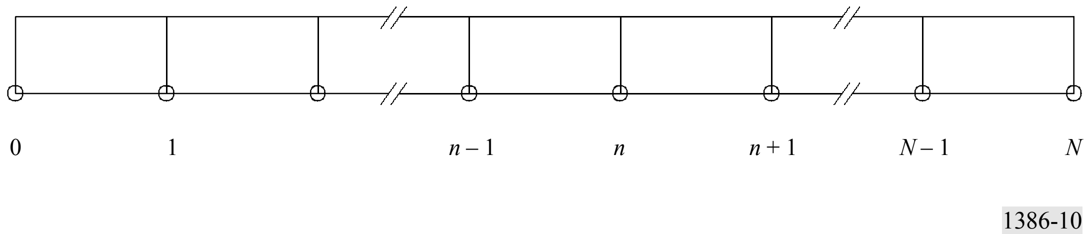
$$\mathbf{E}_{inc}(s_m) \cdot \{[(s_m - s_{m-1}) / 2]\, \mathbf{s}_{m-1/2} + [(s_{m+1/2} - s_m) / 2]\, \mathbf{s}_{m+1/2}\} =$$

$$\mathrm{j}\omega\mathbf{A}(s_m) \cdot \{[(s_m - s_{m-1}) / 2]\, \mathbf{s}_{m-1/2} + [(s_{m+1/2} - s_m) / 2]\, \mathbf{s}_{m+1/2}\} + \varphi(s_{m+1/2}) - \varphi(s_{m-1/2}) \tag{25}$$

Currents are expanded in pulses centred at the junctions of adjacent segments (see Fig. 10).

FIGURE 10

Current expansion by pulses



Pulses are omitted from the wire ends. This is equivalent to placing a half-pulse of zero amplitude at each end, thus imposing the boundary conditions for zero current at unattached wire ends. By substituting equation (20) in equation (25) the system of equations is produced and expressed in matrix form. Each of the matrix element $\mathbf{Z_{mn}}$, associated with the n-th current and the s_m observation point involve scalar and vector potential terms.

These terms have the following integral form:

$$\psi_{m,u,v} = \int_{s_u}^{s_v} k(\mathrm{s}_m - \mathrm{s}')\,\mathrm{ds}' \tag{26}$$

where:

$$k(\mathrm{s}_m - \mathrm{s}') = \frac{1}{2\pi}\int_{-\pi}^{\pi} \frac{\mathrm{e}^{-\mathrm{j}kr_m}}{r_m}\,\mathrm{d}\varphi \tag{27}$$

and

$$r_m = \left[(\mathrm{s}_m - \mathrm{s}')^2 + 4a^2 \sin^2(\varphi/2)\right]^{1/2} \tag{28}$$

a being the radius of the wire radiator.

$$[\mathbf{Z_{mn}}]\,[\mathbf{I_n}] = [\mathbf{V_m}] \tag{29}$$

where:

$$\begin{aligned}\mathbf{Z_{mn}} = -1/4\mathrm{j}\pi\omega\varepsilon\ \{k^2\,(\mathbf{r}_{m+1/2} - \mathbf{r}_{m-/2}) \cdot (\mathbf{s}_{n+1/2}\,\psi_{m,n,n+1/2} + \mathbf{s}_{n-/2}\,\psi_{m,n-/2,n}) - \\ - [\psi_{m+1/2,n,n+1}/(\mathrm{s}_{n+1/2} - \mathrm{s}_n)] + [\psi_{m+1/2,n-1,n}/(\mathrm{s}_n - \mathrm{s}_{n-1})] + \\ + [\psi_{m-1/2,n,n+1}/(\mathrm{s}_{n+1} - \mathrm{s}_n)] - [\psi_{m-1/2,n-1,n}/(\mathrm{s}_n - \mathrm{s}_{n-1})]\}\end{aligned} \tag{30}$$

and

$$\mathbf{V_m} = \mathbf{E}_{inc}(\mathrm{s}_m) \cdot (\mathbf{r}_{m+1/2} + \mathbf{r}_{m-1/2}) \tag{31}$$

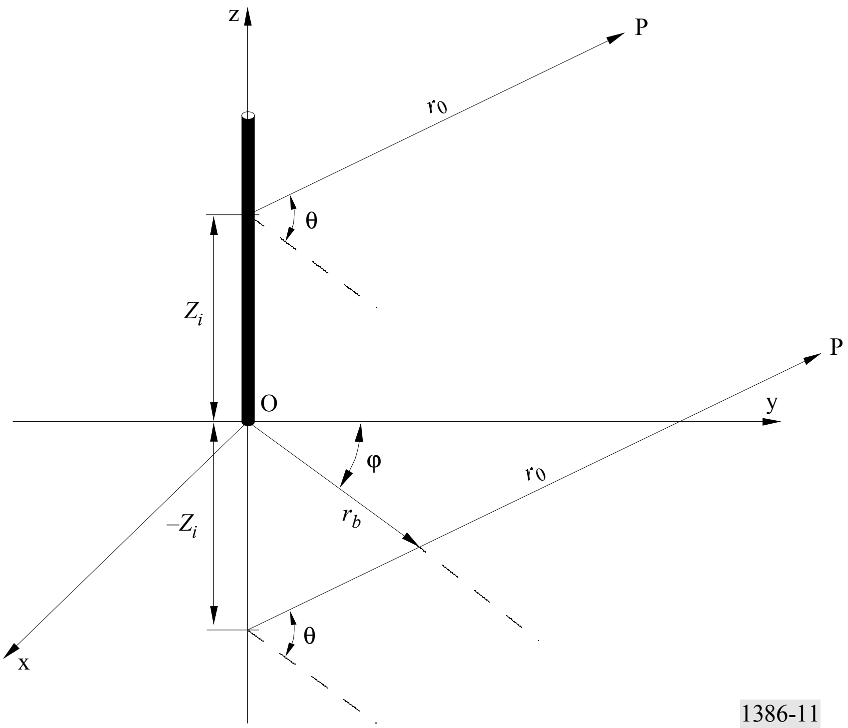
$[\mathbf{Z_{mn}}]$ is a square matrix and $[\mathbf{I_n}]$ and $[\mathbf{V_m}]$ are column matrices, where $n = 1, 2, ..., N$ and $m = 1,......, N$; N being the number of pulses, i.e. of total unknowns. $[\mathbf{V_m}]$ represents an applied voltage that superimposes a constant tangential electrical field along the wire for a distance of one segment length centred coincident with the location of the current pulses. Therefore, for instance, in a transmitting antenna all elements of $[\mathbf{V_m}]$ are set to zero except for the elements corresponding to the pulses located at the desired feed points.

In the adopted calculation procedure the $[\mathbf{Z_{mn}}]$ matrix is filled by the evaluation of an elliptical integral and use of Gaussian quadrature for numerical integration.

When an antenna system is located on a perfectly conducting ground, the method of images is applied to solve for the currents on wires located over the ground. In this case, an antenna system represented by N segments may be replaced by the original structure and its image, as schematically shown in Fig. 11. The far field is obtained by summing the contributions of a direct ray and a reflected ray from each current pulse. Hence, there will be twice as many segments and $2N$ unknowns to be determined. The image currents $I_{N+1}, ..., I_{2N}$ will be equal to the currents on the original structure $I_1,.........., I_N$ so that $I_N = I_{2N-n+1}$. Therefore the equation $[I_{2N}] = [V_{2N}][Z_{2N,2N}]$ contains redundant information and the $2N$ unknowns can be reduced to N.

FIGURE 11

Incident and reflected ray



In the case of an imperfectly conducting ground, the field due to the reflected ray is calculated according to § 2.4.1 of Part 1. The application of the reflection coefficients depends on the ground surface impedance at the reflection point and the angle of incidence. The (imperfect) ground surface impedance can be expressed by:

$$Z_g = 1/\sqrt{(\varepsilon / \varepsilon_0) - j(\sigma / \omega \, \varepsilon_0)} \tag{32}$$

where:

ε: dielectric constant of the ground

ε_0: dielectric constant of empty space

σ: ground conductivity

ω: $2\pi f$

with f: frequency of calculation.

The surface impedance when the reflection point occurs on the earth system is given by:

$$Z_{gs} = j \sqrt{\varepsilon_0 \mu_0} \; (\omega \, r_b / n_r) \log (r_b / n_r d_w) \tag{33}$$

where:

r_b: distance of the reflection point from the current pulse on the horizontal plane

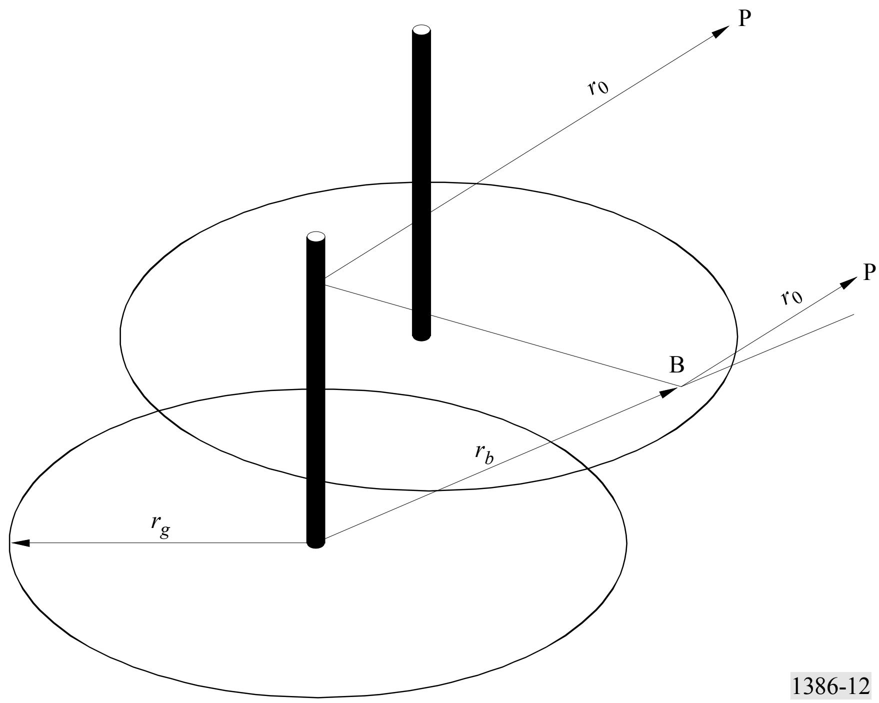
n_r: number of earth system wires

d_w: diameter of earth system wires.

When the reflection point occurs on the earth system, the actual impedance is given by the parallel impedance of the imperfect ground and of the earth system impedance. Therefore, it is necessary to calculate r_b, as shown in Fig. 12, in order to evaluate if the reflection point lies internally to any of the existing earth systems (this requires a special procedure particularly in the case of vertical arrays where in general, each element has its own earth mesh).

FIGURE 12

Reflection on the earth system



In the case of arrays of passive vertical elements there is the need to take into consideration impedances located in the radiating structure (such as base reactance in passive reflector systems). If an impedance $Z_L = R + jX$ is added to the structure so that its location coincides with that of one of the non-zero pulse functions, then the load introduces an additional voltage (drop) equal to the product of the current pulse magnitude and Z_L. In this case equation (33) becomes:

$$[\mathbf{Z'_{mn}}][\mathbf{I_n}] = [\mathbf{V_m}] \tag{34}$$

where:

$\mathbf{Z'_{m,n}} = Z_{mn}$ for $m \neq n$

$\mathbf{Z'_{mn}} = Z_{mn} + Z_L$ for $m = n$.

Hence the impedance value is simply added to the diagonal impedance element of the matrix-corresponding to the pulse in the specific wire.

The power gain of an antenna in a given direction (θ, φ) in the reference coordinate system is:

$$G = 10 \log \left[4\pi \, P(\theta, \varphi) / P_{IN} \right] \quad (35)$$

where:

$P(\theta, \varphi)$: power radiated per unit steradian in the direction (θ, φ)

P_{IN}: total input power to the antenna.

They are calculated according to the following formulas:

$$P_{IN} = \sum_{1}^{N} \mathrm{Re}\left[V_i \, I_i^* \right] / 2 \quad (36)$$

where:

N: total number of the feeding sources

V_i: voltage of the i feeding sources

I_i: current of the i feeding sources

I_i^*: complex conjugate of I_i.

Therefore:

$$P(\theta, \varphi) = r_0^2 \; \mathrm{Re}\left[E \cdot H \right] / 2 = \left[r_0^2 / 2\eta \right] \left[E \cdot E^* \right] \quad (37)$$

where:

r_0: magnitude of the position vector in the direction (θ, φ) (see Fig. 11)

E: electrical field

H: magnetic field

η: free space impedance.

The gains are calculated for individual orthogonal components of the fields determined from equation (35). The power gain thus obtained is in dB above an isotropic antenna. A gain normalizing factor is then calculated so that the pattern values will be referred to the maximum, assumed to be 0 dB (see also Recommendation ITU-R BS.705).

The results of convergence tests performed on the adopted approach indicated that for dipoles shorter than λ, as few as 4 segments can give an accurate result. For best results, 8 to 18 segments should be used, whilst for a wavelength antenna as many as 30 to 36 segments would be recommended.

In addition, the accuracy of the method depends also on the ratio of segment length to radius l_s/a. Test data indicates that accurate results are achieved for thick wires when l_s/a is 2.5 or greater. This condition is generally fulfilled in the present application.

As previously mentioned, the original programme required extensive modifications to allow for:

– calculation on imperfect ground (and not only in free space or perfect ground);
– calculation in the presence of an earth system;
– fast and interactive data entry;
– customization to specific antenna types;
– implementation of graphical and tabular data output.

6 Basic assumptions

In order to meet the requirements listed in Table 1 and hence get a computer program able to run on small computers, a number of basic assumptions are needed to reduce the computation time and the memory requirements. They both depend on the number of wires used to represent the antenna system. The resulting compromise approach is:

– maximum number of wires: 10;

– maximum number of segments: 180.

This solution allowed for the pattern calculation of arrays of up to 10 elements with the following conditions:

– each antenna element is considered to be a circular cross-section wire having the same area as its original cross-section;

– ratio of segment length to radius, l_s/a is > 2.5;

– arrays with no more than 10 elements are considered;

– calculation on imperfect ground is performed by the evaluation of the reflection coefficients;

– any earth system is assimilated to a perfectly conducting surface around the element.

The first condition indeed limits the accuracy of the approach. However, although suitable verification with measured patterns will be needed, the overall accuracy is deemed to be, in any case, substantially improved with respect to the conventional sinusoidal current theory and fully satisfactory for planning purposes.

The second condition also limits the overall accuracy, even if it is generally fulfilled in the LF-MF antenna case. An option may be implemented to give direct access to the calculating procedure to calculate, within the above-mentioned limitations, multi-wire structures, i.e. structures having elements not respecting the condition $l_s/a > 2.5$. The same option can also be used to calculate the patterns of antenna types not included in the built-in set.

The third condition does not appear too limiting, since arrays of up to 10 vertical elements are not very frequently encountered at LF-MF and a wide range of other radiating structures can easily be covered by a 10 wire representation. A slightly more stringent requirement is that the overall number of segments should not exceed 180. The software includes an automatic segmentation routine that optimizes the number of segments for each wire as a function of the wavelength and cross-section for the best accuracy. However, in a 10 wire-antenna system it is evident that the segment number cannot exceed 18 segments per wire.

The fourth condition is the straightforward application of the flat and imperfectly conducting ground model defined by its conductivity and dielectric constant, as implemented in procedures previously developed in the former Study Group 10. The implementation of this feature in the programme has demanded extensive revision of the original calculation routine applicable only to perfect ground. The option to perform calculation on perfect ground has been retained in the programme, since it is used to evaluate the azimuth of maximum radiation.

The fifth condition results in assuming the earth system circular and surrounding the radiating elements. In the case of vertical arrays each radiating element is supposed to have (as in practice) its own circular earth system mesh whose parameters (such as diameter, number and diameter of wires) are common to all elements.

In order to allow for easy data entry, suitable video input masks have been implemented together with menu driven options allowing the user to perform the following calculations:

– gain;
– horizontal pattern at given elevation angle with desired resolution;
– vertical pattern at given azimuth angle with desired resolution;
– creation of full pattern data file for external usage and/or Samson-Flamsteed projection.

PART 2 – PRACTICAL ASPECTS OF LF AND MF TRANSMITTING ANTENNAS

1 Introduction

The conventional method to assess the performance of an LF-MF antenna in the past consisted of evaluating its horizontal radiation pattern by measuring the field strength at ground level.

Today a far better accuracy is provided by evaluating the total radiation patterns of LF-MF antennas by measurements performed with a specially equipped helicopter.

2 Measurements of antenna radiation patterns

2.1 Methods of measurement

2.1.1 Ground-based measurement of horizontal radiation patterns

The conventional method is usually implemented using a field strength meter equipped with a loop antenna placed over a tripod of a height of about 1.5 m. The measurements are carried out at a distance from the antenna of no more than 10 λ at a minimum of 30 points distributed around the antenna.

Field strength values measured with this ground-based method are in general in good agreement with theoretical values when the measurements are performed on a reasonably flat area having height irregularities not exceeding 5 m and no nearby large metallic obstacles are present.

2.1.2 Helicopter-based measurement of radiation patterns

In this case the air-borne receiving antenna is mounted on a mast which can be lowered 3.5 m below the helicopter during measurements, so that the helicopter body does not affect the measurements.

Vertical diagrams are measured by a combination of vertical climbing and approach flights. The helicopter at a distance of 0.5 km from the antenna, begins the measurements close to the ground and climbs to an altitude of 1 000 m (corresponding to an elevation angle of approximately 25°). At that altitude the helicopter continues with an approach flight over the antenna.

The result of the vertical measurement gives the elevation angle at which the antenna diagram could be measured particularly for the purpose of computing the sky-wave field strength. At that angle the helicopter flies in a circle at a fixed radius of 0.5 km or more to obtain the horizontal pattern. (The actual measuring distance is noted on each diagram sheet.)

When measuring the horizontal diagram, there are at least two circles flown to test the consistency of the measurements. The uncertainty margin of these measurements is within 1 dB and generally better than 0.5 dB. The reason for these differences may be that the helicopter has not crossed the main lobe at the same elevation angle, or that the helicopter position on the two circles are not the same.

The indicated antenna gain in the diagram sheets is the antenna system gain which includes the unknown feed network efficiency. It should be noted that the accuracy of the gain calculation depends upon a precise knowledge of the input power to the antenna.

Since the radiation pattern should be measured in the far field, most of the measuring distances mentioned above appear to be somewhat short, but they may be determined by the need to avoid the influence of the other antennas or structures (see § 3.1).

2.2 Measurement equipment

– The measuring antenna for MF is normally a loop antenna (several turns electrostatical shielded).

– Test receiver.

– Computer based control system.

– Global positioning system (GPS) and terrestrial ranging system.

– Helicopter.

– Evaluation equipment: computer and plotter.

2.3 Measurement procedures

2.3.1 Ground

In the conventional method mentioned in § 2.1.1 the loop antenna, placed on a tripod of 1.5 m of height, must be directed upwards to reach a minimum offset field strength and then the test receiver set to null value. Then the loop antenna is directed toward the antenna under test to reach the maximum field strength.

2.3.2 Helicopter

The air-borne field strength meter performs a measurement each time the on-board computer receives a positional update from the ground based positioning equipment (approximately 2 times per second). Using positioning information, the received signal level is corrected to take into account the radiation pattern of the receiving antenna and is related to a fixed distance. Measured signal level data is stored on a floppy disk together with corresponding position data. Further processing consists of averaging data related to two signal level points per degree in the horizontal pattern and several signal points per degree in the climbing part of the vertical pattern.

2.4 Processing the measured data

2.4.1 Ground

All the values measured at different distances should be referred to the same distance, linearly interpolated, from the antenna. These values will be used to establish a polar diagram centred on the antenna site in order to obtain the ground-wave pattern, with non-linear interpolation.

2.4.2 Helicopter

At the end of the flight measurement, disk stored data will be processed by the ground-base evaluation computer. The computer will calculate the field strength taking into account the pattern of the receiving antenna and finally plotting the resulting radiation pattern of the antenna under test.

3 Comparison of theoretical and measured radiation patterns

3.1 Far field

Measurements on LF and MF antenna should be made in their far fields, which are commonly encountered at a distance of 10 λ from the antenna system centre. However, practical considerations may impose considerably lesser distances. These practical distances can be taken as 1 to 5 km for long wave antennas, and 0.5 to 3 km for medium wave antennas. Despite this limitation, pattern measurements made at these distances are in general in good agreement with those calculated through theoretical procedures.

3.2 Variations in practical antenna performance

Figures 13 and 14 show the theoretical horizontal and vertical radiation patterns of an MF 4-tower directional array, whilst in Figs. 15 and 16 the measured horizontal and vertical radiation patterns are presented. These measurements were carried out during the acceptance tests to assess whether the specified patterns in various directions were achieved. A measuring distance of just 500 m was selected to avoid as much as possible the influence of surroundings structures. The corresponding results at a measurement distance of 3 000 m are shown in Figs. 17 and 18.

These measurements show very distorted patterns indicating that the radiation patterns are affected by the surrounding e.g. another existing MW-antenna and an HF curtain antenna system.

The vertical radiation pattern measured at different radiation directions shows that the radiation is concentrated at low radiation angles so that fading due to the sky wave is reduced.

These measurements show that various antenna feeder lines contributed to errors in the measurements.

When measurements were carried out at short distance, the resulting difference from the theoretical value was less than 1 dB. When measurements were carried out at longer distances the largest encountered deviation was 3 dB, possibly due to reflections caused by the environment.

FIGURE 13

Theoretical horizontal radiation pattern of an MF 4-tower directional array

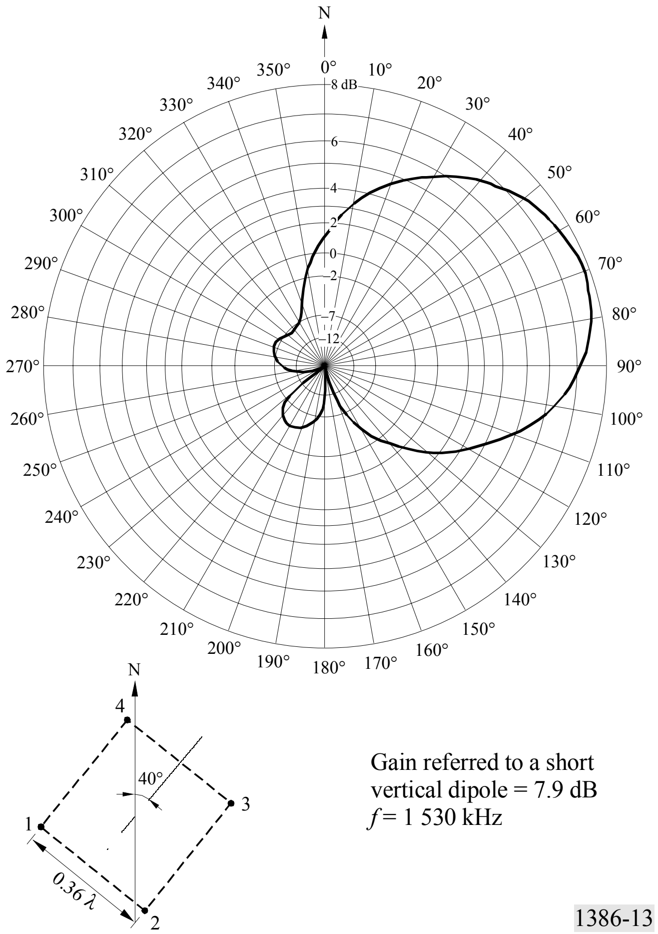


FIGURE 14

Theoretical vertical radiation pattern of an MF 4-tower directional array

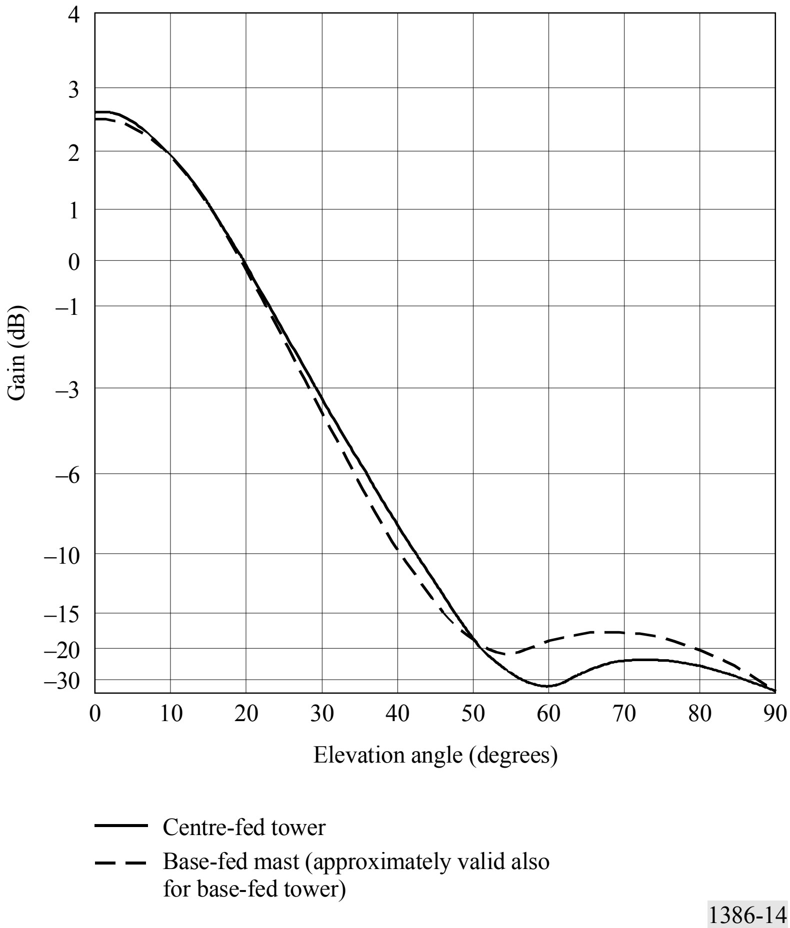
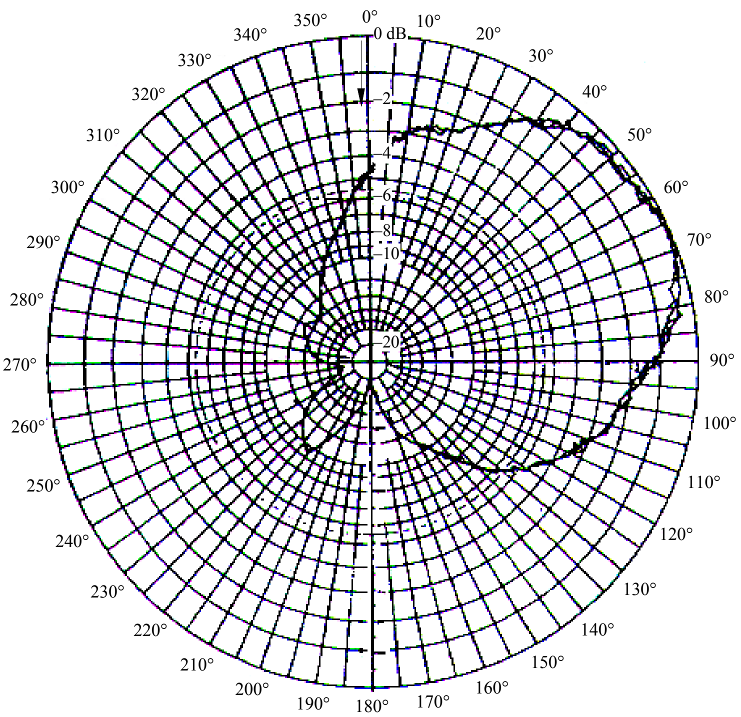


FIGURE 15

Horizontal radiation pattern measured at 500 m of an MF 4-tower directional array



Antenna identity:	MF Pattern B	Measured c.m.f: 180 V (only LF/MF)
Frequency:	1.53 MHz	
Azimuth of maximum radiation:	65°	
Transmited power:	low power	

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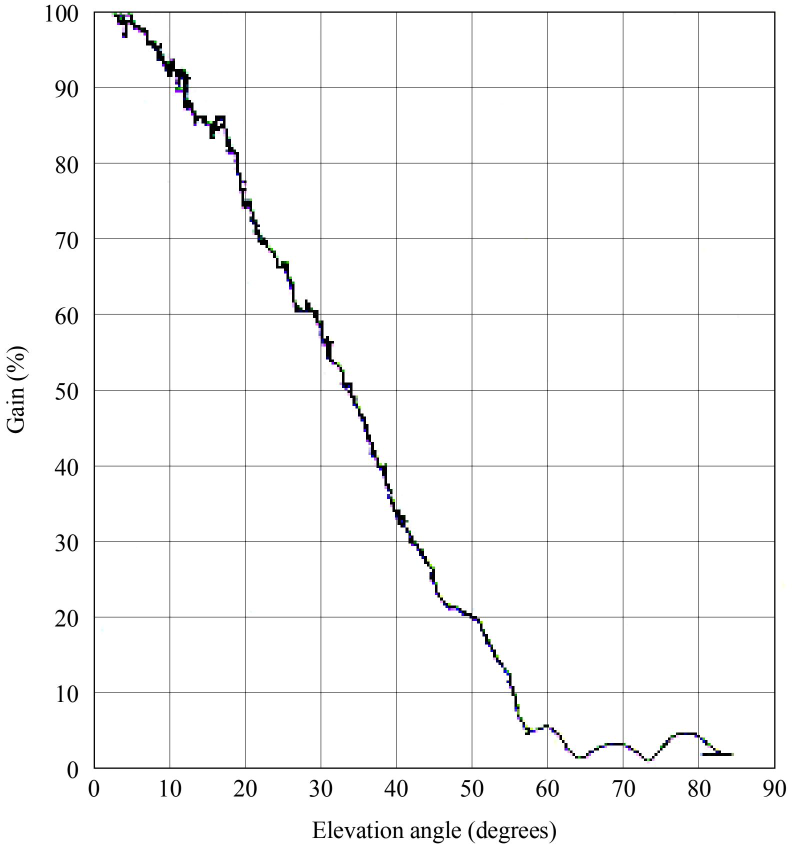
FIGURE 16

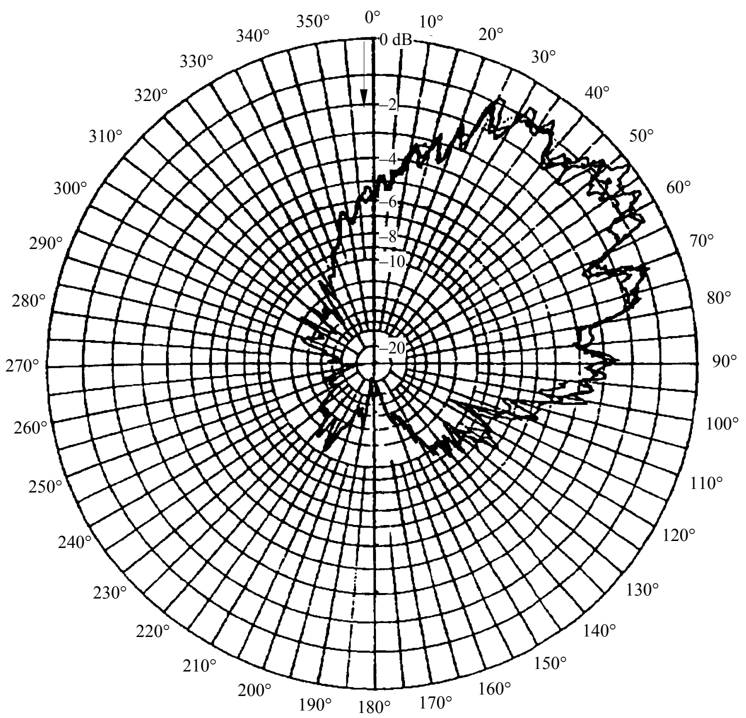
Vertical radiation pattern measured at 500 m of an MF 4-tower directional array



Antenna identity:	MF Pattern B	Measured c.m.f: 180 V (only LF/MF)
Frequency:	1.53 MHz	
Azimuth of maximum radiation:	65°	
Transmited power:	low power	1386-16

FIGURE 17

Horizontal radiation pattern measured at 3 000 m of an MF 4-tower directional array

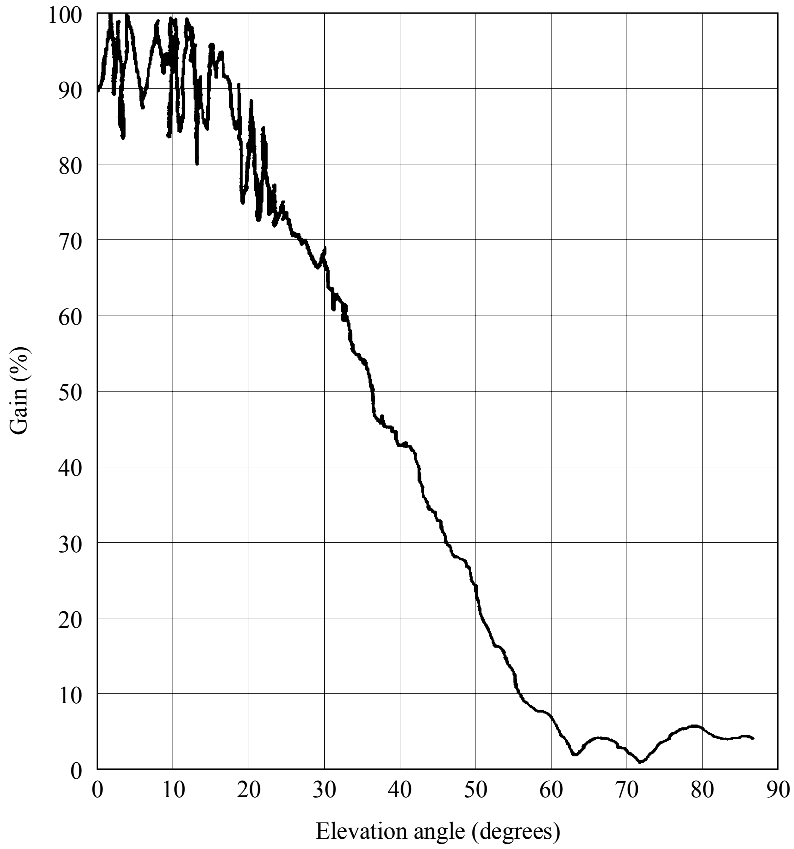


Antenna identity:	MF Pattern B	Measured c.m.f:	8 000 V (only LF/MF)
Frequency:	1.53 MHz		
Azimuth of maximum radiation:	65°		
Transmited power:	high power		

1386-17

FIGURE 18

Vertical radiation pattern measured at 3 000 m of an MF 4-tower directional array



Antenna identity:	MF Pattern B	Measured c.m.f: 8 000 V (only LF/MF)
Frequency:	1.53 MHz	
Azimuth of maximum radiation:	65°	
Transmited power:	high power	

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3.2.1 Influence of surrounding environment on radiation patterns

Figures 13 and 14 represent the calculated patterns. Figures 15 and 16 (pattern at 500 m), and Figs. 17 and 18 (pattern at 3 000 m) show deformations caused by many influencing factors as listed below.

3.2.1.1 Ground conductivity

The measurements of the ground conductivity near the antenna, from 500 m to 3 000 m in agricultural land/soil, with a certain degree of humidity, and the (electrical) characteristics are quasi-constant. As a consequence, the big deformations of patterns at 3 000 m may be considered not to be produced by the changing conductivity of the ground.

3.2.1.2 Ground topography and other site structures

The measurement areas can be considered as flat ground. In Figs. 15 and 16 (500 m distance) no large distortions are introduced and the site has no buildings or roads. But in Figs. 17 and 18 (3 000 m distance) at the azimuthal sector 60° to 90° and in the elevation sector below 25°, a number of large pattern distortions are introduced due to the presence of 3-4 storey buildings and roads.

3.2.2 Feeding arrangements and guy wires

The antenna tested with the helicopter consisted of self-supporting towers, centre fed by coaxial systems, without guy wires. The measurements performed at 500 m did not show distortions produced by the feeding system.

Helicopter measurements performed in another antenna consisting of one guyed mast showed evident pattern distortion at the azimuthal sectors corresponding to the location of guys.